UNIVERSIDAD POLITÉCNICA DE CARTAGENA
Escuela Técnica Superior de Ingeniería de Telecomunicación

HERIOT WATT UNIVERSITY
School of Electronics, Electrical Engineering and Computer Science

Final Degree Project

Development of a Novel Microwave Hyperthermia System for Biomedical Applications

Desarrollo de un Nuevo Sistema de Hipertermia de Microondas para Aplicaciones Médicas.

AUTHOR:	**María Jesús Cañavate Sánchez**
SUPERVISOR:	**José Luis Gómez Tornero**
SECOND SUPERVISOR:	**George Goussetis**

Cartagena, October 2014

Acknowledgements

First I would like to thank all the persons involved in this project, specially to professors Dr. George Goussetis and Dr. José Luis Gómez Tornero. They have provided me the inspiration and motivation to do this project and get involved in microwaves world.

I would like to acknowledge too the support provided by my family and all my friends during all these years. It couldn't have been possible without their help .

Author	María Jesús Cañavate Sánchez
Author's email	mariaj.sanchez92@gmail.com
Director	José Luis Gómez Tornero
Director's email	josel.gomez@upct.es
Co-director	George Goussetis
Title	Development of a Novel Microwave Hyperthermia System for Biomedical Applications

Abstract

Microwave technology is now widely used in a variety of medical applications such as cancer treatment and diagnostics. This project describes the structure of a novel hyperthermia system for biomedical research. The software Ansoft HFSS was used to design a rectangular waveguide applicator. A closed-loop is presented in order to control the output power of the system by the temperature measured on the sample. Initial results from experimental testing are presented. In these results, it is shown that the water temperature can be increased from 21ºC to 40ºC in 12 minutes. Therefore, it has been tested that the system works properly. The next step would be to apply the system to melanoma cancer cells.

Ya existen tecnologías que implican el uso de microondas en una gran variedad de aplicaciones médicas tales como el diagnóstico y el tratamiento del cáncer. Este proyecto describe la estructura de un nuevo sistema de hipertermia para ser usado en todo tipo de investigaciones biomédicas. El software Ansoft HFSS ha sido usado para diseñar una guía de onda rectangular que será el componente final al que se aplicará nuestro sistema. Además, se dispone de un bucle cerrado en el propio sistema para poder controlar la potencia de salida en función de la temperatura medida en la muestra. Los resultados iniciales del experimento se han presentado en este documento. En estos resultados, se muestra que la temperatura del agua puede ser incrementada desde 21ºC hasta 40ºC en unos 12 minutos. Por lo tanto, se ha comprobado que el sistema funciona de forma adecuada. El siguiente paso sería aplicar el sistema directamente sobre células cancerígenas.

Degree	Telecommunications Systems Engineering Degree
Department	Communication and Information Technologies
Submission date	October 2014

Contents

List of Figures

Chapter 1

Summary in Spanish

En este apartado se va a realizar un resumen en español de todo el proyecto. Las referencias usadas en el mismo sólo se mostrarán en el resto de capítulos según su orden de aparición.

1.1 Introducción

Hasta ahora varios sistemas diferentes de hipertermia se han desarrollado. Estas estructuras usualmente incluyen componentes bastante pesados y costosos como por ejemplo un generador de microondas o un medidor de potencia. En general, suele haber una demanda que exige componentes más ligeros, compactos y baratos. Por esta razón, el principal propósito de este proyecto es la realización de un nuevo sistema de hipertermia para el tratamiento de tumores superficiales (como melanoma) que mejor cumpla estas características. Para poder entender las propiedades que han sido elegidas para el sistem, una descripción del concepto de hipertermia se presentará en la siguiente sección.

El objetivo principal del sistema es su aplicación en el tratamiento y la investigación in-vitro. Sin embargo, los componentes empleados en el sistema pueden ser usados con otro aplicador más adecuado para muestras in-vivo. En cuanto a las ventajas del sistema, podemos decir que tiene un control preciso de la temperatura, calienta de forma homogénea las muestras in-vitro y produce un aumento rápido de la temperatura. Una guía de onda a modo de horno será el aplicador de nuestro sistema. El diseño del mismo con el software

HFSS será presentado. Finalmente, para validar la funcionalidad del sistema, un frasco con agua será introducido en el aplicador.

1.1.1 Objetivos del Proyecto

Como resumen, los principales objetivos de este proyecto que envuelve el diseño de un sistema de microondas para el tratamiento de muestras in-vitro son:

- Control de la temperatura.
- Calentamiento uniforme de las muestras.
- Incremento rápido de la temperatura.
- Componentes más ligeros, compactos y baratos.

1.2 Hipertermia en el tratamiento del cáncer

La hipertermia consiste en un tratamiento en el cual elevadas temperaturas se inducen en el tejido corporal durante un periodo específico de tiempo. Cuando la hipertermia se usa para el tratamiento del cáncer, el objetivo es incrementar la temperatura de las células cancerígenas hasta unos 40-44°C durante unos 30-60 minutos mientras que la temperatura de los tejidos cercanos no debe de incrementar. Se ha comprobado que altas temperaturas como las que se usan en este tratamiento producen efectos que pueden provocar la muerte de las células cancerígenas o hacerlas más vulnerables a la radiación ionizante. Por esta razón, varias investigaciones han llegado a la conclusión de que el uso de la hipertermia junto con otras terapias como la radioterapia o la quimioterapia ha provocado la disminución del tamaño del tumor.

1.2.1 Métodos para el tratamiento de hiperthermia

Los principales métodos usados son la hipertermia local, la aplicada a una región del cuerpo y la aplicada a todo el cuerpo. En la figura 1.1, aparece mostrado gráficamente la diferencia, en cuanto a aplicación, de los métodos nombrados.

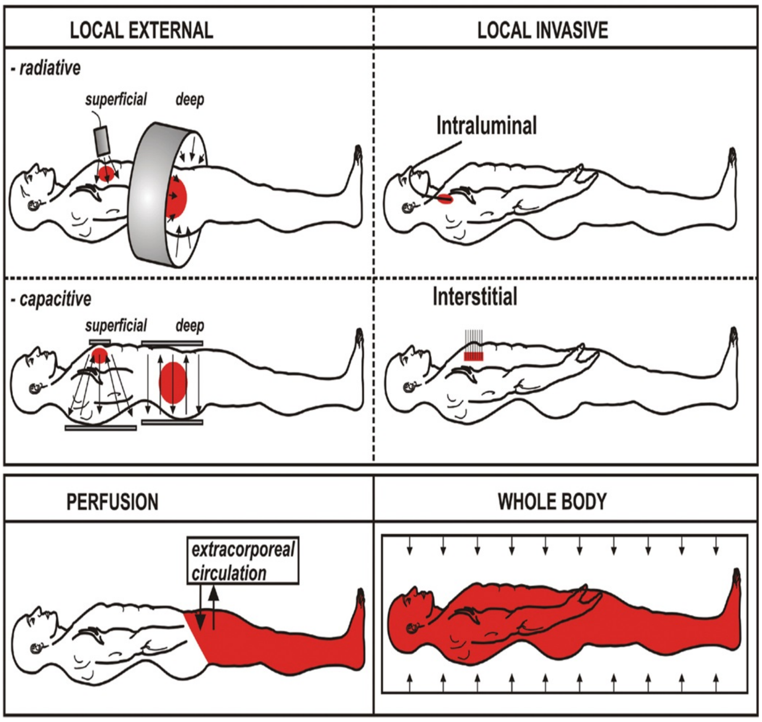


Figure 1.1: Técnicas de hipertermia.

Como el objetivo de este proyecto está centrado en el estudio del tratamiento del cáncer de piel (melanoma), el método superficial parece ser el más adecuado en este caso. Consecuentemente, el sistema proporcionará una potencia a un aplicador que de manera externa centrará la energía en las células cancerígenas de la piel.

1.3 Estructura del sistema

Para poder diseñar el sistema, es muy importante conocer la cantidad de potencia que va a ser necesaria. Para ello, algunas condiciones como la temperatura de comienzo, la temperatura objetivo, el volumen sobre el que se aplica la potencia y el tiempo requerido se deben establecer para calcular esa potencia. Además, la densidad y el calor específico del material sobre el que se aplicaría la potencia son esenciales para el cálculo también.

Una vez obtenidos todos estos datos, en nuestro caso hemos obtenido que la potencia requerida es unos 32 dBm. El cálculo realizado se puede observar en el código de matlab siguiente:

Matlab Code 1.1: Obtener el nivel de potencia.

```
clear all; close all; clc

    % Input
        flask_diameter_m = 0.09;
        flask_height_m = 0.0016;
        starting_temperature_C = 22;
        target_temperature_C = 44;
        ramp_up_time_s = 600;

        % Water Properties
        density_kg_per_m3 = 998.02;
        specific_heat_capacity_J_per_kg_C = 4184;

        flask_area_m2 = pi * (flask_diameter_m / 2)^2;
        flask_volume_m3 = flask_area_m2 * flask_height_m; % 10 ml
        mass_kg = density_kg_per_m3 * flask_volume_m3;
        change_in_temperature_C = abs(target_temperature_C - ...
            starting_temperature_C);
        heat_energy_added_J = specific_heat_capacity_J_per_kg_C * ...
            mass_kg * change_in_temperature_C;

    % Output
        power_level_W = heat_energy_added_J / ramp_up_time_s
        power_level_dBm = 10 * log10(power_level_W * 10^3)
```

Teniendo en cuenta esto y que la frecuencia que se va a usar es la correspondiente a la banda ISm de 915 MHz, en la figura siguiente se muestra el sistema con todos los componentes:

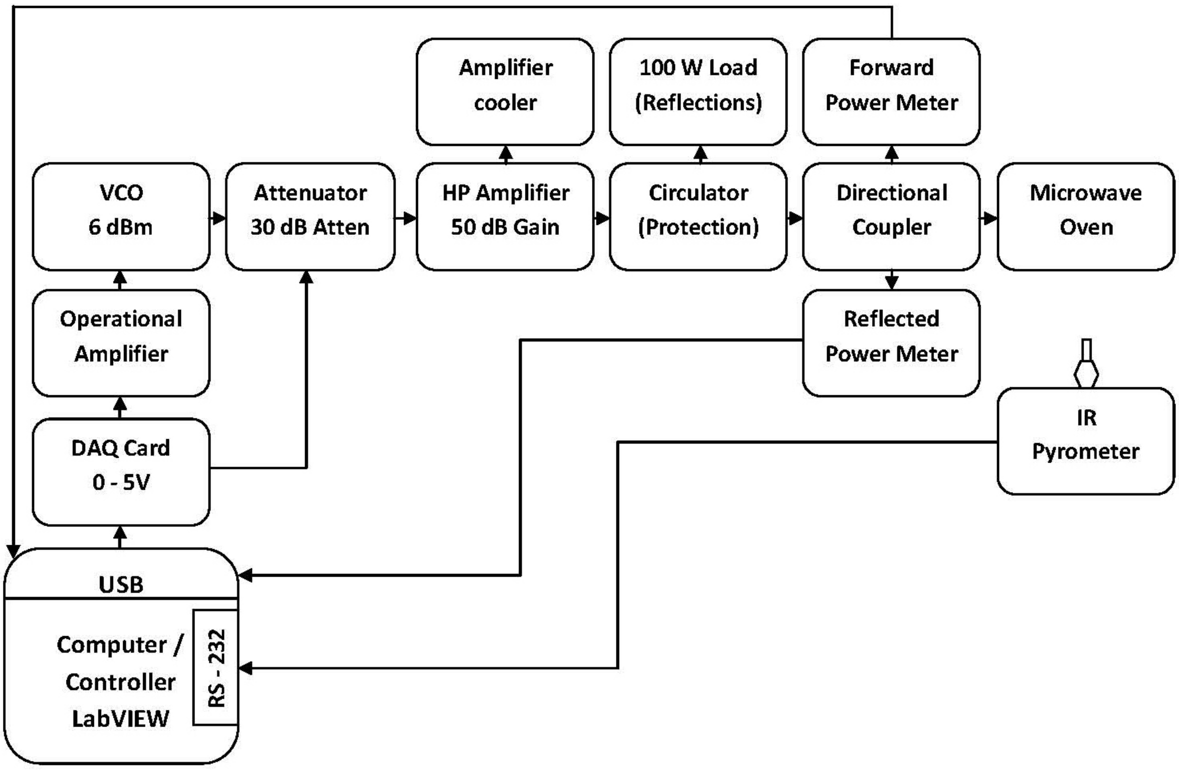


Figure 1.2: Diagrama de bloques de todos los componentes del sistema.

Como se puede observar en la figura anterior, el sistema está formado por un oscilador, el cual va a proporcionar la señal y su frecuencia podrá ser controlada con un voltaje de entrada. A continuación tenemos un atenuador, el cual nos va a servir para controlar el nivel de potencia, ya que el amplificador tiene una ganancia fija. Después del amplificador tenemos un circulador con una carga, que van a servir para aislar el amplificador de posibles reflexiones. El penúltimo componente es un acoplador, que será usado para calcular la potencia de entrada al aplicador y las reflexiones. Finalmente, tenemos el aplicador, cuyo diseño será presentado en la siguiente sección.

1.3.1 Closed-Loop

Todos los parámetros del sistema, como la frecuencia, la potencia y la temperatura, pueden ser monitorizados desde un ordenador personal. El software utlizado para este propósito es LabVIEW.
En primer lugar, para ajustar la frecuencia desde LabVIEW, se requiere una tarjeta de adquisición de datos DAQ que conecte el oscilador al ordenador vía USB. En segundo lugar, el control de la potencia se lleva a cabo con el uso de un atenuador, que se conecta con la misma tarjeta al ordenador.
Finalmente, la temperatura se mide con un termómetro que se coloca sobre el aplicador con la lente enfocada hacia el recipiente con agua. Este termómetro se conecta también al ordenador vía RS-232. Como resultado, el sistema proporciona una medida en tiempo real de la temperatura, a la vez que esa temperatura se usará para el control del nivel de la potencia.

1.4 Diseño del aplicador

En el diseño del aplicador se han tenido en cuenta varios requisitos. Dado que nuestro objetivo es validar el funcionamiento del sistema de hipertermia calentando el agua introducida en un frasco, decidimos colocar dicho recipiente dentro de una guía de onda, puesto que es fácil de diseñar. Para conseguir esto el aplicador está formado por dos cavidades rectangulares de aluminio con una diferencia de anchura para que una lámina de "rohacell" pueda ser posicionada entr las dos cavidades. La razón porque se escoge este material es porque su permitividad es similar a la del aire y por lo tanto no produce una discontinuidad. Gracias a esta estructura es posible colocar el recipiente sobre el rohacell. Además, la cima de la cavidad más corta se puede retirar para permitir la manipulación del recipiente. En ese mismo lugar se ha hecho un orificio del tamaño del termómetro para poder medir la temperatura del agua. Finalmente, un conector de tipo N se ha colocado en la parte inferior de la cavidad más grande para conectar el sistema al aplicador.

Figure 1.3: Cavidad fabricada.

El campo eléctrico en simulado con HFSS es el mostrado en la siguiente figura:

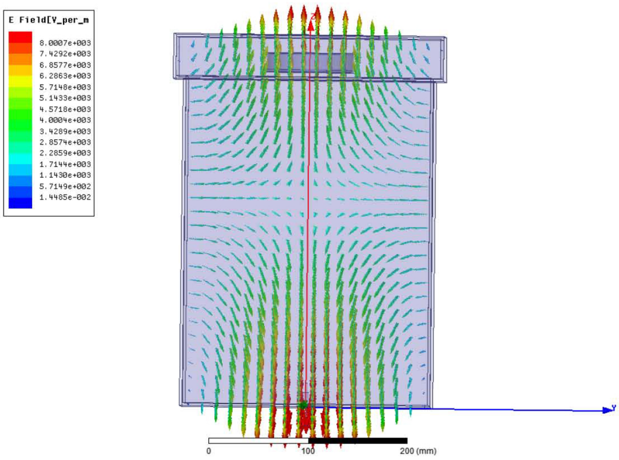


Figure 1.4: Campo eléctrico (modo TM).

El valor del parámetro S_{11}, tanto simulado (HFSS) como medido (VNA) se muestra a continuación:

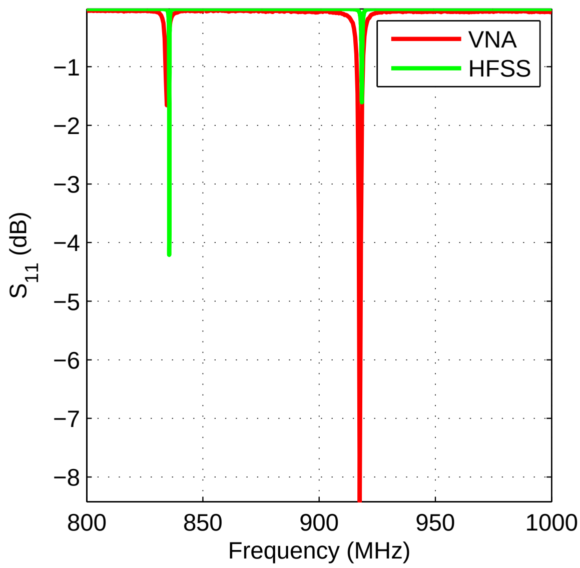


Figure 1.5: Comparación entre el valor del parámetro S_{11} medido y simulado.

sectionMedida de la temperatura Antes de medir la temperatura se ejecuta un bucle creado con el software LabVIEW, que proporciona el voltaje requerido por el oscilador para transmitir a la frecuencia en la que el parámetro S_{11} es más bajo. Una vez se conoce tal frecuencia, es introducida en el programa LabVIEW usado para controlar el sistema. La temperatura obtenida en la primera prueba ha sido la siguiente:

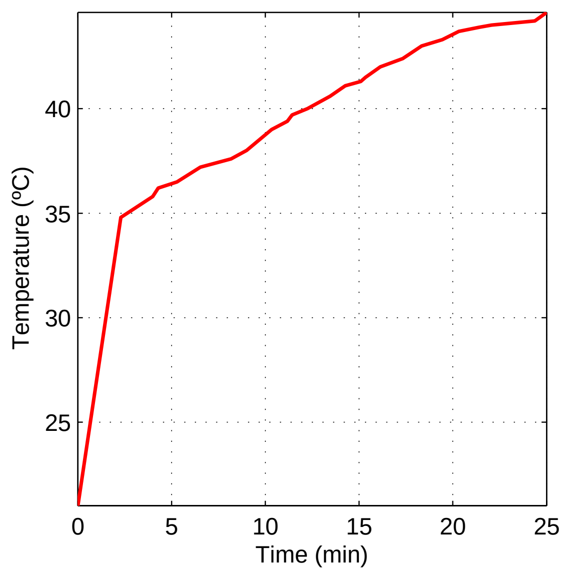


Figure 1.6: Temperatura medida con el sistema.

En la figura anterior se observa que la temperatura del agua ha aumentado y por tanto el sistema funciona. Han sido necesarios 12 minutos para aumentar la temperatura desde 21°C hasta 40°C, lo que supone un resultado satisfactorio en relación a otros sistemas de hipertermia.

1.5 Conclusiones

En este proyecto se presenta un nuevo sistema de hipertermia. Tras escoger todos los componentes que conforman el sistema, una cavidad de guía de onda fue diseñada con HFSS y manufacturada después. Se ha comprobado que la frecuencia de resonancia, tanto del aplicador simulado como del fabricado, coinciden. La diferencia entre ellos es que el valor del parámetro S_{11} es más bajo en el sistema simulado. Esto se puede atribuir al hecho de que la cvidad fabricada tiene en cuenta otros factores físicos que la simulación no tiene en cuenta.

En cuanto a la medida de la temperatura del agua, se ha podido comprobar que sólo 12 minutos se requieren para incrementarla desde 21°C hasta 40°C. Como la temperatura necesaria para el tratamiento de hipertermia se encuentra entre esos valores, un bucle de realimentación será implementado para controlar la potencia de salida del sistema en función de dicha temperatura. El funcionamiento de este sistema consistiría en incrementar el valor de la potencia del sistema si la temperatura es más baja que el valor requerido para el tratamiento, y de incrementarla si fuera más alta que la necesaria. Una vez logrado este objetivo, el siguiente paso sería la aplicación del sistema en células de melanoma.

Chapter 2

Introduction

Up to present, several hyperthermia systems have been developed. These structures usually include heavy and costly components such as a microwave generator or a power meter [1], [2]. In general, there is a demand for lighter, more compact and cheaper systems and for this reason, the main purpose of this project is to establish a new hyperthermia system for treating superficial tumors that best suits these characteristics. In order to understand the features that were chosen for this particular system, a complete description of what hyperthermia is and its methods will be presented in the following chapter.

The system primarily targets in-vitro research although the RF chain can be used with another RF applicator more suitable for in-vivo exposures. In terms of the advantages of the system we can say that it has accurate temperature control, homogeneous heating of the sample and rapid temperature rise. The design of a waveguide applicator by the use of the HFSS software has been presented. Finally, in order to validate the functionality of the system, a flask containing water was introduced into the applicator.

2.1 Project Aims

As a summary, the principal aims of this project which involves the design of a novel hyperthermia system for in-vitro exposures are:

- Control of the temperature.
- Uniformity heat of the exposures.
- Rapid temperature rise.
- More compact, lighter and cheaper components.

Chapter 3

Hyperthermia in Cancer Treatment

3.1 Hyperthermia Concept

Hyperthermia denotes a thermal therapy in which elevated temperatures are induced in body tissue for a specific period of time [3]. When hyperthermia is used to treat cancer, the aim is to increase the temperature in the malignant cells above 40-44°C for 30-60 minutes while maintaining typical physiological temperatures in the nearby tissue. Previous evidence suggests that high temperatures such as the ones reached using this treatment produce cytotoxic effects which can provoke tumor cells death or make them more defenceless to ionizing radiation and chemical toxins, normally with least harm to the healthy tissues [4], [5]. Due to this fact, over the past decade most research in cancer treatment has emphasized the use of hyperthermia combined with other therapies such us radiotherapy and chemotherapy. Regarding that, a number of researches have reported that the use of these treatments together has shown a considerable diminution in tumor size [3]- [6].

In order to understand the science behind hyperthermia, the four major ways in which this treatment helps to attack cancer are described below [7]:

- As it was said, heat can **destroy** or **debilitate cancer cells**.
- Elevated temperatures raise blood flow through the debilitated tumor, which can **enable therapies to penetrate the tumor**, not just affect it from the exterior.
- Intensified blood flow increases oxygen levels in tumors so that **radiotherapy treat-**

ment is more successful.

- If the body perceives high temperature, it **stimulates the natural immune system**, assaulting the tumor cells.

Regarding the third point, it is easy to understand graphically what is happening while applying hyperthermia to the body tissue [7]:

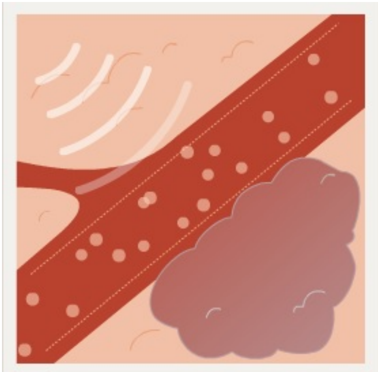


Figure 3.1: Heat provokes blood vessels dilatation.

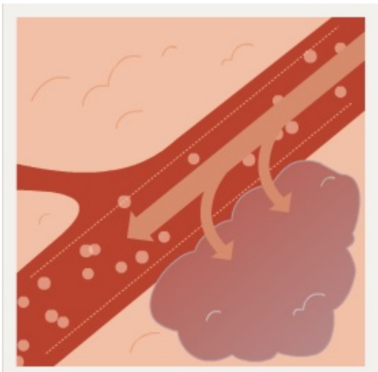


Figure 3.2: Blood flow raises into tumor.

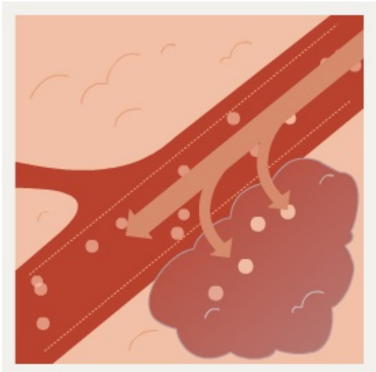


Figure 3.3: The tumor receives oxygen from the blood.

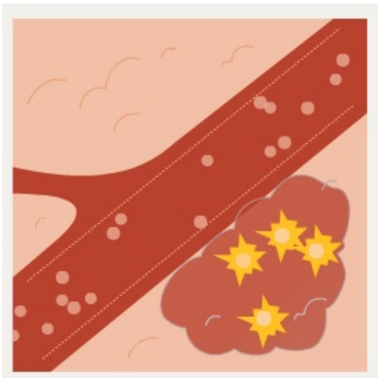


Figure 3.4: Oxigen responds to radiation by damaging the malignant cells.

Several studies have revealed that the reason why this hyperthermia treatment produces more damage in cancer cells than in healthy ones is that, as the vascular system in tumors is irregular and incompletely developed, the blood flow in them is lower than in the healthy tissue, which makes the tumor more vulnerable to heat. As a result, when the temperature of a body part passes its typical value, then the blood flow of both, the tumor and healthy tissue, increases in order to behave as a cooler. As the blood flow of the tumor raises less than the one of the healthy tissue, the cooler efect is consequently lower and the temperature conserved in the tumor is higher [8], [9].

3.2 Methods of Hyperthermia

To date, the main methods of hyperthermia are local, regional and whole-body hyperthermia, which are described below [10]:

- **Local hyperthermia**: heat is focused on a small area in order to raise the tumor temperature. Different ways can be used to apply local hyperthermia and these are determined by the location of the tumor, such as *external* methods which are used for tumors located in or close to the skin. By using this method, applicators are placed next to the affected area of the body in order to concentrate the energy on the cancer cells and increase their temperature. Another technique is the *intraluminal*, mainly used for tumors within or near body cavities. In this case, probes are introduced into the tumor to apply the heat straight to it. The third and last method is the *interstitial* technique, which is used to treat deep tumors. It is possible to achieve a higher temperature than with external techniques by using this method, which consists in placing probes or needles into the tumor while the patient is under anesthesia.

- **Regional hyperthermia**: this technique can be applied by *deep tisue, regional perfusion* or *continuous hyperthermic peritoneal perfusion* (*CHPP*) to treat larger areas of tissue than local hyperthermia. These areas could be body cavities, organs, or limbs. *Deep tissue* is mainly used to treat tumors within the body such as cervical cancer. This may use external application of heat by an external applicator. Regarding the *regional perfusion*, this method is usually used to treat the limbs and some organs, such us the liver or the lungs. During this process, part of the patient's blood is extracted, warmed, and then sent back to the organ. The last method, *CHPP*, is applied to treat tumors within the peritoneal cavity (the area within the abdomen that includes the intestines, stomach, and liver). Throughout surgery, warmed anticancer drugs are introduced into the peritoneal cavity by using a warming machine.

- **Whole-body hyperthermia**: this is the case in which it is treated the cancer that has extended throughout the body, which is called metastatic cancer. Several methods could be suitable to treat this kind of cancer such as the use of thermal chambers or hot water blankets.

In Fig. 3.5, these techniques can be shown graphically [11]:

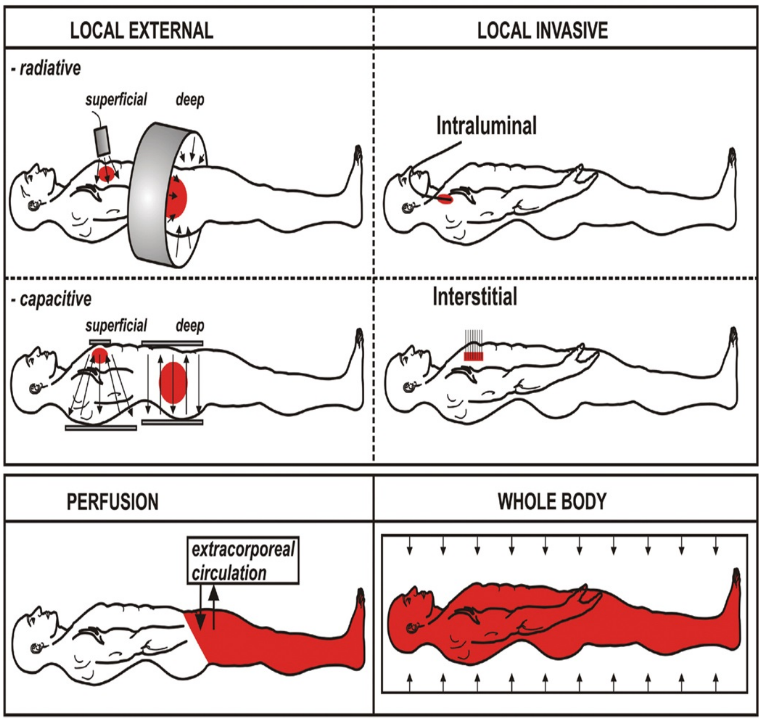


Figure 3.5: Hyperthermia Techniques.

As the aim of this project is to develop a novel hyperthermia system that will be used as a reference for following studies focused on melanoma cancer research and treatment, which is a type of skin cancer, the external hyperthermia method is the most suitable technique in this case. Consequently, the system will apply power to an external applicator which will focus that energy on the cancer cells of the skin in a non-invasive way.

Chapter 4

Structure of the System

This chapter is divided into four sections that help to explain the architecture of this novel hyperthermia system. First of all, the calculation of the necessary power value of the system to be able to achieve the temperature needed in a hyperthermia treatment is presented. Secondly, the characteristics of all the components that form the structure and the functionality of the whole system are described. Finally, at the end of the chapter, a budget including the price of all the elements will be introduced.

4.1 Calculation of the Required Power

Some general conditions, such as starting temperature, ramp-up time and volume, together with some properties, such as specific heat capacity and density, determine the quantity of power necessary to achieve a desired temperature in a specific situation. This system is going to be first used to heat only water in order to check the functionality of the system. Once it has been proved that it works properly, it will be applied to in-vitro exposures (cells). Therefore, the values of these conditions and properties are determined by the power required to heat the amount of water necessary to keep the cells alive.

The general conditions are characteristics that we choose for our system:

- **Starting temperature**: as the first aim is to try the experiment with only water, the temperature of a flask filled with water (the one that would be used for the experiment) was measured by the use of a thermometer (see Appendix section A.1) in order to have an approximation of the starting temperature of the water in the laboratory. This value was around 22°C.

- **Target temperature**: in the previous chapter, it was said that, in a hyperthermia treatment, the temperature of the tumor cells must be increased to around 40-44°C. Therefore, the target temperature should be 44°C in order to be able to operate in a bigger range of temperatures.

- **Ramp-up time**: in order to establish this factor, other hyperthermia systems related to the treatment on in vivo melanoma model such as [1] and [12] have been taken into account. In both systems, a mouse with melanoma cancer is treated by using a hyperthermia method. The time period required to increase the temperature of the tumour core of the mouse from around 32.5°C (starting temperature) to 44°C (target temperature) is approximately 600 seg. As we are interested in a rapid temperature rise and in a cheaper system as well, there should be a balance between these two characteristics since the faster increase of temperature, the more power required (see Equation 4.3) and, as a consequence, the more expensive the system. Therefore, as we do not want our system to be slower than the existing ones and we prefer a cheaper price, the ramp-up time chosen for this calculation is 600 seg.

- **Volume**: this value corresponds to the amount of water needed to keep the cells alive inside the flask that will be used for the experiment. The volume has been calculated below (see Matlab Code 4.1) by taking into account the diameter of the cylindrical flask and the height of it filled with water (both values were given by the biologists from the laboratory involved in the research).

In terms of the properties that are relevant in the calculation of the required power, it is important to know that they correspond to constant values that depend on the material which is going to be heated (water in this case):

- **Density (ρ)**: is the mass (m) per unit volume (V). The density of liquid water is 998.02 kg/m^3 at the starting temperature that was selected. The equation of the density will be used later [13]:

$$\rho = \frac{m}{V} \tag{4.1}$$

- **Specific heat capacity (c)**: the heat capacity (C) is the “measurable physical quantity of heat energy required to change the temperature of an object by a given amount” and the specific heat capacity is the “heat capacity per unit mass”. The value of the specific heat capacity of water is 4184 J/kg°C. The equation that is related to the specific heat capacity is the following [14]:

$$Q = C(T_f - T_i) = cm(T_f - T_i) \tag{4.2}$$

in which Q is the heat that the warmed material absorbs or loses, T_i corresponds to the starting temperature, T_f represents the target temperature and m is the mass of the material.

Once that all these conditions and properties have been taken into account, the equation that calculates the required power can be applied. The average power, P_{avg}, corresponds to the energy used (Q) during a time interval (Δt) [15]:

$$P_{avg} = \frac{Q}{\Delta t} \tag{4.3}$$

in which Δt is the ramp-up time.

As shown in Matlab Code 4.1, a Matlab script was made in order to calculate the required power of the system by the use of all the equations that were presented above. It is relevant to take into account that the flask has a cylindrical shape to be able to calculate its area and volume.

Matlab Code 4.1: Obtaining Power Level.

```
clear all; close all; clc

    % Input
        flask_diameter_m = 0.09;
        flask_height_m = 0.0016;
        starting_temperature_C = 22;
        target_temperature_C = 44;
        ramp_up_time_s = 600;

        % Water Properties
        density_kg_per_m3 = 998.02;
        specific_heat_capacity_J_per_kg_C = 4184;

        flask_area_m2 = pi * (flask_diameter_m / 2)^2;
        flask_volume_m3 = flask_area_m2 * flask_height_m; % 10 ml
        mass_kg = density_kg_per_m3 * flask_volume_m3;
        change_in_temperature_C = abs(target_temperature_C - ...
            starting_temperature_C);
        heat_energy_added_J = specific_heat_capacity_J_per_kg_C * ...
            mass_kg * change_in_temperature_C;

    % Output
        power_level_W = heat_energy_added_J / ramp_up_time_s
        power_level_dBm = 10 * log10(power_level_W * 10^3)
```

The result given by Matlab is the following:

- $P_{avg}(W) = 1.5585$ W
- $P_{avg}(dBm) = 31.9270$ dBm

It is important to highlight that the power that the amount of water that we want to heat needs to increase its temperature from 22°C to 44°C in 600 seg is around 32 dBm. Nevertheless, the manufactured applicator of the system could have some reflexions or losses. In that case, not all the energy applied to the applicator would be consumed by the water. Therefore, the power level chosen for the system is around 40 dBm.

4.2 Identification of the Components

The way heat is produced can vary depending on the depth and the magnitude of the tumor. Regarding this issue, different techniques can be applied for different situations such as ultrasound (2-15 MHz), radiofrequency (13-28 MHz) or microwave (434-2450 MHz) radiation. Taking into account that this study concerns superficial hyperthermia, a low depth penetration of the waves is required. The depth penetration depends on the frequency, the highest frequency, the lowest penetration [16], [17]. Therefore, a microwave system was selected.

Apart from chosing the technology of the system, other characteristics such as the ones that are presented below must be selected:

- **Frequency**: the frequency bands that are more commonly used in microwave hyperthermia are the ISM bands of 434 and 915 MHz [1]. As it is required a low depth penetration, the frequency band chosen was the 915 MHz band. For this reason, we selected components that are allowed to work between 0.9 and 1 GHz.
- **Maximum power**: this value is related to the one calculated in the previous section (required power of the system). Therefore, the maximum power must be around 40 dBm or more.
- **Impedance**: owing to the fact that the spectrum analyzer which is located in the laboratory has an impedance of 50 Ω, the impedance chosen for the system was the same. Moreover, most RF devices have that impedance.
- **Connectors**: several companies which commercialize with RF devices such as Mini-circuits, RF Components or JQL, were checked out in order to know the methods that were most commonly used to connect microwave devices. These methods were surface mount and the use of connectors such as SMA or N (to work at the frequency that is suitable for this system). As surface mount involves components placed directly onto a surface, the method selected was the use of connectors which do not need a surface to connect the devices. By this way, it is easier to add new components if it is required.

In Table 4.1, a summary of the system properties is presented:

Characteristic	**Choice**
Frequency	ISM band 915 MHz
Maximum power	40 dBm
Impedance	50 Ω
Connectors	SMA and N

Table 4.1: Characteristics of the system

In order to design the structure, an existing microwave system for the encapsulation of microelectronic components was selected since its properties were similar to the ones that we needed, although some modifications were perfomed and the components are not the same [18]. The final and modified system is shown in Fig. 4.1.

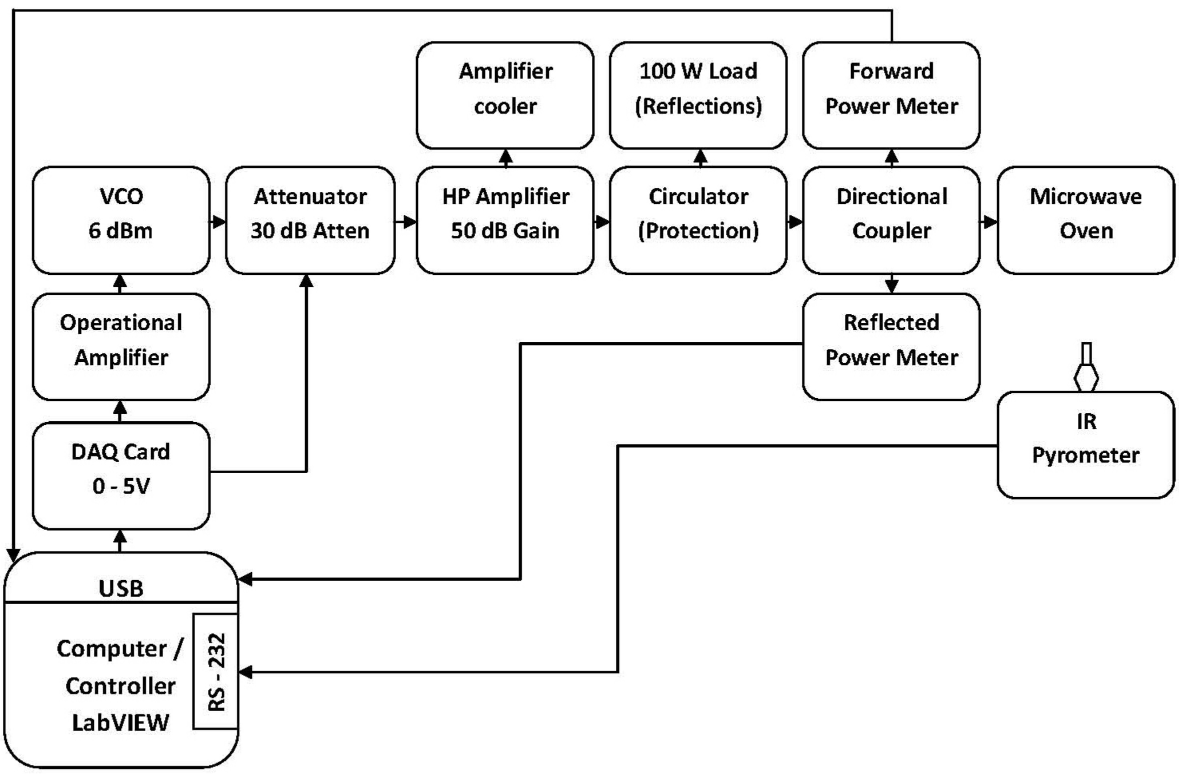


Figure 4.1: Block diagram of the necessary components to drive the microwave induced hyperthermia system.

As shown in Fig. 4.1, the hyperthermia system is composed of some active elements:

- **Voltage-Controlled Oscillator or VCO**: this is the device used to create the signal at the required frequency. This frequency is controlled by an input voltage which can go from 0.5 to 28 V to tune the frequency from 750 to 1010 MHz. The output power is around 6 dBm (see Appendix section A.2).

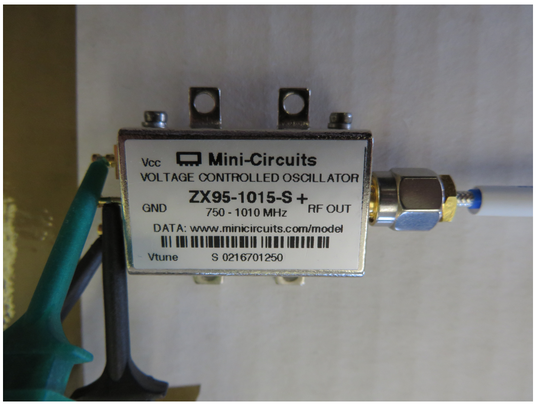


Figure 4.2: Voltage-Controlled Oscillator in the Laboratory.

- **Bus-Powered Multifunction DAQ**: in order to connect the VCO to a PC to be able to adjust the frequency from it, a data acquisition card or DAQ was required. This device has the ability to generate signals as well as collect them. Therefore, thanks to this instrument, it is possible to select the frequency of the VCO by selecting the output voltage of the DAQ card. This can be made by the use of a computer connected to the card via USB and the use of a software. This device has 8 analog inputs (±10 V) and 2 analog outputs (0-5 V) (see Appendix section A.3).

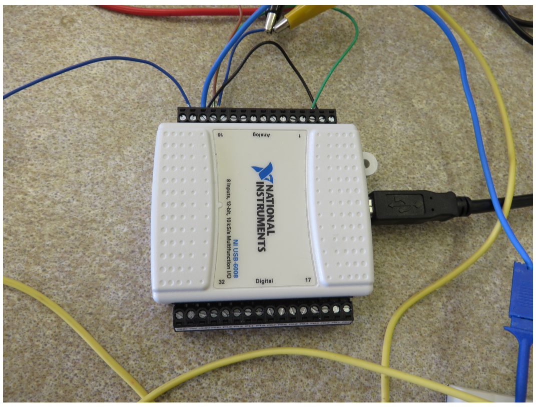


Figure 4.3: Bus-Powered Multifunction DAQ in the Laboratory.

- **Operational Amplifier LN324AN**: As the maximum output voltage value of the DAQ card is 5V (see Appendix section A.3) and the voltage necessary to choose a frequency of the ISM band of 915 MHz on the VCO is around three times greater than 5V (see Appendix section A.2), the card was connected to a 3 dB gain operational amplifier and the output of this one to the tune voltage input of the VCO. As a reminder, the structure of a non-inverting amplifier is the one shown in Fig 4.4 [19]:

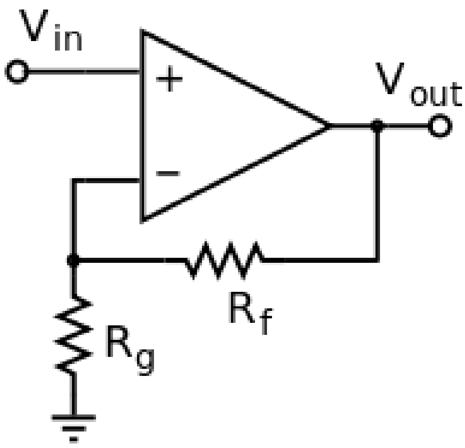


Figure 4.4: Structure of a Non-Inverting Amplifier.

in which the value of the gain (G) depends on the value of the resistors [19]:

$$G = 1 + \frac{R_f}{R_g} \tag{4.4}$$

As we need a gain of 3 dB, the relation between both resistors should be the following:

$$\frac{R_f}{R_g} = G - 1 = 3 - 1 = 2 \tag{4.5}$$

Therefore, the value of resistor R_f should be double the value of R_g. The chosen resistors were: R_f = 300 KΩ and R_g = 150 KΩ.

In order to be able to connect the resistors to the operational amplifier, a protoboard was used. Fig. 4.5, extracted from Appendix section A.4, shows the connections of the Operational Amplifier LN324AN, which is the one that was used:

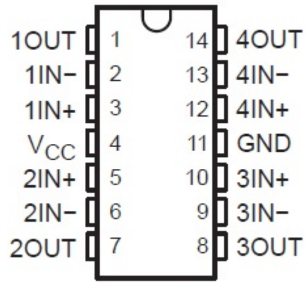


Figure 4.5: Operational Amplifier Connections.

As it is shown in the figure above, this device has four operational amplifiers. Since we used the first one to make the circuit of a non-inverting amplifier, R_f was connected to 1OUT and 1IN- and R_g to 1IN- and GND. In Fig 4.6, it is presented the circuit connected to a protoboard.

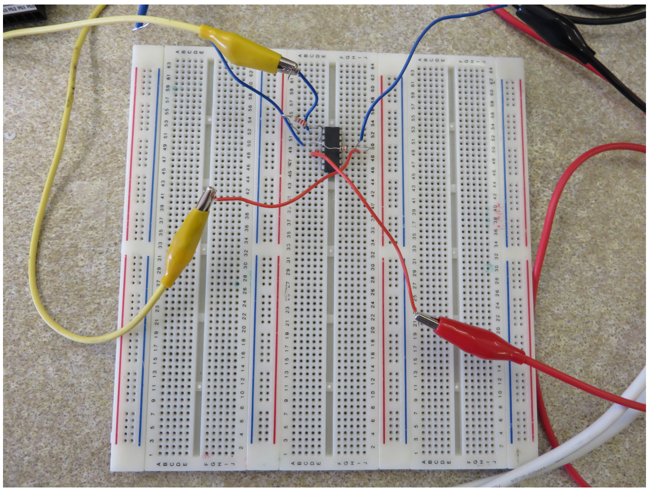


Figure 4.6: Non-Inverting Amplifier Connected to a Protoboard.

- **Voltage Variable Attenuator ZX73-2500+**: due to the fact that the amplifier selected for the system is designed as a fixed gain amplifier (ie: there is no gain control available to the user) and it is necessary for our closed-loop to control the signal level, it was considered the use of a voltage variable attenuator in front of the amplifier to reduce the input level as required. This attenuator model has an attenuation range that goes from 0 to 30-40 dB. The attenuation is set by varying a DC control voltage in the same way as the VCO (see Appendix section A.5). Therefore, the control of the power of the system is accomplished by the use of the attenuator, which is connected to the PC by using the same DAQ card that was presented before.

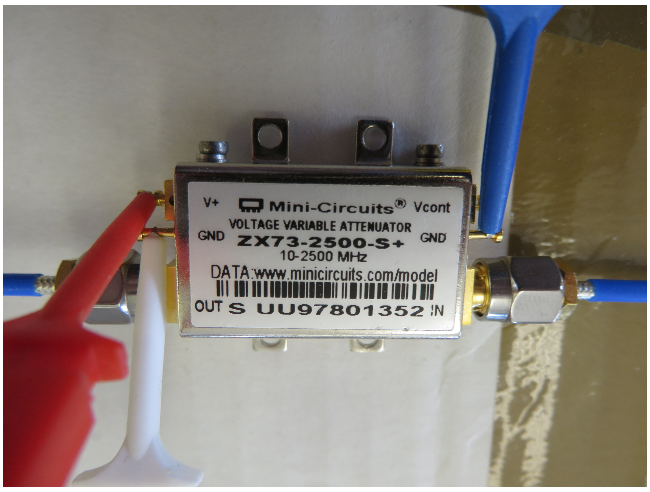


Figure 4.7: Voltage Variable Attenuator in the Laboratory.

- **High Power Amplifier ZHL-100W-13+**: The reason why we selected a fixed gain amplifier instead of a variable gain amplifier is that the second one is much more expensive than buying an attenuator to control it. The gain of this amplifier is 50 dB and the output power at 1 dB compression is around 50 dBm, which means that the maximum output power available while providing linear amplifications is 50 dBm (see Appendix section A.6). What is more, a heat sink was provided to limit maximum base-plate temperature to 60°C, in order to ensure a proper performance.

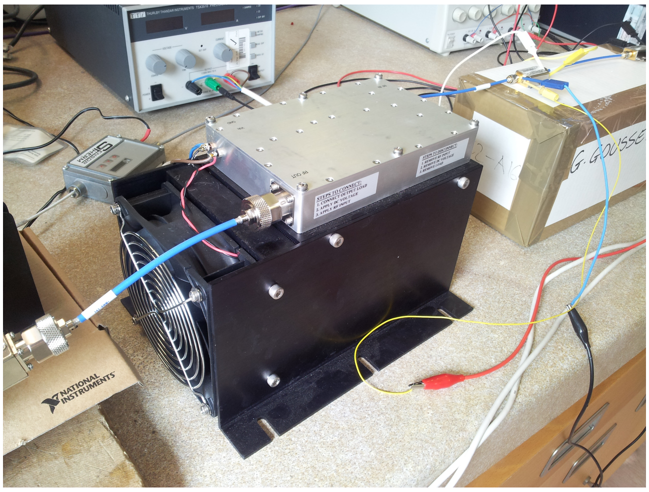


Figure 4.8: High Power Amplifier with a Heat Sink in the Laboratory.

Now that all the active components have been described, it is possible to calculate the power range that could be applied to the passive elements. First of all, the output power of the VCO is fixed and around 6 dBm. Secondly, since the attenuation can vary from 0 to 40 dB, then the output power of the attenuator can vary from -34 dBm to 6 dBm. As the amplifier has a gain of 50 dB and an output power at 1dB compression of 50 dBm, that means that the maximum input power that the amplifier can handle without deformig the signal is 0 dBm. Therefore, if the input signal of the amplifier goes from -34 dBm to 0 dBm, the output power that could be applied to the passive components goes from 16 dBm to 50 dBm.

Now the passive components are described:

- **Circulator JCC0900T1000N20-HER**: this device together with a load form an isolator for protecting the amplifier from reflected signals. The most important characteristic of the circulator is the value of the isolation, which is 21 dB in this case (see Appendix section A.7). This value corresponds to a measure of the power delivered to the port which is not direct, as it can be seen in Equation 4.6 [20]. Consequently, the higher this value the better performance since that means that less power would go to the load (uncoupled port) and more power to the system (direct port).

$$I_{31} = -10 \log \frac{P_3}{P_1} \tag{4.6}$$

  in which, in this case, number 3 corresponds to the input port of the load and 1 is the output port of the amplifier. The direct port is the second one (input of the coupler).

- **Termination TN060M-100W**: the input power of this load is 50 dBm, which means that if all the energy applied to the applicator is reflected, the load could absorb the power (see Appendix section A.8). In Fig 4.9, a picture of the circulator and the load is presented.

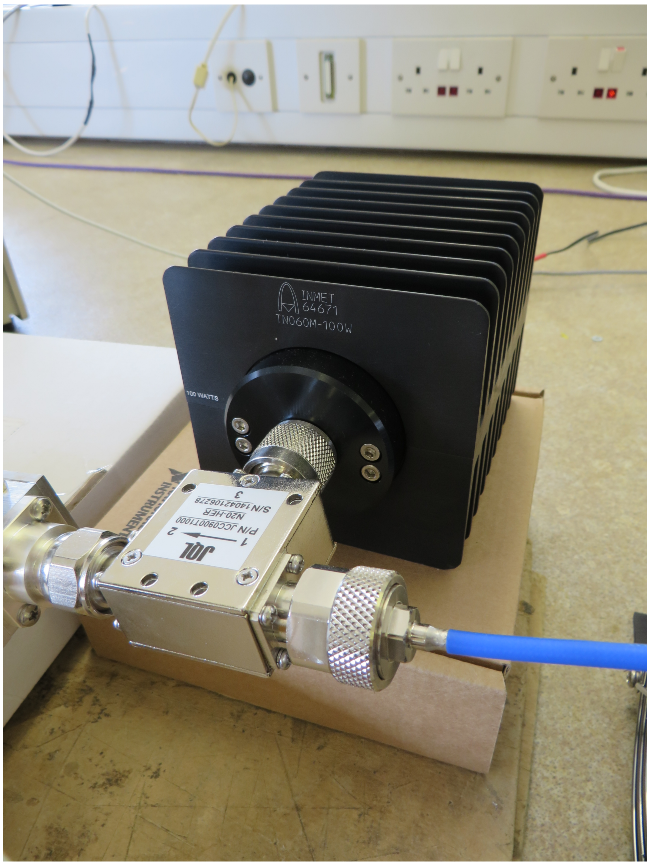


Figure 4.9: Circulator and Termination in the Laboratory.

- **Dual Directional Coupler C2-A12**: the reason why a coupler is required is that it is necessary to calculate the forward and backward power flow in order to know the power that is applied to the applicator and the reflected power from it as well. Thanks to these values, the S_{11} parameter can be calculated. The way to measure the forward and backward power is by connecting the coupled ports to two power sensors. The fraction of the input power that is coupled to the port that is right next to the input port can be calculated by the coupling factor C [20]. The value of the coupling factor in this device is around 30 dB (see Appendix section A.9).

$$C_{31} = -10 \log \frac{P_3}{P_1} \tag{4.7}$$

in which number 1 refers to the input port and number 3 to the coupled port. Consequently, if the input signal is 50 dBm, for example, the fraction of that power that is coupled is around 50 dBm - 30 dB = 20 dBm.

- **USB Smart Power Sensor PWR-4GHS**: as it was said before, these power sensors are connected to the coupled ports of the coupler. Moreover, they can be connected to a computer via USB so that it is possible to visualize, save or use the measurements in real time (see Appendix section A.11). This is really relevant owing to the fact that we want to calculate the S_{11} parameter instantaneously to be able to select the frequency of the system (this will be explained later). In Fig. 4.10, the coupler connected to both sensors is presented.

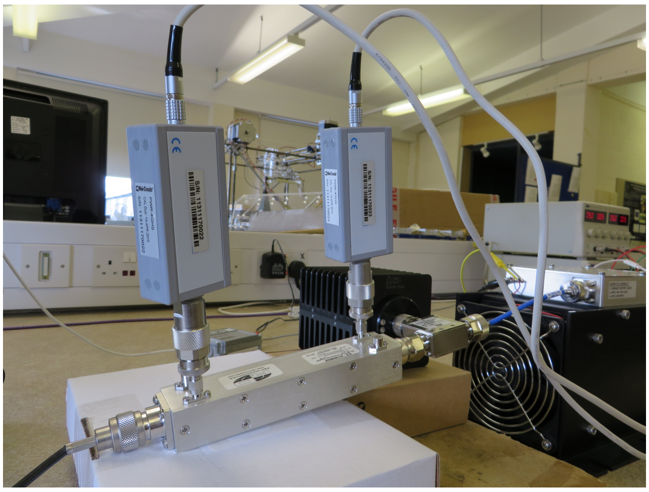


Figure 4.10: Dual Directional Coupler and Power Sensors in the Laboratory.

- **Applicator**: the design of the applicator, which is a rectangular waveguide, will be presented in the next chapter. An N-type connector (see Appendix section A.10) was necessary to connect the cavity to the system. A picture of the applicator is presented below:

Figure 4.11: Applicator in the Laboratory.

- **Miniature-Pyrometer CT84**: this component is a infrared thermometer which measures temperature from distance by the use of a laser. Since it can be connected to a computer via RS232, the temperature of the water can be visualized, saved or used in real time in the same way as the power of the system.

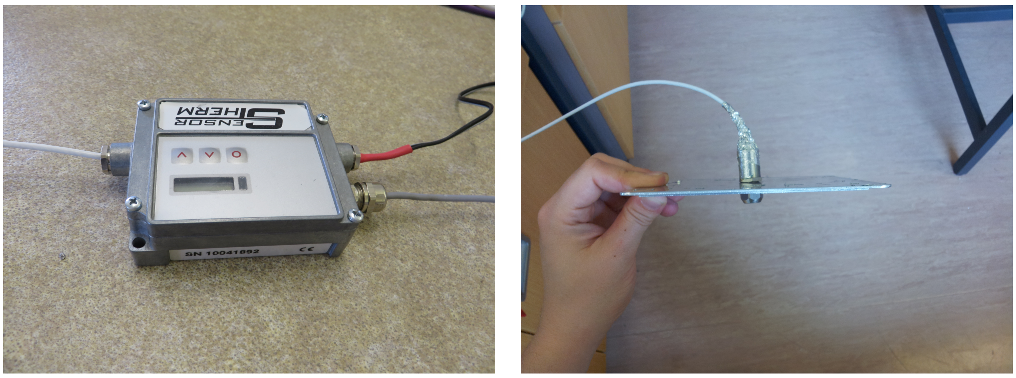


Figure 4.12: Miniature-Pyrometer in the Laboratory.

In order to connect the components of the system, the type of cables used were: SMA (see Appendix section A.12) and N (see Appendix section A.13). Furthermore, SMA to N cables (see Appendix section A.14) were bought to be able to connect the VCO or the attenuator to the spectrum analizer, which has an N-type connector. This was really useful to check the functionality of the VCO since we could visualize the range of frequencies.

The SMA cables were used to connect the VCO to the attenuator and this one to the amplifier. The N cables were used to connect the amplifier to the circulator and the coupler to the applicator.

Regarding the power supply, it was necessary to use two different types, one for the VCO, the attenuator and the operational amplifier, which do not need more supply current than 4 A, and another one for the high power amplifier, which could need up to 10 A, depending on the input power. The reason why the supply current depends strongly on the input power is that this amplifier is class-AB, which means that the current used for the polarization is low (almost all the current is applied to the output signal) and, as a result, the efficiency is high [21]. Both power supplies are shown in Fig. 4.13.

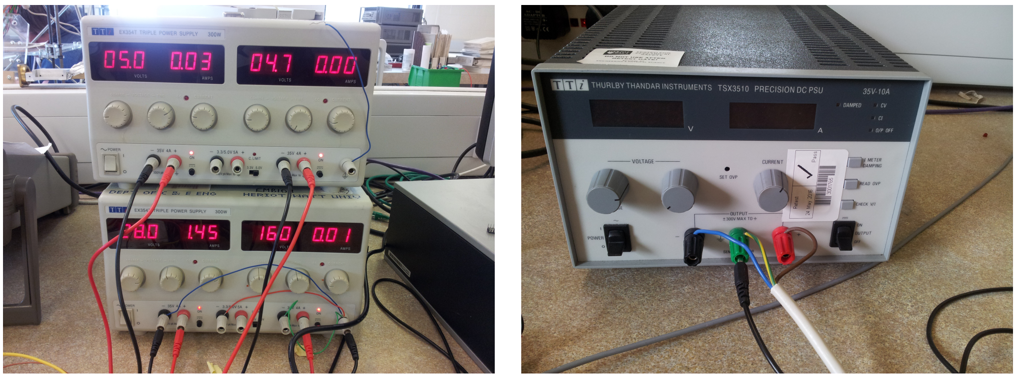


Figure 4.13: Power supplies. First: 35 V, 4 A; Second: 35 V, 10 A.

Finally, the cable used to connect the power supply to the VCO, the attenuator and the operational amplifier, was the typical coaxial banana plug cable to crocodile clip. However, the crocodile clip was not the best choice to connect it to the connector of the VCO or the attenuator. Therefore, the cable showed in Fig. 4.14 was connected to the crocodile clip and then to the devices.

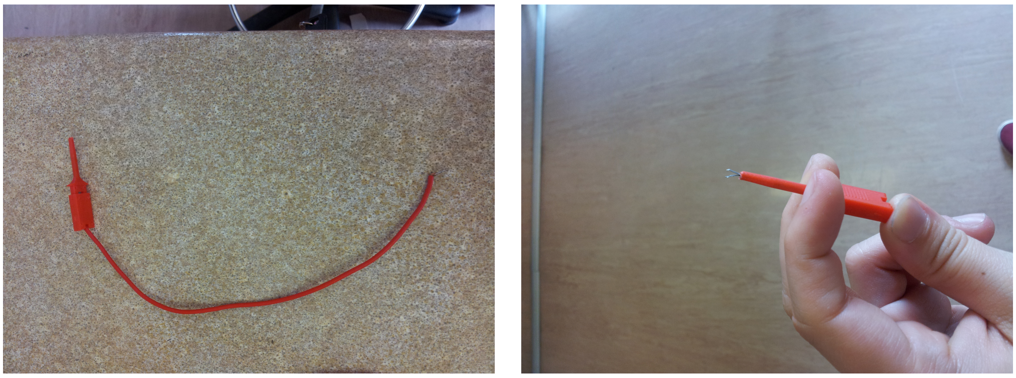


Figure 4.14: Cable used to connect the power supply to the VCO and the attenuator.

In the case of the high power amplifier, the cables used for the VCO or the attenuator cannot be connected to it since the needed current is higher than the value they can handle. Thus, cables that were suitable for 10 A were soldered to the connectors of the amplifier as it can be seen in Fig. 4.15.

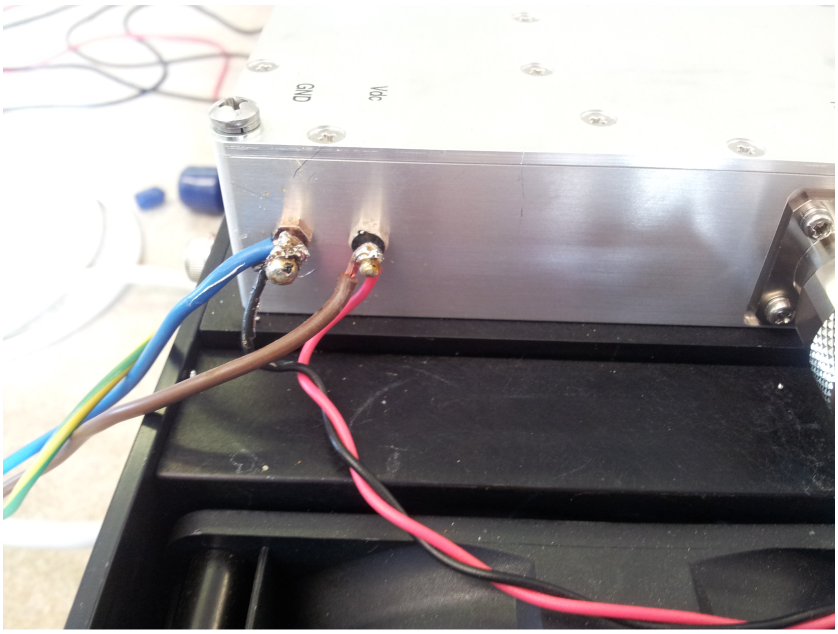


Figure 4.15: Power supply cables soldered to the amplifier.

The following figure shows all the system in the laboratory:

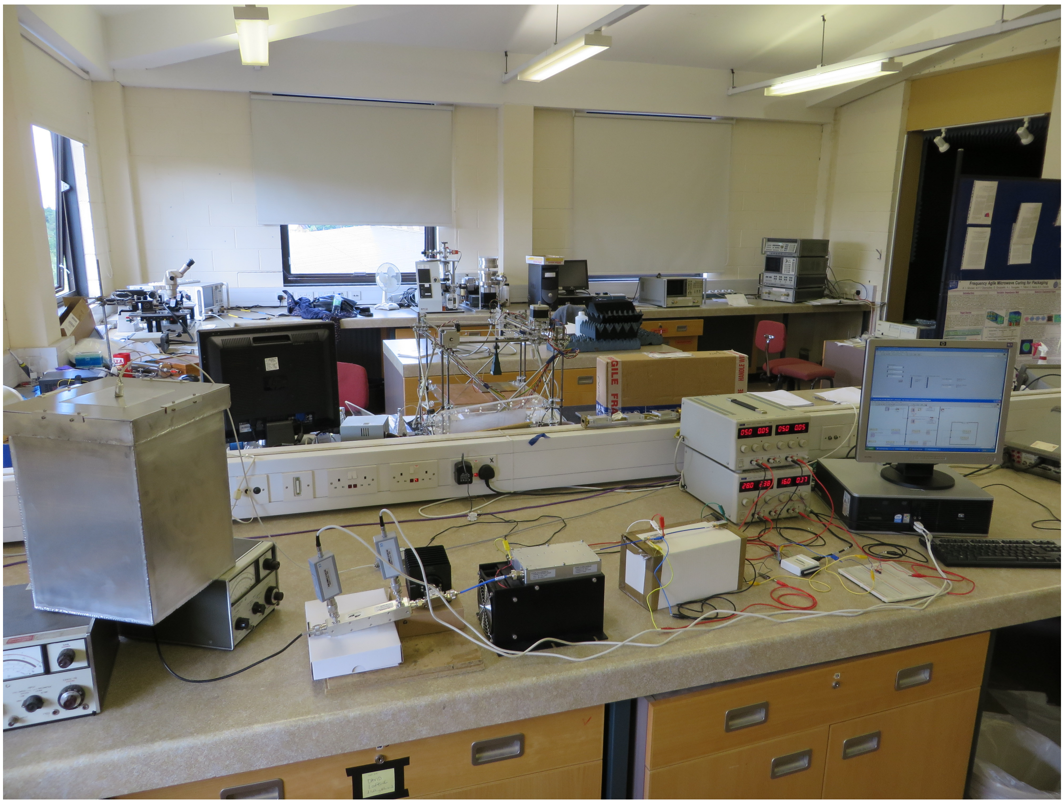


Figure 4.16: System in the laboratory.

4.3 Closed-Loop

All the system parameters such us frequency, power and temperature can be monitored from a personal computer or PC. The software chosen for this purpose was LabVIEW (National Instruments). A summary of the elements used to control these parameters from a computer is introduced below.

First of all, in order to adjust the frequency from LabVIEW, it was said that a data acquisition card or DAQ was required to connect the VCO to a PC via USB.

Secondly, the control of the power is accomplished by the use of the attenuator, which is connected to the PC via USB by using the same DAQ card. Additionally, the power reflection coefficient is calculated with the use of the backward and forward power flow obtained by the sensors. This coefficient will be used to further enhance control of the temperature.

Finally, the temperature is measured by a pyrometer which is positioned at the top of the cavity with the lens focused to the flask containing the water. This pyrometer is also connected to the PC via RS-232. As a result, the system provides real time display of the temperature at the same time that this temperature is used to control the power levels. The functionality of the closed-loop is as follows: while the measured temperature is lower than requested, the attenuator should be reducing the attenuation to increase the power level until the target temperature is achieved. In the same way, when the measured temperature is higher than requested, the attenuator should increase the attenuation to reduce the power.

4.4 Budget

Not all the components were bought since some of them were borrowed from the laboratory. In Table 4.2, a budget including all the components that were bought and their companies is presented.

Component	Company	Price (£)
VCO	Mini-Circuits	32,4
Attenuator	Mini-Circuits	39,52
DAQ Card	National Instruments	129,00
Amplifier	Mini-Circuits	1.736,55
Circulator	JQL Electronics	198,00
Termination	RF Components	233,00
Directional Coupler	RF Components	275,00
PWR Sensors	Mini-Circuits	2 x 628,96
SMA Cables	Mini-Circuits	2 x 7,72
N Cables	Mini-Circuits	2 x 15,51
SMA to N Cable	Mini-Circuits	16,30
N Type Connector	RS	22,37

Table 4.2: Budget of the bought components (VAT not included).

Total price: 3986,52 £= 5106,09 €

Chapter 5

Design of the Applicator

In this chapter, the process of designing the applicator is described. First of all, it will be characterized the structure of the final applicator. Secondly, the way the dimensions were calculated and the simulations obtained by the use of the Software HFSS 13.0 are presented. Finally, the real measurements of the manufactured applicator are shown. These readings were measured by the use of a Vector Network Analyzer, VNA.

5.1 Applicator Structure

In the design of the applicator, several requirements were taken into account. As our aim is to validate the functionality of the hyperthermia system by heating water introduced in a flask, we decided to locate the flask inside a waveguide, which is easy to design. In order to achieve that, the applicator is formed by two rectangular aluminum waveguides that have a different width so that a rohacell layer could be placed between the two cavities. The reason why the rohacell was chosen is that its permittivity value is similar to the air permittivity so it does not introduce a discontinuity (see Appendix section A.15). Thanks to this structure, it is possible to position the flask over the rohacell. Furthermore, the top of the shortest cavity can be removed in order to take out the flask and change the sample. There is a hole at the top of this cavity for the pyrometer to measure the temperature of the water. Finally, an N-type connector was set at the bottom of the largest cavity in order to connect the system to the applicator. Another picture of the applicator is shown in Fig. 5.1.

Figure 5.1: Manufactured Oven.

5.2 Calculation of the Dimensions

The height of the main cavity of the applicator (d) has been obtained by using the equation that calculates the resonant frequency of a TM_{mnl} mode taking into account that we wanted to achieve the second transverse mode TM_{111} in correspondence of the working frequency [22]. The value of the other two dimensions (a, b) was established as 0.25 m to be able to introduce flasks with different shapes and sizes and check the uniformity of the fields. As the cavities are filled with air, the value of the permittivity is 1. In Equation 5.1, it is presented the equation that was used to calculate (d).

$$f_{mnl} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \tag{5.1}$$

As shown in Matlab Code 5.1, a Matlab script was made in order to calculate the required height of the main cavity. The frequency band chosen was the 915 MHz band and our components are allowed to work between 0.9 and 1 GHz. As the higher resonant frequency, the lower height (when the other dimensions are fixed), we chose a resonant frequency a bit higher than 915 MHz. The frequency selected was 940 MHz.

Matlab Code 5.1: Obtaining Main Cavity Dimensions

```
clear all; close all; clc

    % Input parameters
            m = 1;
            n = 1;
            l = 1;
            a_m = 0.25;      % b = a < d (bottom is a square)
            b_m = 0.25;
            c_mps = 3E8;
            ur = 1;
            er = 1;          % (no dielectric --> no loss)
            f_111_Hz = 940 * 10^6;

    % Output parameters
            % f_111 = c_mps /(2*pi*sqrt(ur*er)) * sqrt((m*pi/a_m)^2 + ...
                (n*pi/b_m)^2 + + (l*pi/d_m)^2)

        % TM111 (TMmnl)
            % For resonant frequency
            k_111 =  ( f_111_Hz*2*pi*sqrt(ur*er) ) / c_mps;
            d_m = l*pi / sqrt(k_111^2 - (m*pi/a_m)^2 - (n*pi/b_m)^2)

            % For cutoff frequency
            fc_TM11_Hz = c_mps / (2*pi*sqrt(ur*er)) * sqrt((m*pi/a_m)^2 ...
                + (n*pi/b_m)^2)
            fc_TM11_MHz = fc_TM11_Hz / 10^6
```

Finally, we obtained a height value of 0.37 m.

5.3 Design of the Cavity by the Use of HFSS

As I had not used the Software HFSS before, the user manual provided by ANSOFT Corporation was really useful to learn how to use it [23].

5.3.1 Properties and Dimensions to Take into Account

Before presenting the structure that was created, the characteristics that we took into account for the selection are described below:

- **Impedance Matching**: as the applicator has only one port (were the N-type connector is placed), the only S parameter that can be calculated is the S_{11}. This parameter helps to know in which frequencies the input signal is transmited. As our system can provide much more power than it is necessary (50 dBm) and the reflections are controlled by the use of the isolator, it is not important if the value of the S_{11} at the resonant frequency is not really low.
- **Frequency**: the resonant frequency should be located between 0.9 and 1 GHz.
- **Uniformity**: this characteristic is really relevant since the system must heat the water uniformly. The aim is to focus the heat on a specific region so that all the cells can be warmed in the same way.
- **Electric field**: as the N-type connector is located at the bottom of the main cavity, the modes that were taken into account were the TM modes since there is an electric field along the direction of propagation.

Furthermore, it is relevant to say that the structure that was chosen does not have to be the one that will be applied to in-vivo exposures. This structure will be mainly used for checking the functionality of the system so that is the reason why the shape of it is really simple. Once it has been checked that the system works properly, the applicator could be modified.

The dimensions that were fixed in the structure are shown in Table 5.1. The ones related to the flask were provided by the biologists, and the thickness of the rohacell and the aluminum walls, which is the material used for the cavity, were provided by the people from the workshop (these people were in charge of manufacturing the applicator). Regarding the dimensions of the N-Type connector, these were shown in its datasheet.

Dimension	**Value (mm)**
Cells Box Diameter	87
Cells Box Height	20
Cells Box Thickness	1
Water Height	1.6822
Aluminum Thickness	3
Rohacell Thickness	5
N-Type Connector Pin Length	17.9
N-Type Connector Pin Diameter	1.7
N-Type Connector Dielectric Length	15
N-Type Connector Dielectric Diameter	5.3
N-Type Connector Length	18.7

Table 5.1: Fixed Dimensions of the Applicator.

5.3.2 Final Design with HFSS

In order to introduce the process of designing the cavity, the following points will be described:

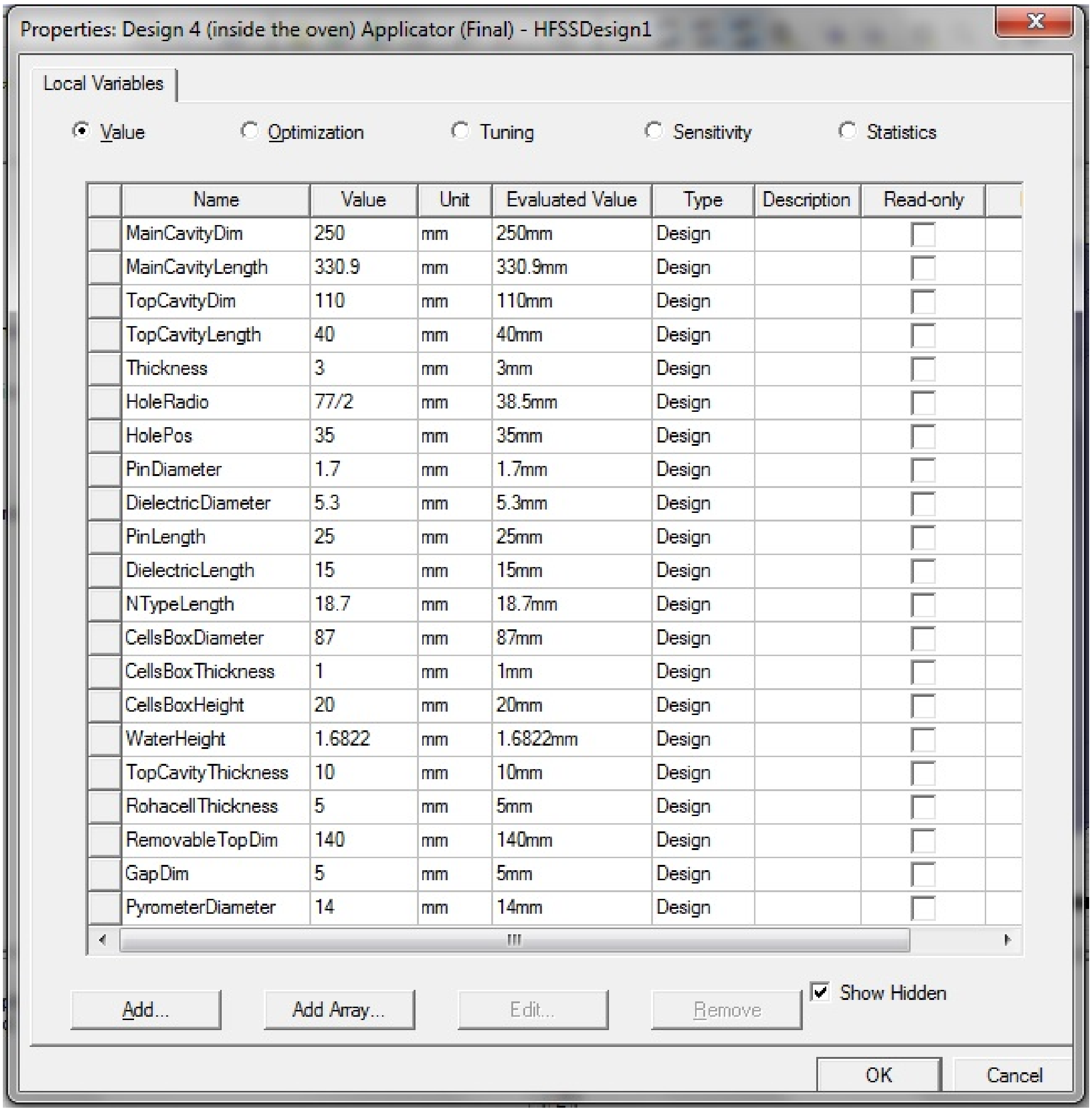
1. Materials used.
2. Design properties.
3. Obtaining the S_{11} parameter.
4. Electric field distribution.

First of all, the materials used for the design with HFSS are:

- **Air**: for the interior of the flask and the whole cavity and for the hole to place the pyrometer.
- **Aluminum**: for the walls of the cavity and the removable top.

- **Copper**: for the pin of the N-type connector.
- **Polystyrene**: for the structure of the flask.
- **Teflon**: for the cover of the N-type connector pin.
- **Water fresh**: for the water introduced in the flask.

Secondly, the design properties were established:



Name	Value	Unit	Evaluated Value	Type	Description	Read-only
MainCavityDim	250	mm	250mm	Design		☐
MainCavityLength	330.9	mm	330.9mm	Design		☐
TopCavityDim	110	mm	110mm	Design		☐
TopCavityLength	40	mm	40mm	Design		☐
Thickness	3	mm	3mm	Design		☐
HoleRadio	77/2	mm	38.5mm	Design		☐
HolePos	35	mm	35mm	Design		☐
PinDiameter	1.7	mm	1.7mm	Design		☐
DielectricDiameter	5.3	mm	5.3mm	Design		☐
PinLength	25	mm	25mm	Design		☐
DielectricLength	15	mm	15mm	Design		☐
NTypeLength	18.7	mm	18.7mm	Design		☐
CellsBoxDiameter	87	mm	87mm	Design		☐
CellsBoxThickness	1	mm	1mm	Design		☐
CellsBoxHeight	20	mm	20mm	Design		☐
WaterHeight	1.6822	mm	1.6822mm	Design		☐
TopCavityThickness	10	mm	10mm	Design		☐
RohacellThickness	5	mm	5mm	Design		☐
RemovableTopDim	140	mm	140mm	Design		☐
GapDim	5	mm	5mm	Design		☐
PyrometerDiameter	14	mm	14mm	Design		☐

Figure 5.2: Design Properties HFSS.

As it can be seen in Fig. 5.2, there is a main cavity and a top cavity. The top cavity has been made in order to have a step so that the rohacell can be placed between the two cavities. The sum of the height of the main cavity and the height of the top cavity is equal to the height calculated before (d). The thickness of the top cavity corresponds to the difference between its dimension and the dimension of the main cavity. Furthermore, the hole radio value refers to the value of the hole located at the top cavity. In order to select this value, the diameter of the pyrometer was taken into account since the idea was to introduce part of the pyrometer inside the top cavity to measure the temperature of the water. Finally, the dimension of the removable top was created by taking into account the diameter of the flask since there must be enough space to remove and introduce it into the cavity.

Apart from all of these dimensions, it is important to highlight that the value of the pin length is higher than the one which appears in the N-type connector datasheet. The reason why this happens is that the matching was improved by making it higher. That was not a problem since the pin of the N-type connector could be modified in order to make it higher.

If someone is interested in how the structure was generated, the HFSS file used to create the applicator is included in this CD. In Fig. 5.3, the simulated structure of the cavity is shown.

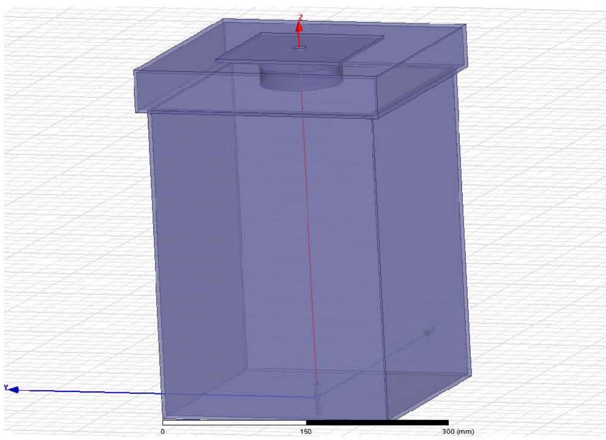


Figure 5.3: Simulated Structure of the Applicator.

The S_{11} obtained by simulating the structure above is the following:

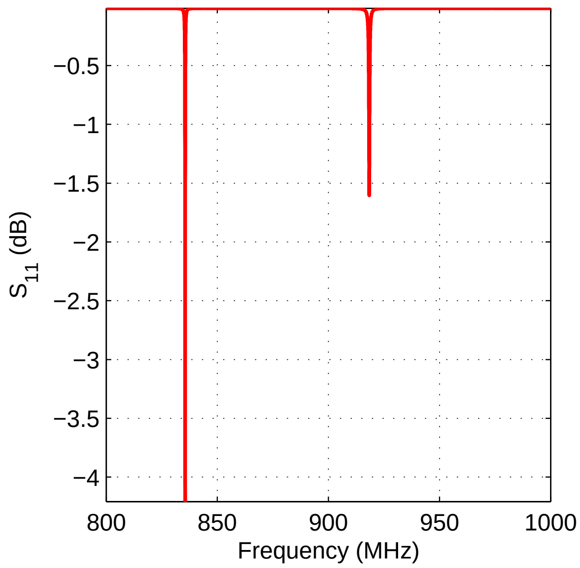


Figure 5.4: Simulated S_{11} by the use of HFSS.

In Fig. 5.4, it can be seen that only the second mode (TM_{111}) is located between 0.9 and 1 GHz. Regarding the value of the S_{11} parameter, it seems really low. However, as we said before, that is not a problem since this design is for checking the functionality of the system and it can provide more power than needed.

The next step is to simulate the electric field at the frequency of the second mode in order to ensure that the mode is TM and not TE. In Fig. 5.5 the simulated electric field within the oven cavity is shown.

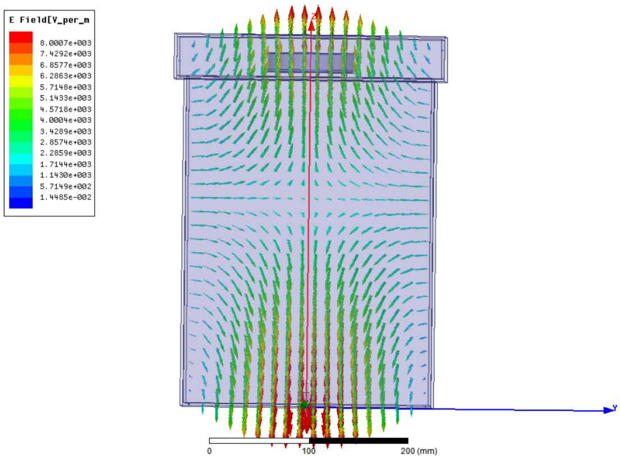


Figure 5.5: Simulated electric field within the oven cavity.

Then, as the electric field appears in the same plane as the direction of propagation, it is confirmed that the second mode is TM.

Finally, the uniformity of the electric field was checked:

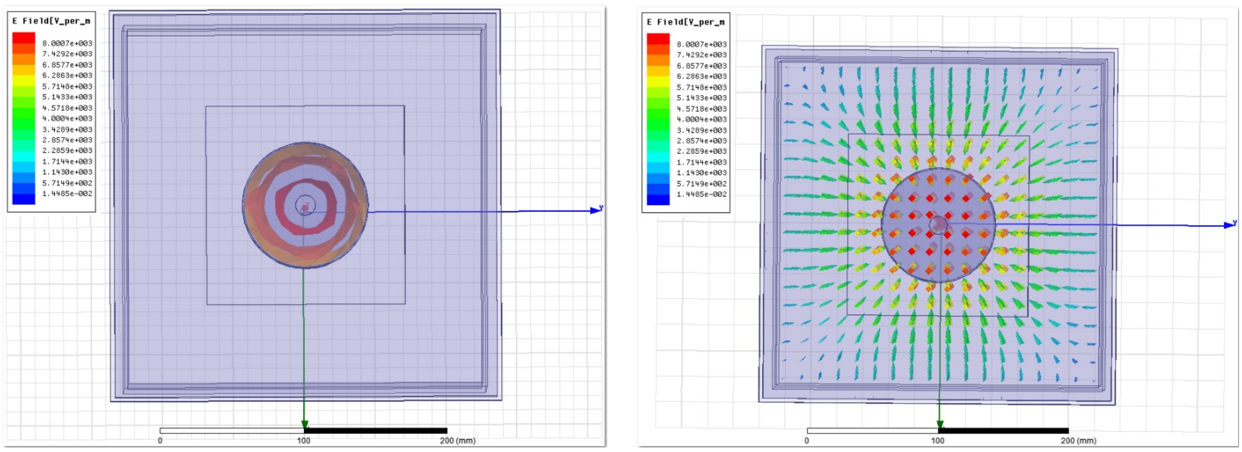


Figure 5.6: Electric field within the water. First: magnitude; second: vector.

In the figures above, it is shown that the distribution of the electric field between the two cavities is considerably uniform, although the power is a bit stronger in the middle of the flask than at the edges.

5.3.3 Other Cavities Created

Before selecting the final design of the cavity, other structures with a different way of placing the flask inside the cavity were built. One of them has an aluminum step between the two cavities to locate the flask over it. Another one has an aluminum plate with holes between the two cavities. The reason why these structures were not chosen for the system was that the uniformity in both of them was worse than in the final design. These two solutions are presented in the following figures:

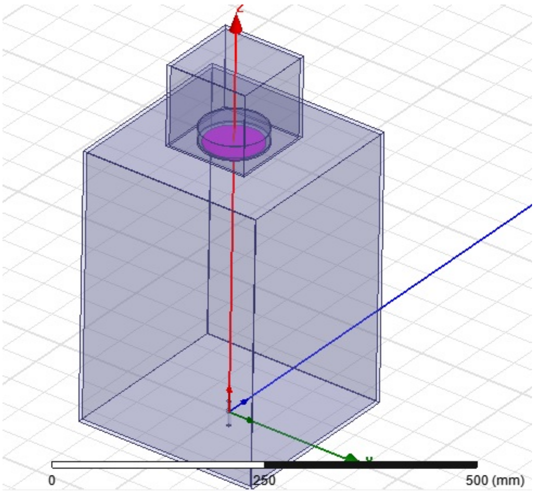


Figure 5.7: Cavity with aluminum step to place the flask.

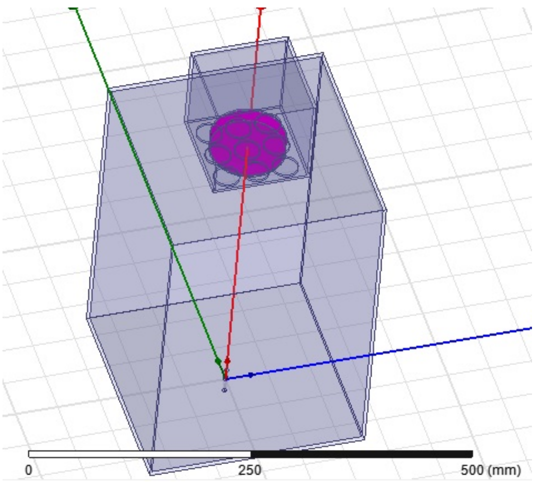


Figure 5.8: Cavity with alternated holes to place the flask.

5.4 Manufactured Cavity

In this section, the VNA that was used to measure the S_{11} parameter of the applicator is presented. Afterwards, the readings of that parameter will be introduced.

5.4.1 Use of the VNA

The vector network analyzer that was used is shown in Fig. 5.9. It is formed by 4 different components: a synthesized sweeper, a network analyzer, a S-parameter test set and a display. Before starting to measure, the cable that will be used to calculate the S_{11} should be connected to the S-parameter test set device, and the frequency range and the number of points should be established.

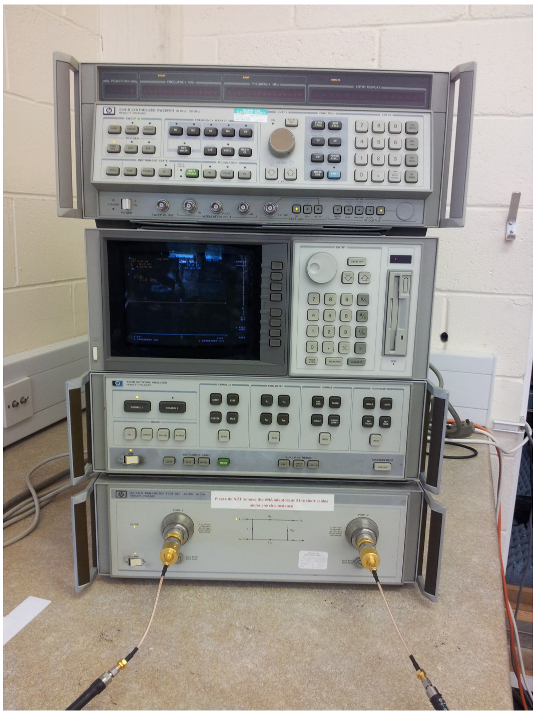


Figure 5.9: Vector Network Analyzer in the Laboratory.

Once the other steps have been done, the VNA must be calibrated by using the calibration kit, which is presented in Fig. 5.10. This kit includes two open terminations (male and female), two short terminations (male and female), two broadband load terminations (male and female), one male to female termination, one male to male termination and one female to female termination.

Figure 5.10: Calibration kit for the VNA.

In order to calibrate the VNA, the open, the short and the broadband load terminations (male or female depending on the cable used) should be connected one by one to the cable of the first port when the device is in calibration mode. Once the calibration is finished, it must be checked that the VNA is measuring properly. To achieve this, the terminations should be connected again to observe the results obtained. For example, if the open termination is connected, the value of the S_{11} must be 0 dB at all the frequencies since all the power is reflected. It is the same case if the short termination is connected. However, if the broadband load is connected, the S_{11} must be around -70 dB, which means that the energy is transmited at a huge range of frequencies.

After a proper calibration, the VNA is ready for measuring the parameters of our cavity.

5.4.2 Measure of the S_{11} Parameter

The first measurements of the S_{11} parameter of the applicator were not accurate since every reading was measuring a different value. The reason why that happened was that the manufactured applicator had some imperfections. Particularly, the joints made to stick one wall to the other were not perfectly cover so there were some gaps. Moreover, depending on how the removable top was placed, the impedance matching could change. Therefore, a metal tape was used to cover all these gaps and the joints of the removable top as well. The covered applicator is presented in Fig. 5.11.

Figure 5.11: Applicator covered with metal tape.

The S_{11} parameter measured after covering the applicator with the metal tape was:

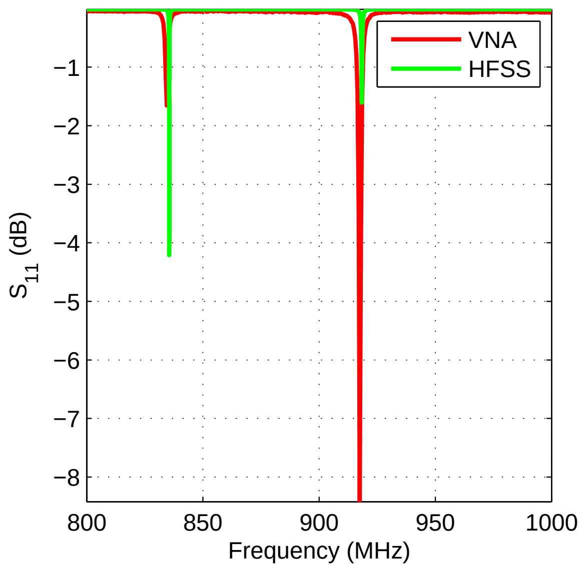


Figure 5.12: Comparison between the S11 parameter obtained by simulation (HFSS) and measurement (VNA) for the microwave oven.

As it is shown in Fig. 5.12, the frequencies of the first and the second modes are the same in both cases although the impedance matching of the manufactured applicator is better, which is a good point. However, the important issue here is that the range of frequencies in which there is transmission of the power is really narrowband. Therefore, it was necessary to check the accuracy of the VCO, which is 7-15 MHz/V. So if we take the worst case (15 MHz/V), we can say that if we can make a scanning by tuning the tune voltage of the VCO from 0 to 5 V every 0.05 V, then, 0.05 V x 15 MHz/V = 0.75 MHz. That means that every 0.05 V, the frequency could vary 0.75 MHz. As a result, as the 3 dB bandwidth of the measured S_{11} is 1 MHz, there should not be a problem to achieve the resonant frequency by adjusting the voltage of the VCO. Despite that, some losses were introduced inside the cavity to check if the bandwidth could be higher. A conductive foam was used to introduce the losses (see Appendix section A.16). The first experiment consisted of placing a foam layer just below the rohacell layer. The last experiment consisted of sticking only some pieces of this foam to the rohacell layer to introduce less losses than in the first one (see Fig. 5.13). The results of these experiments are shown in Fig. 5.14.

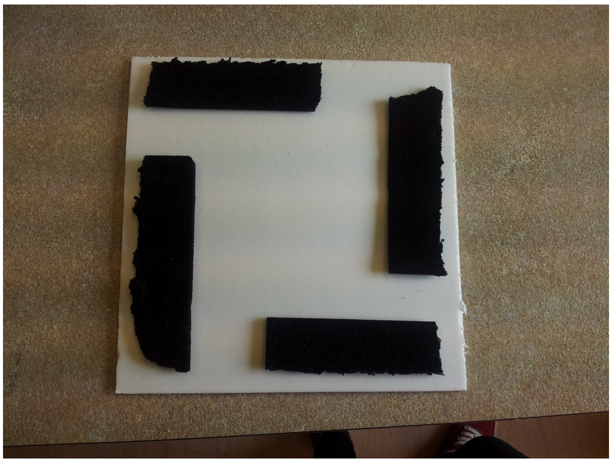


Figure 5.13: Foam sticked to the rohacell to produce losses inside the cavity.

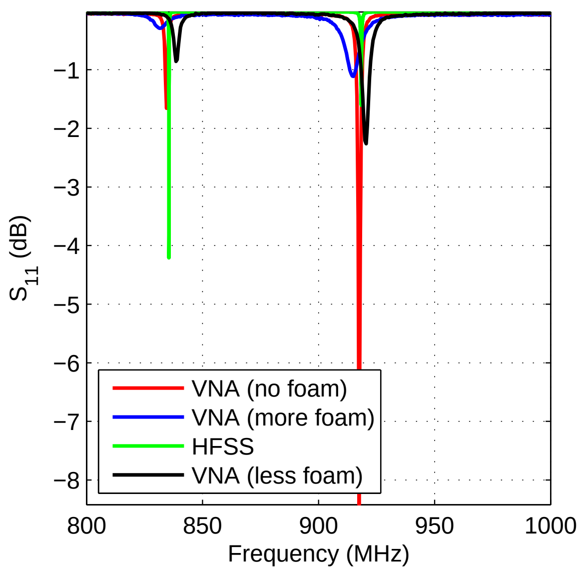


Figure 5.14: Comparison between the S11 parameter obtained by simulation (HFSS) and measurement (VNA) when foam is introduced inside the cavity.

As it can be seen in the figure above, the losses have improved the bandwidth. However, the impedance matching is worse. Therefore, the losses were removed in order to check if the system can achieve the resonant frequency only with the rohacell. If that was not possible, we could add some losses.

Chapter 6

Control of the System by LabVIEW

In this chapter, it will be shown how the components are controlled by the LabVIEW software. It is relevant to add that there are two while loops: one for measuring the temperture by using the pyrometer and another one for controlling the VCO, the attenuator and the two sensors. These two loops are working in parallel.

6.1 Control of the VCO and the Attenuator

In the LabVIEW Help, available by selecting Help»LabVIEW Help in LabVIEW, all the information regarding how to use the DAQ card is presented:

- **Getting Started with LabVIEW»Getting Started with DAQ**: includes overview information and a tutorial to learn how to take an NI-DAQmx measurement in LabVIEW using the DAQ Assistant.
- **VI and Function Reference»Measurement I/O VIs and Functions» DAQmx - Data Acquisition VIs and Functions**: describes the LabVIEW NI-DAQmx VIs and functions.

The LabVIEW code used to control the VCO and the attenuator is presented in Fig. 6.1.

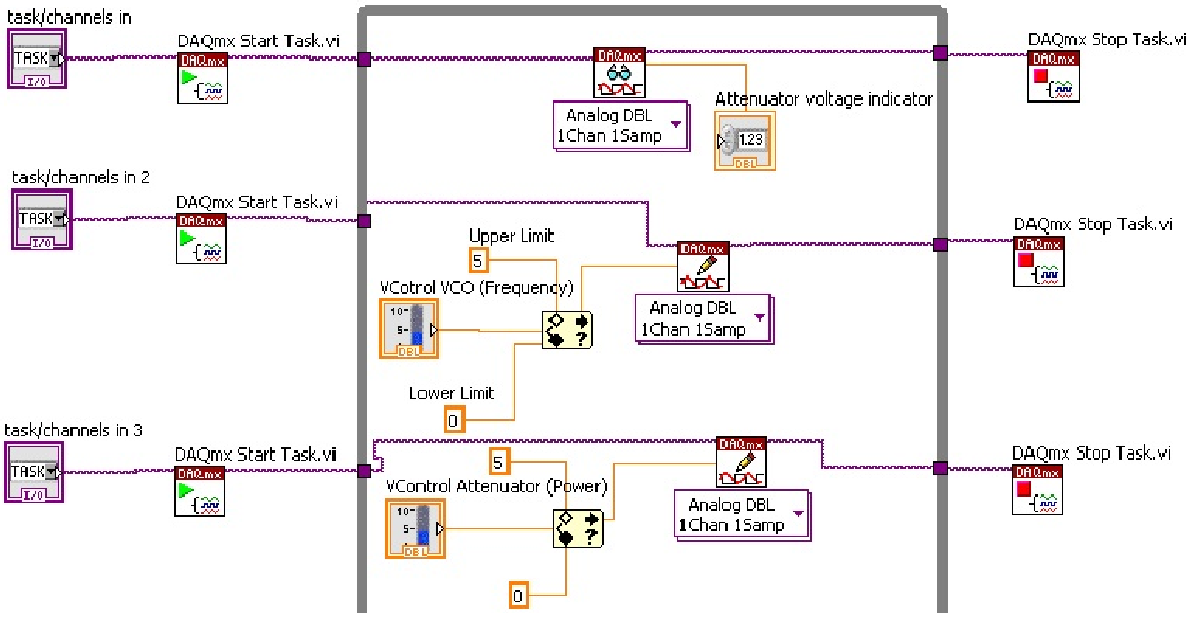


Figure 6.1: Control of the VCO and the Attenuator.

The tasks that appear in the program are used for the configuration of the ports of the DAQ card: if it is using an input or output port, if it is digital or analog, the number of the port, etc. The first task is used for reading the voltage value of the attenuator (this has been added only to learn how to read from the DAQ card and will be used for the routine to look for the lowest S_{11}, which will be shown later), the second one is used for establishing the voltage value of the VCO, and the last one is used for writing the voltage value of the attenuator. As the voltage value of the outputs ports of the DAQ card cannot be higher than 5 V, a limiter was added.

6.2 Control of the Sensors

In order to know how to connect the sensors to the computer by using LabVIEW, the "Project Examples" file that is included in the Power Meter section of the Mini-Circuits webpage was checked [24].

The LabVIEW code used to control the sensors is presented in Fig. 6.2 and Fig. 6.3.

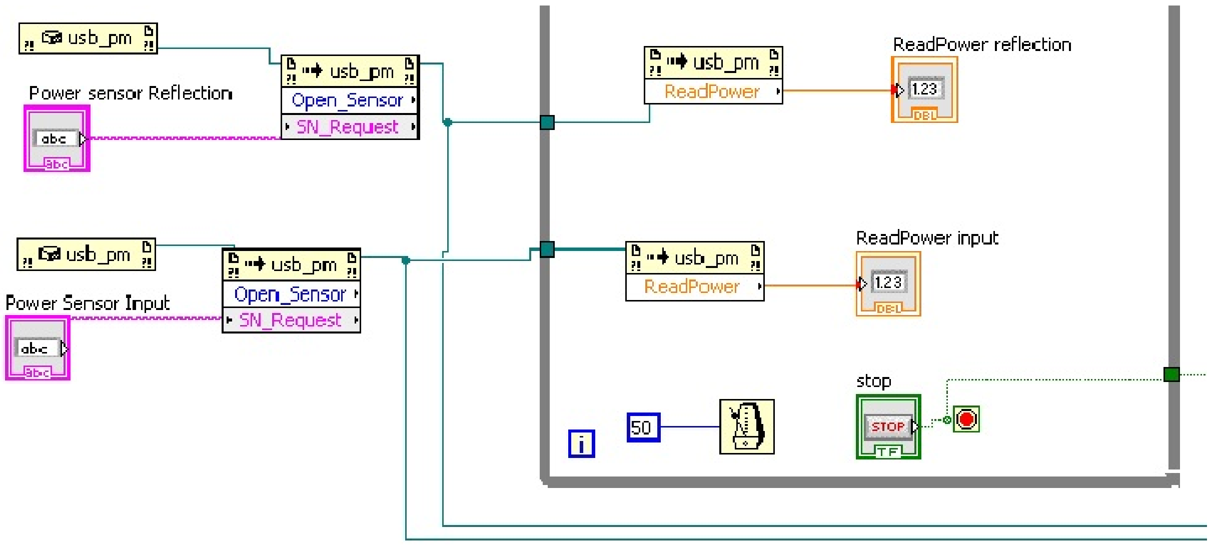


Figure 6.2: Control of the sensor (1).

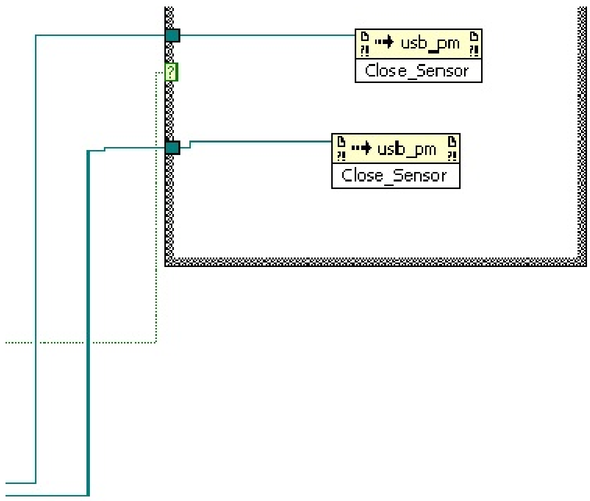


Figure 6.3: Control of the sensor (2).

As it can be seen in Fig. 6.2, there are two functions outside the while loop that are used to establish a connection between the computer and the sensor via USB. In order to be selected, every sensor has a code that is written as a constant in “SNRequest”. The function that is used to read from the sensor and an indicator to be able to see the value of it are located inside the while loop. Finally, there is a case statement outside the while loop to stop reading from the sensor when the loop has finished (see Fig. 6.3).

6.3 Control of the Pyrometer

A pyrometer was already available in the laboratory, so we did not need to buy a new one, the LabVIEW code to control the pyrometer was provided as well. This program establishes a connection between the computer and the pyrometer via RS232 in order to measure the temperature in real time. The figures below represent all the LabVIEW code to achieve this:

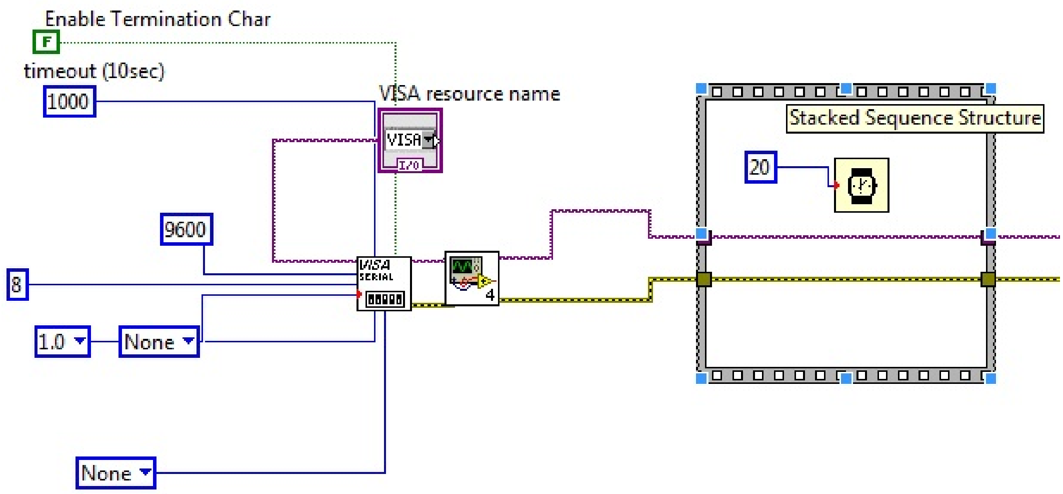


Figure 6.4: Control of the pyrometer (1).

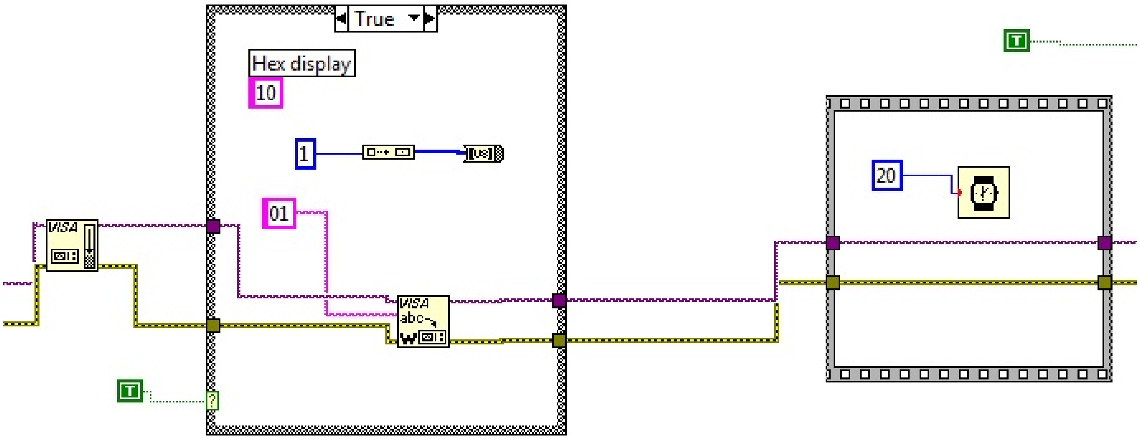


Figure 6.5: Control of the pyrometer (2).

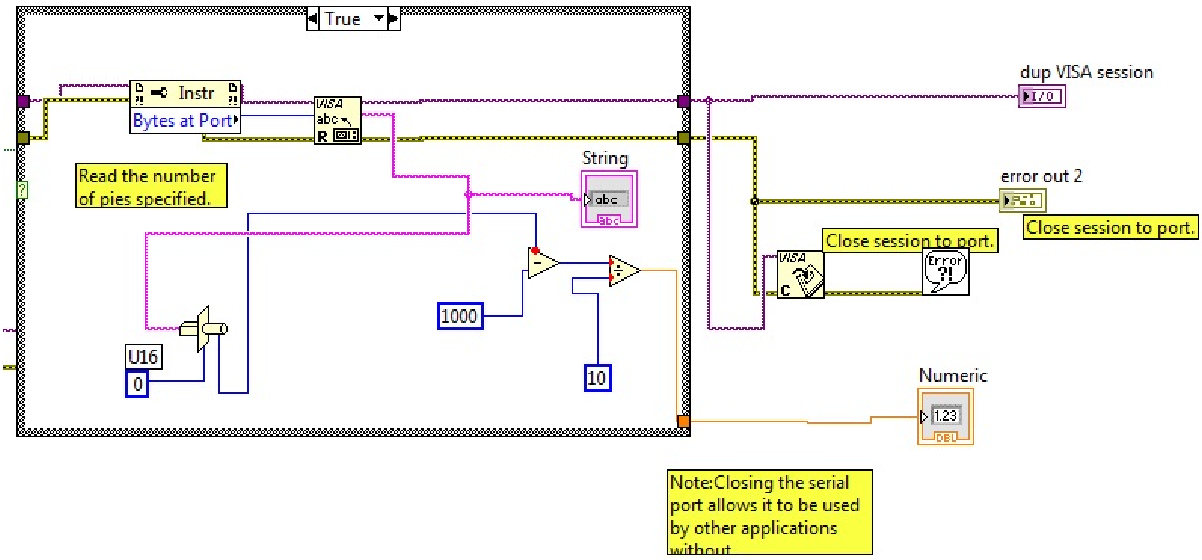


Figure 6.6: Control of the pyrometer (3).

As the code to control the pyrometer is too long, it was saved in a function as shown in Fig. 6.7.

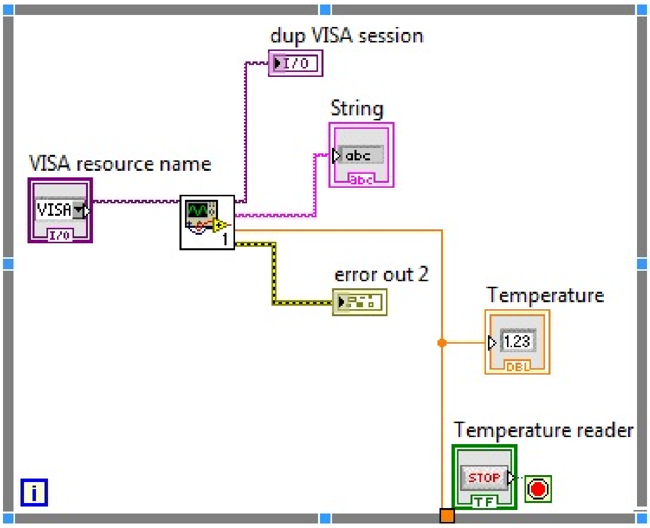


Figure 6.7: Control of the pyrometer (4).

6.4 Calculation of the Frequency

By using LabVIEW, it is possible to select the frequency of the VCO. In order to know the value of that frequency, the following steps were executed:

1. By using a spectrum analyzer, the frequency of the VCO should be measured in terms of the tune voltage (this graph is included in the next chapter).

2. The readings obtained in the first point are used to calculate the linear coeficients of the function "frequency vs. voltage".

3. This function can be used to calculate the frequency in terms of the voltage selected in LabVIEW.

In order to calculate the linear coeficients, the Matlab function polyfit(x,y,N) was used. In our case, x refers to the voltage, y to the frequency and N to the number of linear coeficients that we want to calculate. We checked that 11 coeficients were enough. The matlab code used to calculate the frequency by using these coeficients is shown in Fig. 6.1.

Matlab Code 6.1: Obtaining the Frequency.

```
function frequency=getFreq(x)
coeficients =  [0.0332452742488470 -0.882994079677641 10.1714818543415 ...
    -66.6590619226646 273.847061722463 -731.843133576516 ...
    1275.94892452871 -1413.50348976077 936.747986094759 ...
    -330.523059676041 84.8739458201596 735.011545454634];
polynomial = [x^11 x^10 x^9 x^8 x^7 x^6 x^5 x^4 x^3 x^2 x^1 1];
mult = coeficients .* polynomial;
frequency = sum(mult);
end
```

It was proved that the frequency calculated matched the frequency read.

Therefore, the LabVIEW code used to calculate the frequency is the following:

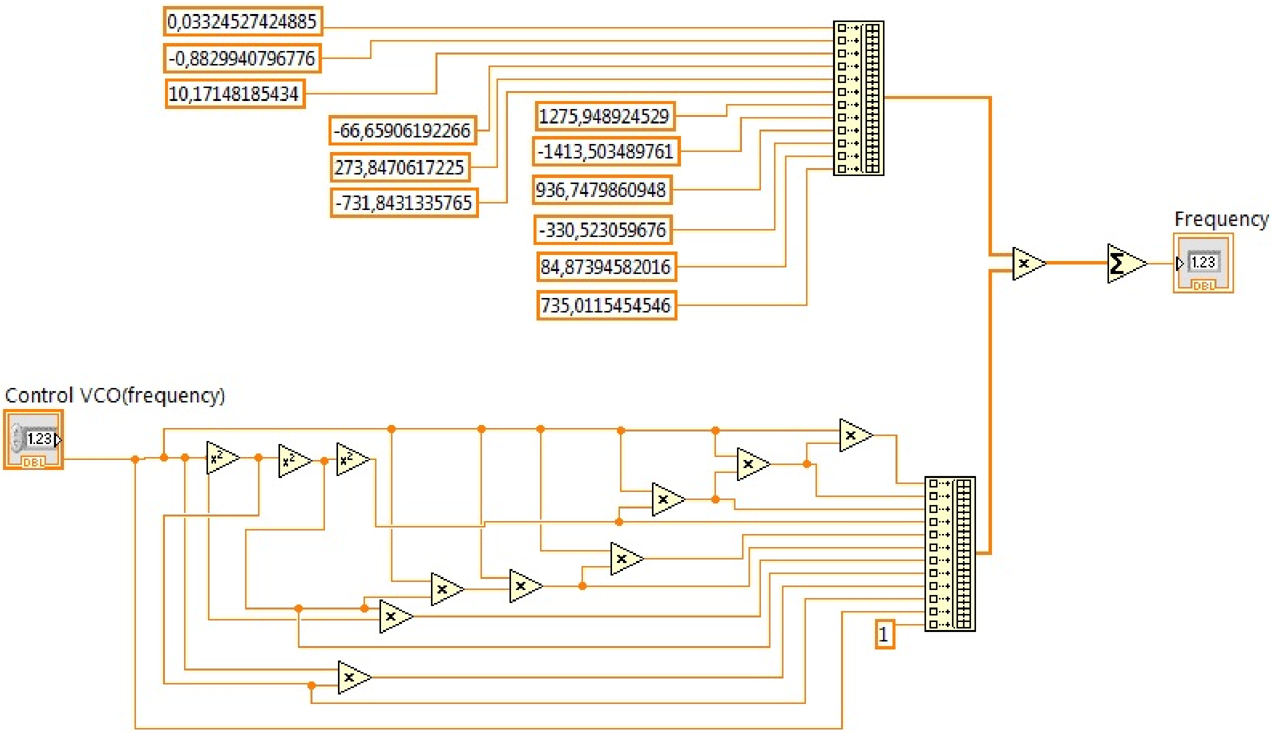


Figure 6.8: Getting the Frequency.

The LabVIEW code of Fig. 6.8 was saved as a subVI. The input voltage value of the VCO was connected to the input port of this function and an indicator to the output port.

6.5 Calculation of the Reflected and Forward Power in dBm and Watts

In order to calculate the forward or reflected power, the only thing that it is necessary to do is adding 30 dB to the power readings measured by the power meters since that is the value of the directional coupler coupling factor.

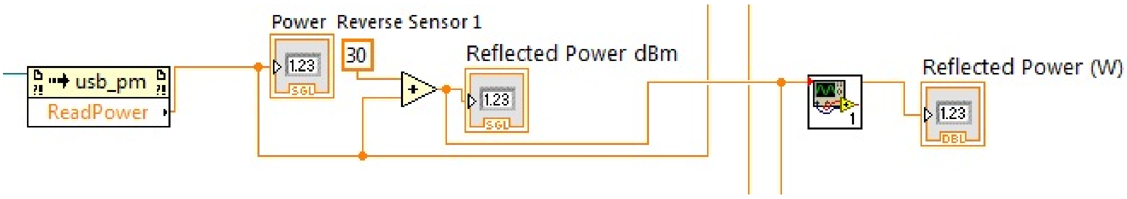


Figure 6.9: Getting the Reflected Power.

The subVI shown in Fig. 6.9 is a function that converts dBm to Watts. The converter is presented in the following figure:

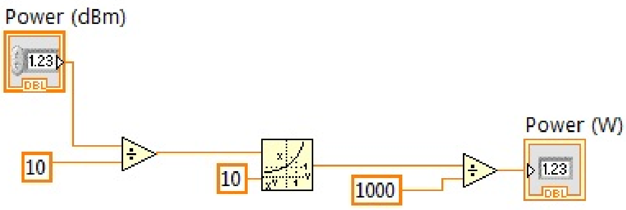


Figure 6.10: dBm to W Converter.

6.6 Routine to Look for the Lowest S_{11}

This routine has not been finished yet since some modifications should be done in order to connect it to the principal program. However, such modifications will be done soon, since the project is going to be continued in the following months. Part of this routine is shown in Fig. ??.

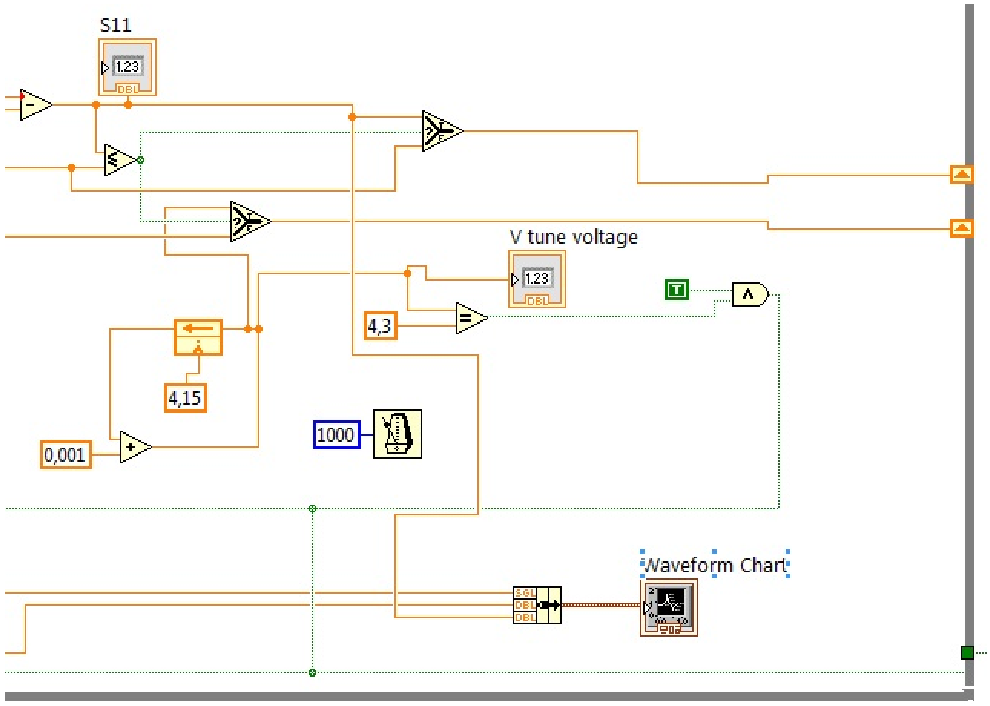


Figure 6.11: Feedback Loop to Calculate the Lowest S_{11}.

It is relevant to say which are the inputs that do not appear in the code above:

- **Subtract Function**: the inputs of this function are the power readings from the sensors.
- **Less Or Equal? Function**: the second input of this function is the value of the first register, which has an initial value of 0.
- **Select Function**: the second input of this function is the value of the second register, which has an initial value of 0 as well.
- **Waveform Chart**: the inputs are the S_{11} parameter and the input and output power levels after adding 30 dB to the readings from the sensors.

The idea of this routine is to find the lowest S_{11} by comparing the next S_{11} of the scan to a saved S_{11} (which would be the lowest one until that moment). Therefore, the principal issue is that there is a scan of all the frequencies by changing the value of the tune voltage of the VCO (From 0 to 5 V). Every frequency corresponds to a different S_{11} value and this one will be compared to the saved S_{11}. If the value of the new S_{11} is lower than the one saved, that value, together with the value of the related voltage, will be the new parameters saved. At the end of the routine (when the voltage value is 5 V) the principal program would use the voltage value saved in the register.

Finally, the front panel of the program is presented in Fig. 6.12.

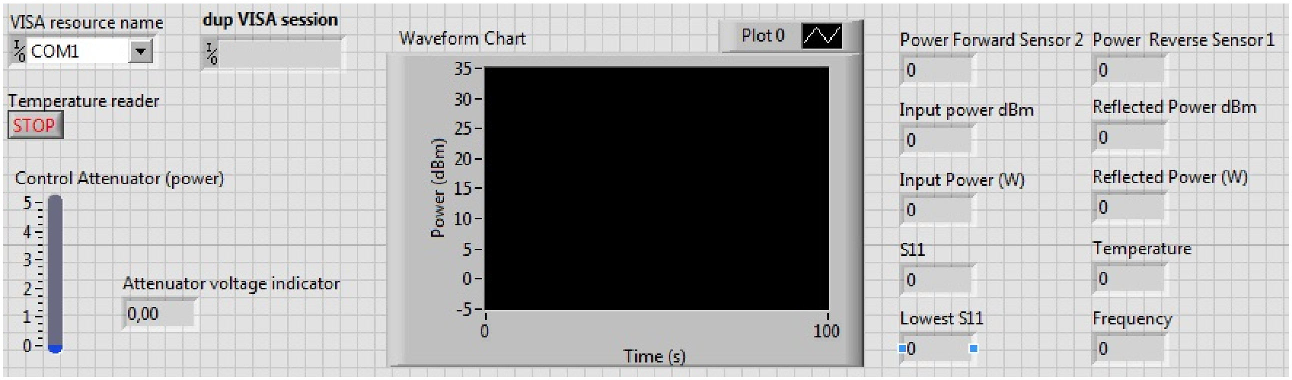


Figure 6.12: Front Panel of the LabVIEW Program.

Chapter 7

Tests and Initial Results

In this chapter, a test of every component is presented in order to check if they work as expected. Moreover, the measure of the temperature of the water when the whole system is set up is presented as well.

7.1 VCO

In order to check the range of frequencies that can be achieved by tuning the voltage of the VCO, it was connected to a spectrum analyzer (see Appendix section A.17). The LabVIEW program created was used to change the frequency of the VCO. In Fig. 7.1, a comparison between the datasheet of the VCO and the readings obtained from the spectrum analizer is presented.

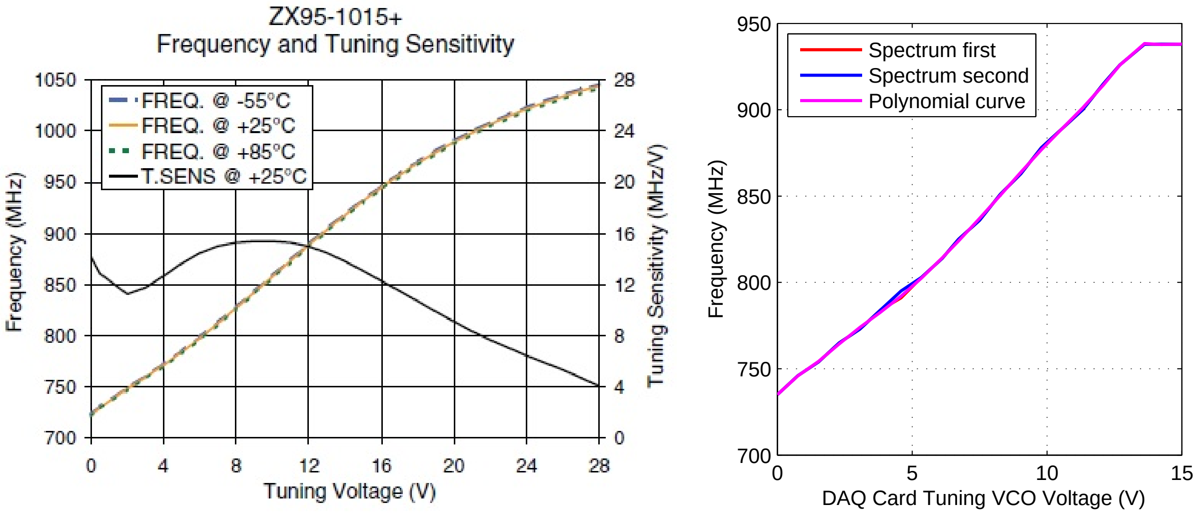


Figure 7.1: Test of the frequency of the VCO. First: datasheet; second: readings.

As it can be seen in the figure above, the performance of the VCO is like expected. In order to ensure that the measurements are correct, the scan was done twice. The polynomial curve used to calculate the frequency for the LabVIEW program has been represented as well.

Furthermore, the output power of the VCO in terms of the frequency was measured by the use of the power sensor.

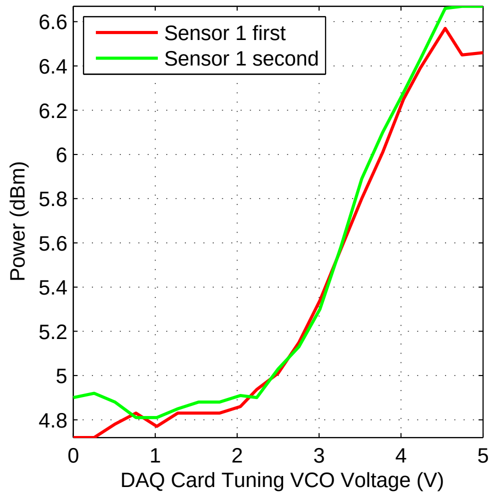


Figure 7.2: Test of the VCO Power.

In Fig. fig:TestVCO2, it seems that the power of the VCO is higher at elevated frequencies. In spite of that, the power value is around 5 or 7 dBm, which is not really far from the datasheet value (6 dBm).

7.2 Attenuator

In order to check the attenuation, the VCO was connected to the attenuator and this one to a power sensor. Then, a frequency was selected to enable a scan of the possible control voltage values of the attenuator (from 0 to 5 V).The frequency used for this measurement was 926 MHZ (VCO control voltage = 4.235 V). The output power obtained is shown in Fig. 7.3.

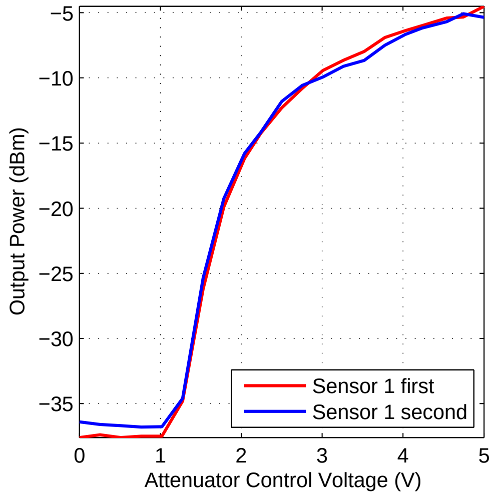


Figure 7.3: Test of the Attenuator Output Power.

The dynamic range of the power sensor goes from -30 to 20 dBm. Therefore, from -37 to -30 dBm the values measured should not be taken into account. In Fig. 7.4, a comparison between the datasheet of the attenuator and the readings obtained from the power sensor is presented. The voltage supply selected was 5 V.

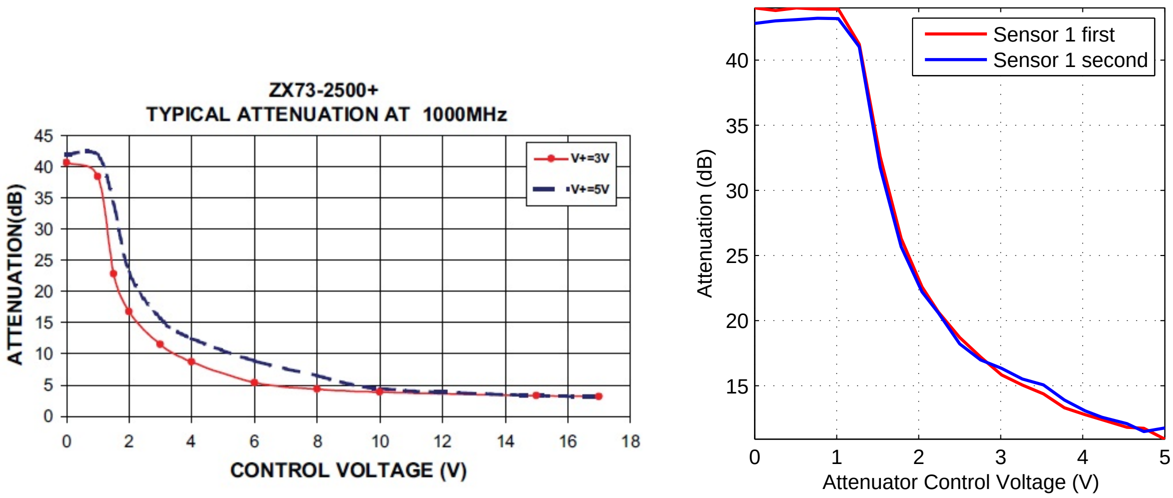


Figure 7.4: Test of the Attenuation. First: datasheet; second: readings.

As shown in the figure above, the attenuator works properly.

7.3 Circulator

In this case, the VCO was connected to the second port of the circulator. Then, the third port is the direct port and the first one is the isolated port. The output power of the third and the first port were measured by using the power sensor. While a port is being measured, the other port is connected to the termination so that there are no reflections. The frequency was modified for the scan.

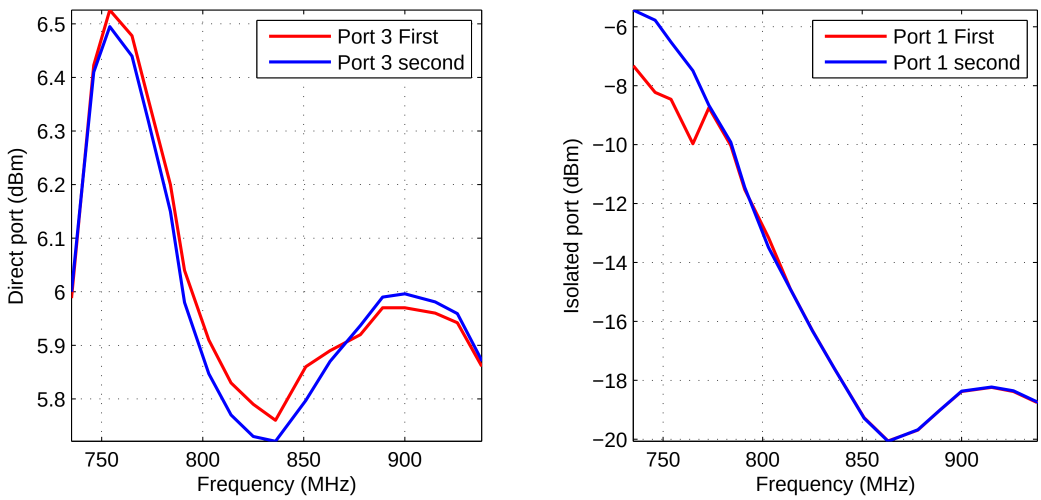


Figure 7.5: Output power of the circulator ports.

As the circulator works properly from 0.9 to 1 GHz, the way it works at other frequencies is not relevant. After measuring the output power of both ports, the losses can be calculated by doing this: input power (port 2) - output power of the direct port (3). The isolation was calculated by doing the same but using the isolated port (1). The results are shown in Fig. 7.6.

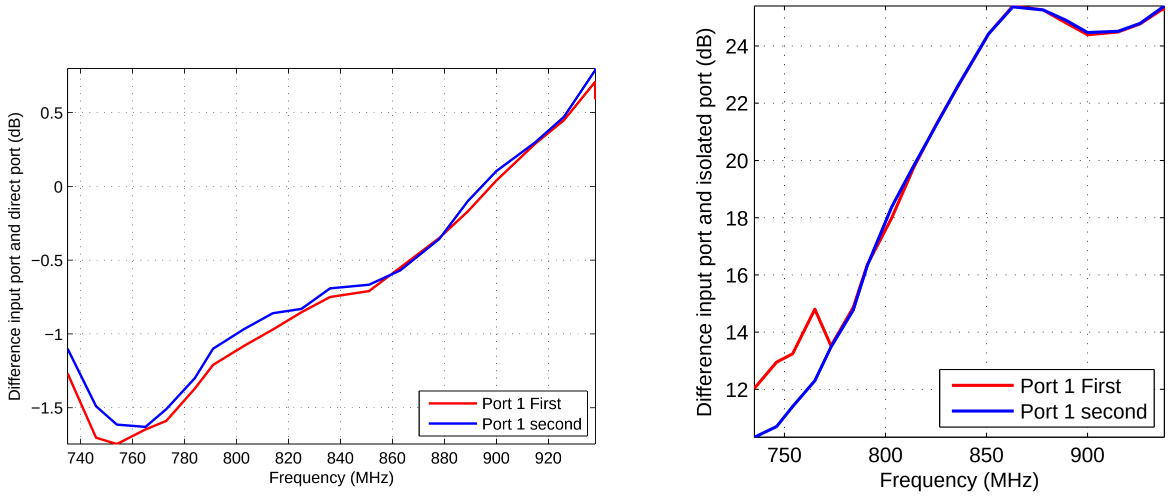


Figure 7.6: First: losses; second: isolation.

As shown in the figures above, the maximum losses are 0.7 dB (from 0.9 to 1 GHz). In terms of the isolation, the value is around 25 dB, so it works properly since that value is similar to the one from the datasheet.

7.4 Coupler

In order to measure the output port of the coupler (not the coupled ports) the VCO was connected to the input port and a power sensor to the output one. The value of the output power of the coupler is shown in Fig. 7.7.

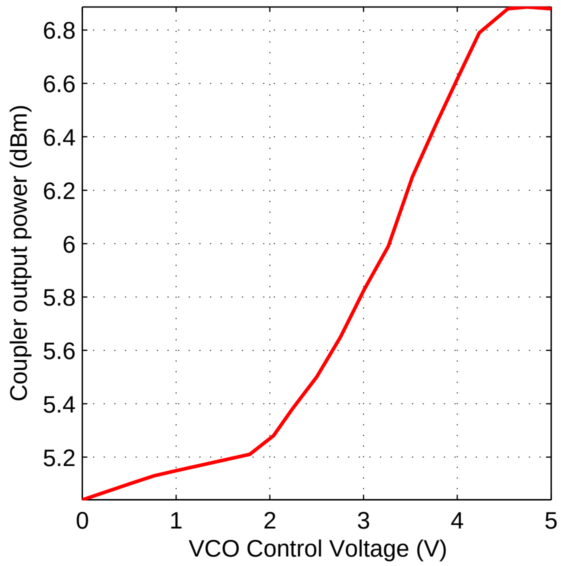


Figure 7.7: Test of the Coupler Output Power.

Then, the value of the insertion loss was calculated by using the output power of the VCO measured before.

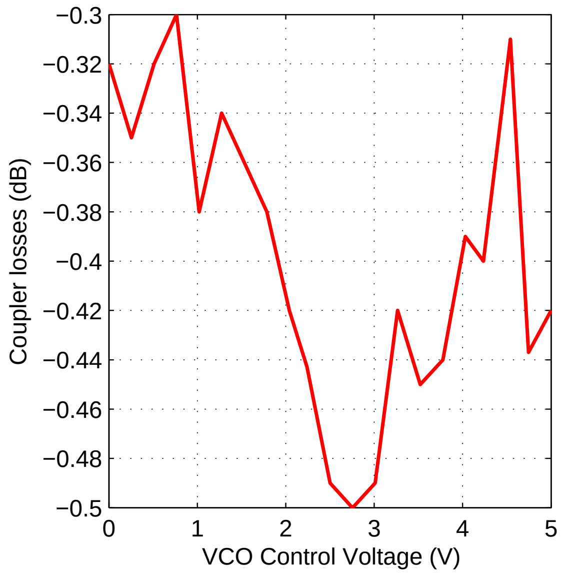


Figure 7.8: Insertion loss due to the coupler.

As it can be seen in Fig. 7.8, the value of the insertion loss is low.

The functionality of the coupled ports was not tested in the same way as the other components since the output power of the coupled ports is really low if only the VCO is connected to the coupler. Therefore, the measurement of the power sensors would not be accurate in this case.

7.5 Temperature Measurement

Finally, the whole system was set up in order to check if the temperature of the water is increased while it is working at the resonant frequency. Before measuring the temperature, the routine to look for the lowest S_{11} was executed in order to select the proper VCO control voltage. In Fig. 7.9, the result of executing this routine is shown.

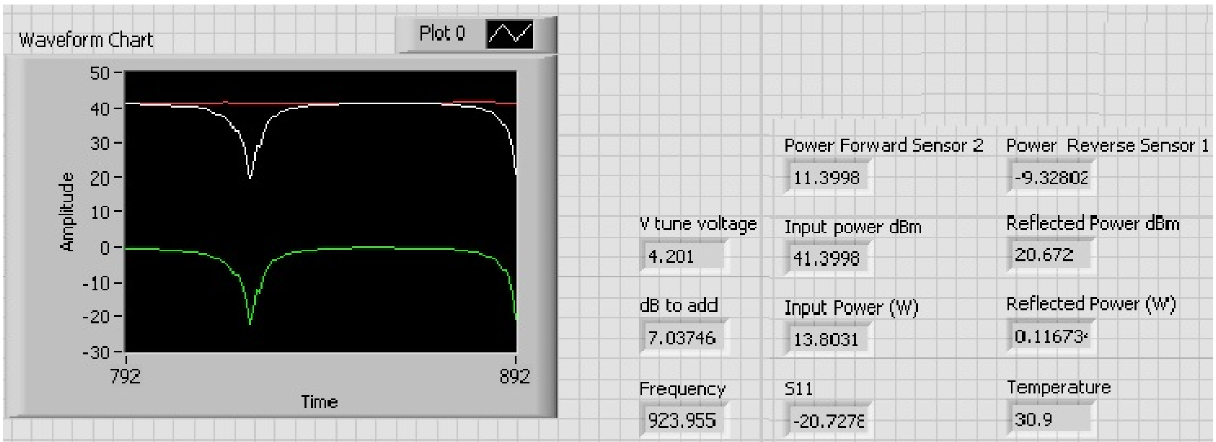


Figure 7.9: Measure of the Lowest S_{11}.

As seen in the figure above, the resonant frequency calculated is 923.955 MHz and the control voltage of the VCO is 4.2 V (remember that this value is multiplied by 3 due to the operational amplifier). The value of the control voltage of the attenuator was 5 V. Then, the temperature of the water was measured by selecting that frequency and attenuation values.

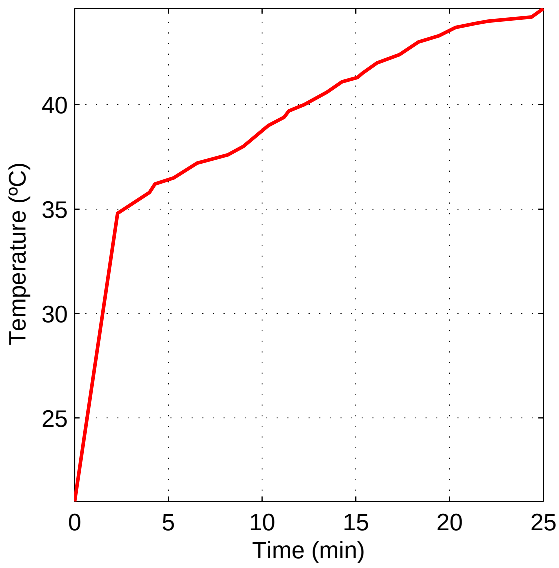


Figure 7.10: Measured temperature of the sample (water in this case) while the system is working at the resonance frequency (second mode).

In Fig. 7.10, it is shown that the temperature of the water has been increased. Therefore, it has been proved that the system works. Moreover, 12 minutes are required to increase the temperature of the water from 21° to 40° and 22 minutes to increase it up to 44°. If we compare these results to the ones obtained by the systems mentioned in the introduction, we can confirm that the results are satisfactory. Furthermore, the designed system can be connected to another kind of applicator.

Chapter 8

Conclusions and Future Research Lines

A novel hyperthermia system has been presented in this project. After choosing all the components that conform the system, a waveguide cavity was designed with HFSS and manufactured afterwards. It has been shown that the measured resonance frequency is the same as the simulated one. The difference between them is the matching: the results measured show a better matching than the ones simulated. That could be attributed to the fact that the manufactured applicator takes into account several physical factors that the simulated one does not. Furthermore, it is shown in the same figure that two electromagnetic modes are propagated in the range from 0.8 MHz to 1 GHz. Due to the fact that the second mode (917 MHz) has a better matching than the first one (835 MHz), this was the one selected for our system.

Regarding the temperature results seen in the previous chapter, it is shown that around 12 minutes are required to increase the temperature of the water from 21° to 40° and 22 minutes to increase it up to 44°. As the temperature needed for the hyperthermia treatment is located between these values, a feedback loop will be created in order to control the output power of the system in terms of such temperature. The functionality of this feedback loop would consist of increasing the value of the power of the system if the temperature is lower than the value required for the treatment, and decreasing it if the temperature is higher than required. After finishing this loop and the routine to get the lowest S_{11}, the next step would be to use the system in melanoma cancer cells.

Finally, it is relevant to say that I have a paper on this project submitted and accepted for the 4th International Conference on Wireless Mobile Communication and Healthcare "Transforming healthcare through innovations in mobile and wireless technologies", which takes place in Athens from the 3th to the 5th of November. Therefore, the paper will be published in the proceedings of the conference and submitted to the IEEE Xplore Digital Library. The paper is shown in Appendix section A.18.

Bibliography

[1] P. Togni, J. Vrba, and L. Vannucci, “Microwave applicator for hyperthermia treatment on in vivo melanoma model,” *Med. Biol. Eng. Comput.*, vol. 48, pp. 285–292, 2010.

[2] O. A. Arabe, P. F. Maccarini, E. L. Jones, G. Hanna, and et al., “A 400 mhz hyperthermia system using rotating spiral antennas for uniform treatment of large superficial and sub-surface tumors,” 2007.

[3] B. Hildebrandt, P. Wust, O. Ahlers, and et al., “The cellular and molecular basis of hyperthermia,” *Critical reviews in Oncology/Hematology*, vol. 43(1), pp. 33–56, 2002.

[4] J. V. der Zee, “Heating the patient: a promising approach?” *Annals of Oncology*, vol. 13(8), pp. 1173–1184, 2002.

[5] M. Converse, E. J. Bond, B. D. V. Veen, and S. C. Hagness, “A computational study of ultra-wideband versus narrowband microwave hyperthermia for breast cancer treatment,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, NO. 5, May 2006.

[6] P. Wust, B. Hildebrandt, G. Sreenivasa, and et al., “Hyperthermia in combined treatment of cancer,” *The Lancest Oncology*, vol. 3(8), pp. 487–497, 2002.

[7] BSD Medical Corporation, “The Science behind Hyperthermia,” http://www.bsdmedical.com/usa/patients_science.php.

[8] A. Cheung and J. Al-Atrash, “Microwave hyperthermia for cancer therapy,” *IEEE Proceedings*, vol. 134, Pt. A, No. 6, June 1987.

[9] M. Converse, E. J. Bond, B. D. V. Veen, and S. C. Hagness, "Evaluation of an equipment for cancer treatment using microwave hyperthermia," *Proceedings of the 37th European Microwave Conference*, October 2007.

[10] X. Yang, J. Du, and Y. Liu, "Advances in hyperthermia technology," *Proceedings of the 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, September 1-4, 2005.

[11] J. van der Zee, Z. Vujaskovic, M. Kondo, and T. Sugahara, "The kadota fund international forum 2004–clinical group consensus." *Int J Hyperthermia*, 2008.

[12] P. Togni, J. Vrba, and L. Vannucci, "System to study the effects of microwave hyperthermia on in-vivo melanoma model," *Proceedings of the 38th European Microwave Conference*, October 2008.

[13] D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., chapter 1, p. 7, equation (1.8), 2013.

[14] ——, *Fundamentals of Physics*, 10th ed., chapter 18, p. 524, 2013.

[15] ——, *Fundamentals of Physics*, 10th ed., chapter 7, p. 166, 2013.

[16] G. Ma and G. Jiang, "Review of tumor hyperthermia technique in biomedical engineering frontier," *3rd International Conference on Biomedical Engineering and Informatics*, 2010.

[17] S. L. Ho, S. Niu, and W. N. Fu, "Design and analysis of novel focused hyperthermia devices," *IEEE Transactions on magnetics*, vol. 48, No. 11, November 2012.

[18] S. K. Pauvuluri, M. Ferenets, G. Goussetis, M. P. Y. Desmulliez, T. Tilford, and et al., "Encapsulation of microelectronic components using open-ended microwave oven," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 2, No. 5, 2012.

[19] W. Jung, *Op Amp Applications Handbook*, 2005.

[20] D. M. Pozar, *Microwave Engineering*, 4th ed., chapter 7, p. 322, equation (7.20c) 2012.

[21] A. P. Malvino, *Malvino electronic principles*, 6th ed., chapter 12, 1999.

[22] D. M. Pozar, *Microwave Engineering*, 4th ed., chapter 6.3, p. 286, equation (6.40) 2012.

[23] ANSOFT, *User Guide HFSS High Frequency Structure Simulator*, June 2005.

[24] Mini-Circuits, “Mini-Circuits - Software Downloads,” http://217.34.103.131/support/software_download.html.

Appendix A

Components

A.1 Miniature-Pyrometer CT84

Technical Datasheet

Miniature-Pyrometer *CT84*

Precise non-contact temperature measurement from -50 to 975°C

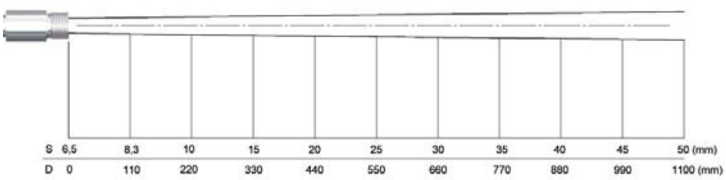
Features:

- One of the smallest infrared sensors worldwide with 22:1 optical resolution
- Rugged and usable up to 180°C ambient temperature without cooling
- Separate electronics with easy accessible programming keys and LCD backlit display
- Selectable analog output: 0/4-20 mA, 0 - 5 V/0 - 10 V, thermocouple type K or J
- Optional USB, RS485, RS232, CAN, Profibus DP interfaces, relay outputs (2x optically isolated)
- Installation of max. 32 Sensors in one network (via RS485)
- Wide Power supply range from 8 to 36 V DC

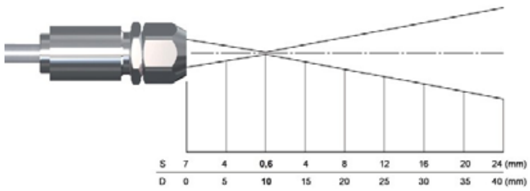
Model and temperature ranges (scaleable via programming keys or software)

Model	CT84-00	CT84-05	CT84-02
Spectral range	8 – 14 µm		
Temperature range	-50 – 975°C	-50 – 600°C	-50 – 600°C

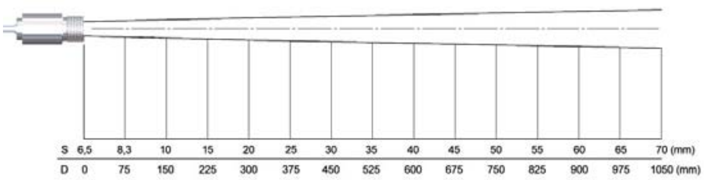
Optical Specifications



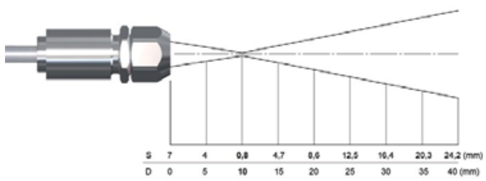
CT84-00 with optical resolution 22:1



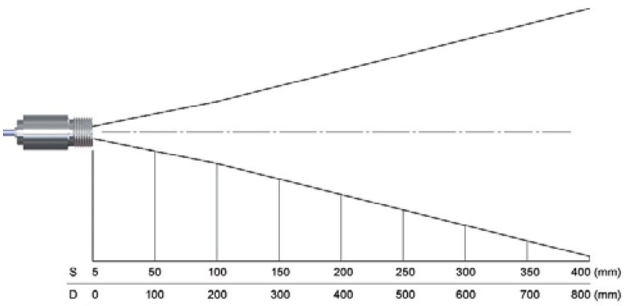
CT84-00 with close focus lens CZ01-00



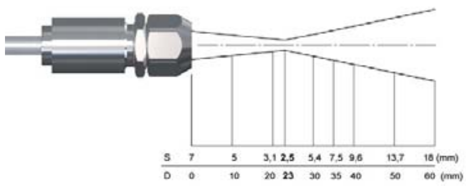
CT84-05 with optical resolution 15:1



CT84-05 with close focus lens CZ01-05



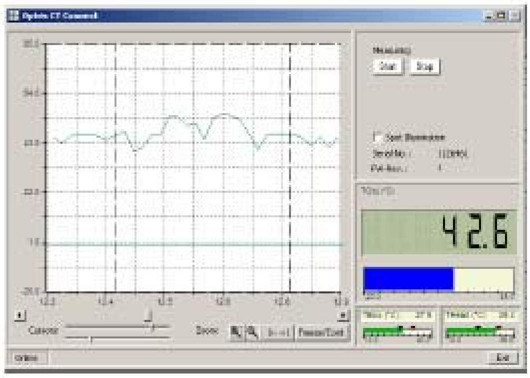
CT84-02 with optical resolution 2:1



CT84-02 with close focus lens CZ01-02

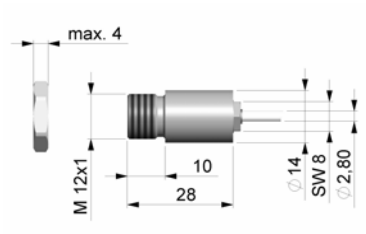
Remark: CT series sensing heads are exchangeable. After exchanging a sensor the calibration code of the replacement sensor must be entered into the electronics.

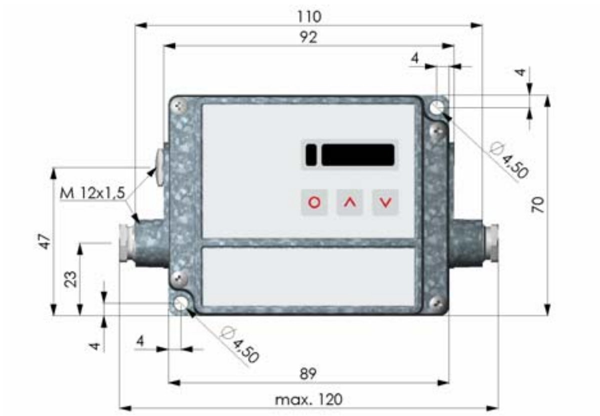
Optional Software

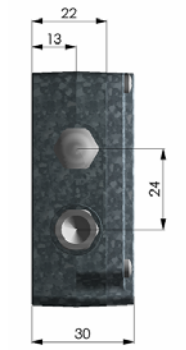


- easy sensor setup and remote controlling
- automatic data logging for analysis and documentation
- grafic display of temperature trends
- adjustment of extended signal processing functions
- programming of analog and digital input for external emissivity and ambient temperature compensation
- programming of alarm output (head or object temperature)
- digital remote communication of up to 32 sensors in one network)

Dimensions







Specifications

General specifications	
Environmental rating	IP65 (NEMA-4)
Ambient temperature	
Sensing head	-20 – 180 °C (130 °C @ 2:1)
Electronics	0 – 85 °C
Storage temperature	
Sensing head	-40 – 180 °C (130 °C @ 2:1)
Electronics	-40 – 85 °C
Relative humidity	10 – 95 %, non condensing
Vibration (sensor)	IEC 68-2-6: 3G, 11-200 Hz, any axis
Shock (sensor)	IEC 68-2-27: 50G, 11 ms, any axis
Weight	Sensor 40 g, Electronic 420 g
Electrical specifications	
Outputs-analog	Chanel 1: 0/ 4 – 20 mA, 0 – 5/ 10 V, Thermocouple Typ J or K
	Chanel 2: Sensing head temperature (-20 – 180°C as 0 – 5 V or 0 – 10 V), Alarmoutput
Option relay output	2 x 60 VDC / 42 VAC$_{eff}$; 0,4 A; optically isolated
Option digital output	USB, RS232, RS485 CAN-Bus, Profibus DP, Ethernet (per order)
Output impedances	mA max. 500 Ω (with 8 – 36 V DC)
	mV min. 100 kΩ load impedance
	Thermocouple 20 Ω
Inputs	Programmable functional inputs for external emissivity adjustment, ambient temperature compensation, trigger (reset of hold functions)
Sensor-cable length	Standard 1 m, option 3 m, 8 m, 15 m *
Power supply	8 – 36 VDC, max. 100 mA

* Caution: Cabel may be shortened, but never lengthened. To shorten the cable may cause additional measuring errors of about 0.1 K/ m.

Specifications are subject to change without notice .DB_CT84_en_12.03.29

Measurement specifications	
System accuracy	±1 % oder ±1 °C[1] (at ambient temperature 23 ± 5°C)
Repeatability	±0,5 % oder ±0,5 °C1 (at ambient temperature 23 ± 5°C)
Temp. coefficient	0,05 % or 0,05 °C/K, [1,2]
Temp. resolution	0,1 °C
Response time	150 ms (95 %)
Emissivity/Gain	0,100 – 1,100 (adjustable via programming keys or software)
Transmissivity/Gain	0,100 – 1,100 (adjustable via programming keys or software)
Signalprocessing	peak hold, valley hold, average; extended hold function with threshold and hysteresis (parameter adjustable via programming keys or software, respectively)
Calibration certificate	optional

[1] whichever is greater

[2] at sensing head temperature 0 - 180°C (130°C with 2:1)

Sensortherm GmbH
Infrared Measurement- and Control-Systems
Hauptstr. 123
65843 Sulzbach/Ts
Tel.: 0049-6196-64065-80
Fax: 0049-6196-64065-89

info@sensortherm.de
www.sensortherm.com

A.2 Voltage Controlled Oscilator ZX95-1015+

Coaxial

Voltage Controlled Oscillator

ZX95-1015+

Linear Tuning 750 to 1010 MHz

Features
- low phase noise
- low pushing
- low pulling
- protected by US patent 6,790,049

Applications
- r & d
- lab
- instrumentation
- wireless communications
- mobile TV

CASE STYLE: GB956

Connectors	Model	Price	Qty.
SMA	ZX95-1015-S+	$40.95 ea.	(1-9)

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Electrical Specifications

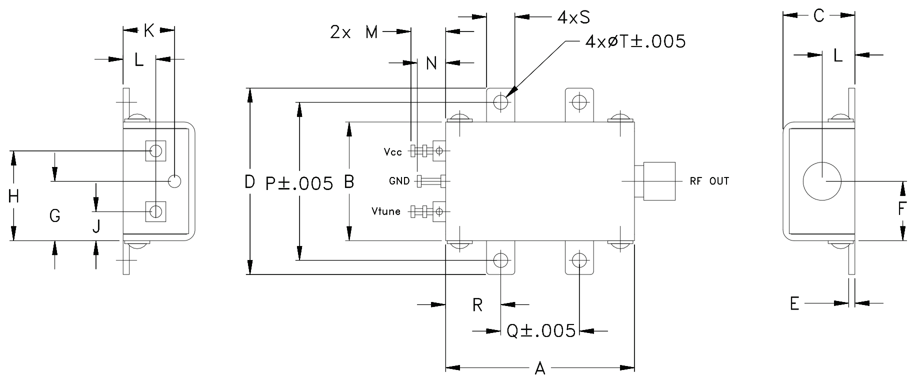
MODEL NO.	FREQ. (MHz)		POWER OUTPUT (dBm)	PHASE NOISE dBc/Hz SSB at offset frequencies,kHz Typ.				TUNING VOLTAGE RANGE (V)		TUNING SENSI-TIVITY (MHz/V)	TUNING PORT CAP (pF)	TUNING 3 dB MODULATION BANDWIDTH (MHz)	NON HARMONIC SPURIOUS (dBc)	HARMONICS (dBc)		PULLING pk-pk @12 dBr (MHz)	PUSHING (MHz/V)	DC OPERATING POWER Vcc (volts)	DC OPERATING POWER Current (mA)
	Min.	Max.	Typ.	1	10	100	1000	Min.	Max.	Typ.	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	Typ.		Max.
ZX95-1015+	750	1010	+6	-85	-113	-134	-154	0.5	28	7-15	70	35	-90	-20	-10	1	1.5	5	35

Maximum Ratings

Operating Temperature	-55°C to 85°C
Storage Temperature	-55°C to 100°C
Absolute Max. Supply Voltage (Vcc)	6V
Absolute Max. Tuning Voltage (Vtune)	30V
All specifications	50 ohm system

Permanent damage may occur if any of these limits are exceeded.

Outline Drawing



Outline Dimensions (inch / mm)

A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	wt.
1.20	**.75**	**.46**	**1.18**	**.04**	**.38**	**.38**	**.57**	**.18**	**.33**	**.21**	**.22**	**.18**	**1.00**	**.50**	**.35**	**.18**	**.106**	grams
30.48	19.05	11.68	29.97	1.02	9.65	9.65	14.48	4.57	8.38	5.33	5.59	4.57	25.40	12.70	8.89	4.57	2.69	35.0

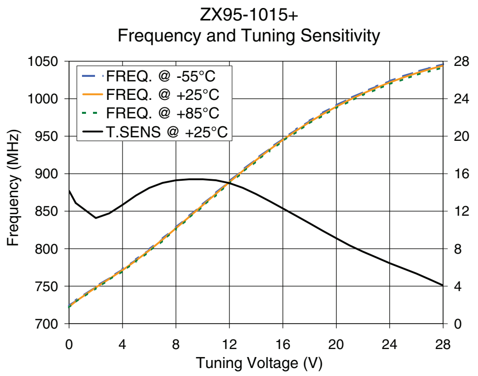
Performance Data & Curves*

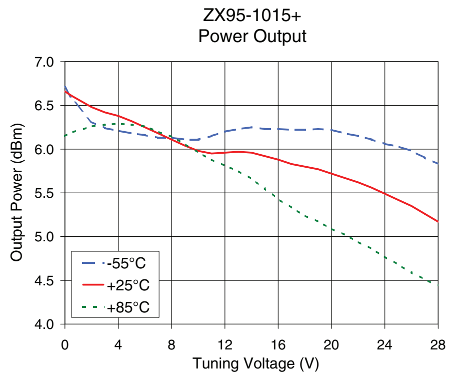
ZX95-1015+

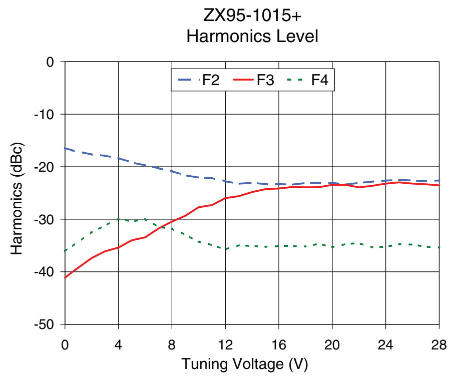
V TUNE	TUNE SENS (MHz/V)	FREQUENCY (MHz)			POWER OUTPUT (dBm)			Icc (mA)	HARMONICS (dBc)			FREQ. PUSH (MHz/V)	FREQ. PULL (MHz)	PHASE NOISE (dBc/Hz) at offsets			
		-55°C	+25°C	+85°C	-55°C	+25°C	+85°C		F2	F3	F4			1kHz	10kHz	100kHz	1MHz
0.00	14.17	723.9	722.6	721.6	6.71	6.66	6.15	23.06	-16.5	-41.1	-36.0	0.49	0.60	-87.2	-114.8	-136.3	-156.6
0.50	12.87	731.0	729.7	728.7	6.58	6.61	6.19	23.09	-16.9	-40.1	-35.3	0.27	0.51	-88.1	-115.7	-137.1	-156.9
2.00	11.27	749.7	748.4	747.3	6.31	6.48	6.26	23.12	-17.7	-37.4	-32.4	0.05	0.26	-90.3	-117.2	-138.5	-157.1
4.00	12.68	772.9	771.4	770.0	6.21	6.38	6.29	23.06	-18.4	-35.4	-29.9	0.05	0.19	-89.5	-117.2	-138.7	-156.5
6.00	14.48	799.1	797.7	796.2	6.16	6.25	6.26	22.93	-19.8	-33.5	-30.0	0.20	0.58	-89.2	-116.9	-138.5	-156.2
8.00	15.29	828.5	827.2	825.7	6.13	6.11	6.14	22.82	-20.9	-30.5	-31.8	0.71	0.75	-87.2	-116.2	-138.0	-156.7
10.00	15.40	859.1	857.9	856.3	6.11	5.98	5.96	22.74	-22.1	-27.7	-34.3	1.23	0.58	-85.4	-114.1	-136.0	-155.4
11.00	15.30	874.5	873.3	871.7	6.15	5.95	5.88	22.69	-22.2	-27.3	-34.9	1.44	0.39	-85.0	-112.6	-135.0	-154.7
12.00	14.99	889.9	888.6	886.9	6.20	5.96	5.81	22.68	-22.8	-26.0	-35.7	1.62	0.15	-83.9	-111.7	-134.2	-153.9
13.00	14.49	905.1	903.6	901.9	6.23	5.97	5.75	22.70	-23.2	-25.6	-34.9	1.77	0.62	-83.7	-111.2	-133.7	-153.2
14.00	13.82	919.7	918.1	916.4	6.25	5.96	5.66	22.71	-23.1	-24.8	-35.1	1.89	1.13	-83.6	-111.2	-133.7	-153.5
15.00	13.07	933.6	931.9	930.3	6.23	5.92	5.55	22.72	-23.3	-24.3	-35.2	1.98	1.48	-84.3	-111.2	-134.1	-153.5
16.00	12.30	946.8	945.0	943.4	6.23	5.88	5.43	22.72	-23.3	-24.1	-35.1	2.02	1.58	-84.8	-111.0	-134.6	-154.0
17.00	11.51	959.1	957.3	955.6	6.22	5.83	5.33	22.72	-23.4	-23.9	-35.1	1.99	1.50	-85.2	-111.1	-134.6	-154.2
18.00	10.71	970.6	968.8	967.1	6.22	5.80	5.24	22.73	-23.1	-23.9	-35.2	1.89	1.27	-85.9	-111.0	-134.9	-153.8
20.00	9.12	991.2	989.4	987.5	6.22	5.72	5.09	22.82	-23.1	-23.4	-35.3	1.53	0.43	-85.8	-111.2	-134.5	-153.4
22.00	7.68	1008.8	1006.9	1004.8	6.15	5.62	4.94	22.92	-23.1	-23.9	-34.6	1.17	0.75	-85.5	-111.2	-134.6	-153.9
24.00	6.45	1023.5	1021.6	1019.4	6.06	5.49	4.77	22.98	-22.6	-23.2	-35.3	0.93	1.37	-85.4	-111.0	-134.1	-153.2
26.00	5.35	1035.9	1034.0	1031.6	5.98	5.35	4.59	23.03	-22.6	-23.2	-34.8	0.81	1.71	-86.4	-110.7	-133.4	-152.5
28.00	4.08	1046.0	1044.1	1041.4	5.83	5.17	4.44	23.07	-22.6	-23.6	-35.4	0.70	1.77	-85.4	-110.7	-133.2	-152.7

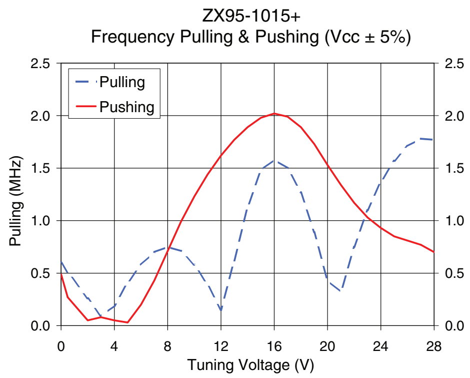
FREQ OFFSET (KHz)	PHASE NOISE at 880 MHz (dBc/Hz)
1.0	-83.22
2.0	-93.07
3.5	-100.38
6.0	-106.96
8.5	-110.45
10.0	-112.04
20.8	-119.59
35.5	-125.08
60.7	-129.77
86.7	-132.84
100.0	-134.27
148.1	-137.47
177.0	-139.00
211.6	-140.82
302.4	-144.15
361.5	-145.88
507.5	-148.37
606.7	-150.29
851.6	-153.21
1000.0	-153.92

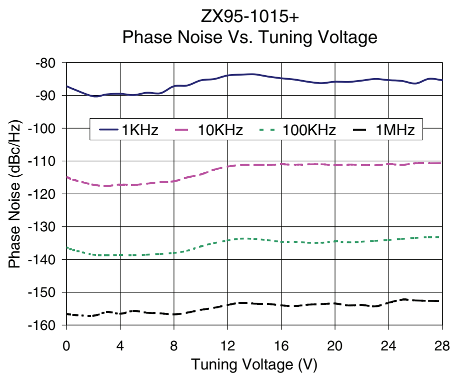
*at 25°C unless mentioned otherwise

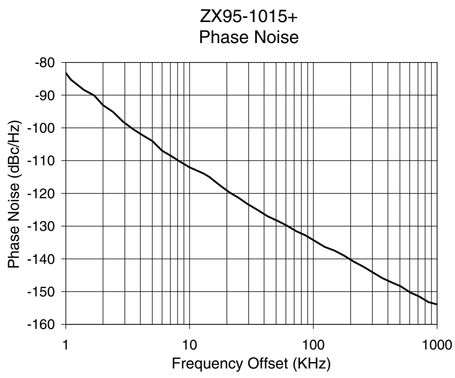












A.3 Bus-Powered Multifunction DAQ

Technical Sales
United States
(866) 531-6285
info@ni.com

Requirements and Compatibility | Ordering Information | Detailed Specifications
For user manuals and dimensional drawings, visit the product page resources tab on ni.com.

Last Revised: 2013-07-10 09:55:53.0

Low-Cost, Bus-Powered Multifunction DAQ for USB

12- or 14-Bit, Up to 48 kS/s, 8 Analog Inputs

- 8 analog inputs at 12 or 14 bits, up to 48 kS/s
- 2 analog outputs at 12 bits, software-timed
- 12 TTL/CMOS digital I/O lines
- One 32-bit, 5 MHz counter
- Digital triggering
- Bus-powered
- 1-year warranty

Overview

With recent bandwidth improvements and new innovations from National Instruments, USB has evolved into a core bus of choice for measurement applications. The NI USB-6008 and USB-6009 are low-cost DAQ devices with easy screw connectivity and a small form factor. With plug-and-play USB connectivity, these devices are simple enough for quick measurements but versatile enough for more complex measurement applications.

Back to Top

Requirements and Compatibility

OS Information
Mac OS X
Windows 2000/XP
Windows 7
Windows CE
Windows Mobile
Windows Vista 32-bit
Windows Vista 64-bit

Driver Information
NI-DAQmx
NI-DAQmx Base

Software Compatibility
ANSI C/C++
LabVIEW
LabWindows/CVI
Measurement Studio
SignalExpress
Visual Basic .NET
Visual C#

Back to Top

Comparison Tables

Product	Analog Inputs	Input Resolution	Max Sampling Rate (kS/s)	Analog Outputs	Output Resolution	Output Rate (Hz)	Digital I/O Lines	32-Bit Counter	Triggering
USB-6008	8 single-ended/4 differential	12	10	2	12	150	12	1	Digital
USB-6009	8 single-ended/4 differential	14	48	2	12	150	12	1	Digital

Back to Top

Application and Technology

The USB-6008 and USB-6009 are ideal for applications where a low-cost, small form factor and simplicity are essential. Examples include the following:

Data logging—quick and easy environmental or voltage data logging
Academic lab use—student ownership of data acquisition hardware for completely interactive lab-based courses (Academic pricing available. Visit the academic product page for details.)
OEM applications as I/O for embedded systems

Recommended Software

National Instruments measurement services software, built around NI-DAQmx driver software, includes intuitive application programming interfaces, configuration tools, I/O assistants, and other tools designed to reduce system setup, configuration, and development time. National Instruments recommends using the latest version of NI-DAQmx driver software for application development in NI LabVIEW, SignalExpress, LabWindows™/CVI, and Measurement Studio software. To obtain the latest version of NI-DAQmx, visit ni.com/support/daq/versions.

NI measurement services software speeds up your development with features including the following:

A guide to create fast and accurate measurements with no programming using the DAQ Assistant
Automatic code generation to create your application in LabVIEW
LabWindows/CVI; SignalExpress; and C#, Visual Studio .NET, ANSI C/C++, or Visual Basic using Measurement Studio
Multithreaded streaming technology for 1,000 times performance improvements
Automatic timing, triggering, and synchronization routing to make advanced applications easy
More than 3,000 free software downloads at ni.com/zone to jump-start your project
Software configuration of all digital I/O features without hardware switches/jumpers
Single programming interface for analog input, analog output, digital I/O, and counters on hundreds of multifunction DAQ hardware devices; M Series devices are compatible with the following versions (or later) of NI application software—LabVIEW, LabWindows/CVI, or Measurement Studio versions 7.x; and SignalExpress 2.x

Every National Instruments DAQ device includes a copy of SignalExpress LE data-logging software, so you can quickly acquire, analyze, and present data without programming. The NI-DAQmx Base driver software is provided for use with Linux, Mac OS X, Windows Mobile, and Windows CE OSs.

Recommended Accessories

The USB-6008 and USB-6009 have removable screw terminals for easy signal connectivity. For extra flexibility when handling multiple wiring configurations, NI offers the USB-600x Connectivity Kit, which includes two extra sets of screw terminals, extra labels, and a screwdriver. In addition, the USB-600x Prototyping Kit provides space for adding more circuitry to the inputs of the USB-6008 or USB-6009.

NI USB DAQ for OEMs

Shorten your time to market by integrating world-class National Instruments OEM measurement products into your embedded system design. Board-only versions of NI USB DAQ devices are available for OEM applications, with competitive quantity pricing and available software customization. The NI OEM Elite Program offers free 30-day trial kits for qualified customers. Visit ni.com/oem for more information.

Information for Student Ownership

To supplement simulation, measurement, and automation theory courses with practical experiments, NI has developed the USB-6008 and USB-6009 student kits, which include the LabVIEW Student Edition and a ready-to-run data logger application. These kits are exclusively for students, giving them a powerful, low-cost, hands-on learning tool. Visit ni.com/academic for more details.

Information for OEM Customers

For information on special configurations and pricing, call (800) 813-3693 (United States only) or visit ni.com/oem. Go to the Ordering Information section for part numbers.

Back to Top

Ordering Information

For a complete list of accessories, visit the product page on ni.com.

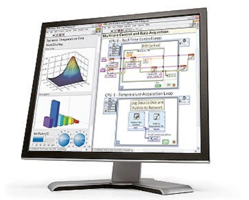
Products	Part Number	Recommended Accessories	Part Number
NI USB-6008			
NI USB-6008 with NI-DAQmx software, LabVIEW SignalExpress LE, and a USB cable.	779051-01	No accessories required.	
NI USB-6008 OEM (no enclosure)	193132-02	No accessories required.	
NI USB-6008 Student Kit with NI-DAQmx software, LabVIEW SignalExpress LE, and a USB cable. Includes LabVIEW Student Edition.	779320-22	No accessories required.	
Prototyping Kit			
NI USB-600x Prototyping Kit	779511-01	No accessories required.	
Connectivity Kit			
NI USB-600x Connectivity Kit	779371-01	No accessories required.	
NI USB-6009			
NI USB-6009 OEM (no enclosure)	193132-01	No accessories required.	
NI USB-6009 Student Kit with NI-DAQmx software, LabVIEW SignalExpress LE, and a USB cable. Includes LabVIEW Student Edition.	779321-22	No accessories required.	
NI USB-6009 with NI-DAQmx software, LabVIEW SignalExpress LE, and a USB cable.	779026-01	No accessories required.	

Back to Top

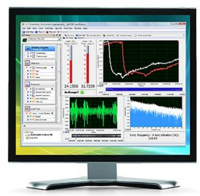
Software Recommendations

NI LabVIEW Full Development System for Windows — Fully integrated graphical system design software

SignalExpress for Windows — Quickly configure projects without programming
Control over 400 PC-based and stand-alone instruments



Support for a wide range of measurement hardware, I/O, and buses
Custom, event-driven user interfaces for measurement and control
Extensive signal processing, analysis, and math functionality
Advanced compiler to ensure high-performance execution and code optimization

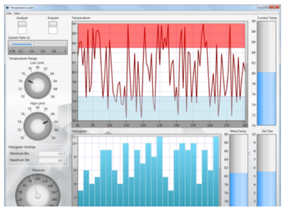


Log data from more than 250 data acquisition devices
Perform basic signal processing, analysis, and file I/O
Scale your application with automatic LabVIEW code generation
Create custom reports or easily export data to LabVIEW, DIAdem or Microsoft Excel

NI LabWindows™/CVI for Windows

Real-time advanced 2D graphs and charts
Complete hardware compatibility with IVI, VISA, DAQ, GPIB, and serial
Analysis tools for array manipulation, signal processing statistics, and curve fitting
Simplified cross-platform communication with network variables
Measurement Studio .NET tools (included in LabWindows/CVI Full only)
The mark LabWindows is used under a license from Microsoft Corporation.

NI Measurement Studio Standard Edition



Customizable graphs and charts for WPF, Windows Forms, and ASP.NET Web Forms UI design
Analysis libraries for basic signal generation
Hardware integration support with data acquisition and instrument control libraries
Project setup wizards to speed up development
Support for Microsoft Visual Studio .NET 2012/2010/2008

Back to Top

Support and Services

System Assurance Programs

NI system assurance programs are designed to make it even easier for you to own an NI system. These programs include configuration and deployment services for your NI PXI, CompactRIO, or Compact FieldPoint system. The NI Basic System Assurance Program provides a simple integration test and ensures that your system is delivered completely assembled in one box. When you configure your system with the NI Standard System Assurance Program, you can select from available NI system driver sets and application development environments to create customized, reorderable software configurations. Your system arrives fully assembled and tested in one box with your software preinstalled. When you order your system with the standard program, you also receive system-specific documentation including a bill of materials, an integration test report, a recommended maintenance plan, and frequently asked question documents. Finally, the standard program reduces the total cost of owning an NI system by providing three years of warranty coverage and calibration service. Use the online product advisors at ni.com/advisor to find a system assurance program to meet your needs.

Technical Support

Get answers to your technical questions using the following National Instruments resources.

Support - Visit ni.com/support to access the NI KnowledgeBase, example programs, and tutorials or to contact our applications engineers who are located in NI sales offices around the world and speak the local language.
Discussion Forums - Visit forums.ni.com for a diverse set of discussion boards on topics you care about.
Online Community - Visit community.ni.com to find, contribute, or collaborate on customer-contributed technical content with users like you.

Repair

While you may never need your hardware repaired, NI understands that unexpected events may lead to necessary repairs. NI offers repair services performed by highly trained technicians who quickly return your device with the guarantee that it will perform to factory specifications. For more information, visit ni.com/repair.

Training and Certifications

The NI training and certification program delivers the fastest, most certain route to increased proficiency and productivity using NI software and hardware. Training builds the skills to more efficiently develop robust, maintainable applications, while certification validates your knowledge and ability.

Classroom training in cities worldwide - the most comprehensive hands-on training taught by engineers.
On-site training at your facility - an excellent option to train multiple employees at the same time.
Online instructor-led training - lower-cost, remote training if classroom or on-site courses are not possible.
Course kits - lowest-cost, self-paced training that you can use as reference guides.
Training memberships and training credits - to buy now and schedule training later.

Visit ni.com/training for more information.

Extended Warranty

NI offers options for extending the standard product warranty to meet the life-cycle requirements of your project. In addition, because NI understands that your requirements may change, the extended warranty is flexible in length and easily renewed. For more information, visit ni.com/warranty.

OEM

NI offers design-in consulting and product integration assistance if you need NI products for OEM applications. For information about special pricing and services for OEM customers, visit ni.com/oem.

Alliance

Our Professional Services Team is comprised of NI applications engineers, NI Consulting Services, and a worldwide National Instruments Alliance Partner program of more than 700 independent consultants and integrators. Services range from start-up assistance to turnkey system integration. Visit ni.com/alliance.

Back to Top

Detailed Specifications

FThe following specifications are typical at 25 °C, unless otherwise noted.

Analog Input

Converter type	Successive approximation
Analog inputs	8 single-ended, 4 differential, software selectable
Input resolution	
NI USB-6008	12 bits differential, 11 bits single-ended
NI USB-6009	14 bits differential, 13 bits single-ended
Max sampling rate (aggregate) [1]	
NI USB-6008	10 kS/s
NI USB-6009	48 kS/s
AI FIFO	512 bytes
Timing resolution	41.67 ns (24 MHz timebase)
Timing accuracy	100 ppm of actual sample rate
Input range	
Single-ended	±10 V
Differential	±20 V [2] , ±10 V, ±5 V, ±4 V, ±2.5 V, ±2 V, ±1.25 V, ±1 V
Working voltage	±10 V
Input impedance	144 kΩ
Overvoltage protection	±35
Trigger source	Software or external digital trigger
System noise [3]	
Single-ended	
±10 V range	5 mVrms
Differential	
± 20 V range	5 mVrms
±1 V range	0.5 mVrms

Absolute accuracy at full scale, single-ended		
Range	Typical at 25 °C (mV)	Maximum over Temperature (mV)
±10	14.7	138

Absolute accuracy at full scale, differential [4]		
Range	Typical at 25 °C (mV)	Maximum over Temperature (mV)
±20	14.7	138
±10	7.73	84.8
±5	4.28	58.4
±4	3.59	53.1
±2.5	2.56	45.1
±2	2.21	42.5
±1.25	1.70	38.9
±1	1.53	37.5

Analog Output

Analog outputs	2
Output resolution	12 bits
Maximum update rate	150 Hz, software-timed

Output range	0 to +5 V
Output impedance	50 Ω
Output current drive	5 mA
Power-on state	0 V
Slew rate	1 V/μs
Short circuit current	50 mA
Absolute accuracy (no load)	7 mV typical, 36.4 mV maximum at full scale

Digital I/O

Digital I/O	
P0.<0..7>	8 lines
P1.<0..3>	4 lines
Direction control	Each channel individually programmable as input or output
Output driver type	
NI USB-6008	Open collector (open-drain)
NI USB-6009	Each channel individually programmable as active drive (push-pull) or open collector (open-drain)
Compatibility	TTL, LVTTL, CMOS
Absolute maximum voltage range	–0.5 to 5.8 V with respect to GND
Pull-up resistor	4.7 kΩ to 5 V
Power-on state	Input

Digital logic levels

Level	Min	Max	Units
Input low voltage	–0.3	0.8	V
Input high voltage	2.0	5.8	V
Input leakage current	—	50	μA
Output low voltage (I = 8.5 mA)	—	0.8	V
Output high voltage			
Active drive (push-pull), I = –8.5 mA	2.0	3.5	V
Open collector (open-drain), I = –0.6 mA, nominal	2.0	5.0	V
Open collector (open-drain), I = –8.5 mA, with external pull-up resistor	2.0	—	V

External Voltage

+5 V output (200 mA maximum)	+5 V typical, +4.85 V minimum
+2.5 V output (1 mA maximum)	+2.5 V typical
+2.5 V accuracy	0.25% max
Reference temperature drift	50 ppm/°C max

Counter

Number of counters	1
Resolution	32 bits
Counter measurements	Edge counting (falling-edge)
Counter direction	Count up
Pull-up resistor	4.7 kΩ to 5 V
Maximum input frequency	5 MHz
Minimum high pulse width	100 ns
Minimum low pulse width	100 ns
Input high voltage	2.0 V

Input low voltage	0.8 V

Power Requirements

USB	
4.10 to 5.25 VDC	80 mA typical, 500 mA max
USB suspend	300 µA typical, 500 µA max

Physical Characteristics

Dimensions	
Without connectors	6.35 cm × 8.51 cm × 2.31 cm (2.50 in. × 3.35 in. × 0.91 in.)
With connectors	8.18 cm × 8.51 cm × 2.31 cm (3.22 in. × 3.35 in. × 0.91 in.)
I/O connectors	USB series B receptacle, (2) 16 position terminal block plug headers
Weight	
With connectors	84 g (3 oz)
Without connectors	54 g (1.9 oz)
Screw-terminal wiring	16 to 28 AWG
Torque for screw terminals	0.22–0.25 N · m (2.0–2.2 lb · in.)

Safety

If you need to clean the module, wipe it with a dry towel.

Safety Voltages

Connect only voltages that are within these limits.

Channel-to-GND	±30 V max, Measurement Category I

Measurement Category I is for measurements performed on circuits not directly connected to the electrical distribution system referred to as MAINS voltage. MAINS is a hazardous live electrical supply system that powers equipment. This category is for measurements of voltages from specially protected secondary circuits. Such voltage measurements include signal levels, special equipment, limited-energy parts of equipment, circuits powered by regulated low-voltage sources, and electronics.

Caution Do not use this module for connection to signals or for measurements within Measurement Categories II, III, or IV.

Safety Standards

This product is designed to meet the requirements of the following standards of safety for electrical equipment for measurement, control, and laboratory use:
IEC 61010-1, EN 61010-1
UL 61010-1, CSA 61010-1

Note For UL and other safety certifications, refer to the product label or visit ni.com/certification, search by model number or product line, and click the appropriate link in the Certification column.

Hazardous Locations

The NI USB-6008/6009 device is not certified for use in hazardous locations.

Environmental

The NI USB-6008/6009 device is intended for indoor use only.

Operating temperature	
(IEC 60068-2-1 and IEC 60068-2-2)	0 to 55 °C
Operating humidity	
(IEC 60068-2-56)	5 to 95% RH, noncondensing
Maximum altitude	2,000 m (at 25 °C ambient temperature)
Storage temperature	
(IEC 60068-2-1 and IEC 60068-2-2)	–40 to 85 °C
Storage humidity	
(IEC 60068-2-56)	5 to 90% RH, noncondensing
Pollution Degree (IEC 60664)	2

Electromagnetic Compatibility

This product is designed to meet the requirements of the following standards of EMC for electrical equipment for measurement, control, and laboratory use:
EN 61326 EMC requirements; Minimum Immunity

EN 55011 Emissions; Group 1, Class A
CE, C-Tick, ICES, and FCC Part 15 Emissions; Class A

Note For EMC compliance, operate this device with double-shielded cables.

CE Compliance

This product meets the essential requirements of applicable European Directives, as amended for CE marking, as follows:
2006/95/EC; Low-Voltage Directive (safety)
2004/108/EC; Electromagnetic Compatibility Directive (EMC)

Note Refer to the Declaration of Conformity (DoC) for this product for any additional regulatory compliance information. To obtain the DoC for this product, visit ni.com/certification, search by module number or product line, and click the appropriate link in the Certification column.

Environmental Management

National Instruments is committed to designing and manufacturing products in an environmentally responsible manner. NI recognizes that eliminating certain hazardous substances from our products is beneficial not only to the environment but also to NI customers.

For additional environmental information, refer to the *NI and the Environment* Web page at ni.com/environment. This page contains the environmental regulations and directives with which NI complies, as well as other environmental information not included in this document.

Waste Electrical and Electronic Equipment (WEEE)

EU Customers At the end of their life cycle, all products *must* be sent to a WEEE recycling center. For more information about WEEE recycling centers and National Instruments WEEE initiatives, visit ni.com/environment/weee.htm.

电子信息产品污染控制管理办法 （中国 RoHS）

中国客户 National Instruments 符合中国电子信息产品中限制使用某些有害物质指令 (RoHS)。关于 National Instruments 中国 RoHS 合规性信息，请登录 ni.com/environment/rohs_china。(For information about China RoHS compliance, go to ni.com/environment/rohs_china.)

[1] System dependent.

[2] ±20 V means that |AI+ – (AI–)| ≥ 20 V. However, AI+ and AI– must both be within ±10 V of GND.

[3] System noise measured at maximum sample rate.

[4] Input voltages may not exceed the working voltage range.

Back to Top

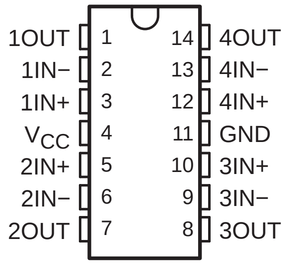
A.4 Operational Amplifier LN324AN

LM124, LM124A, LM224, LM224A, LM324, LM324A, LM2902, LM2902V, LM224K, LM224KA, LM324K, LM324KA, LM2902K, LM2902KV, LM2902KAV
QUADRUPLE OPERATIONAL AMPLIFIERS

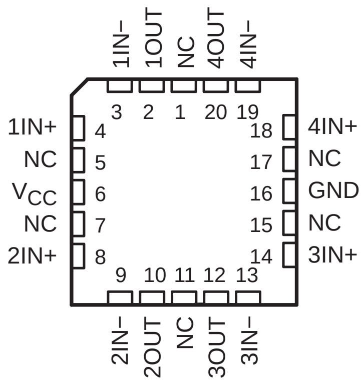
SLOS066R − SEPTEMBER 1975 − REVISED JANUARY 2005

- **2-kV ESD Protection for:**
  - **LM224K, LM224KA**
  - **LM324K, LM324KA**
  - **LM2902K, LM2902KV, LM2902KAV**
- **Wide Supply Ranges**
  - **Single Supply . . . 3 V to 32 V (26 V for LM2902)**
  - **Dual Supplies . . . ±1.5 V to ±16 V (±13 V for LM2902)**
- **Low Supply-Current Drain Independent of Supply Voltage . . . 0.8 mA Typ**
- **Common-Mode Input Voltage Range Includes Ground, Allowing Direct Sensing Near Ground**
- **Low Input Bias and Offset Parameters**
  - **Input Offset Voltage . . . 3 mV Typ**
    A Versions . . . 2 mV Typ
  - **Input Offset Current . . . 2 nA Typ**
  - **Input Bias Current . . . 20 nA Typ**
    A Versions . . . 15 nA Typ
- **Differential Input Voltage Range Equal to Maximum-Rated Supply Voltage . . . 32 V (26 V for LM2902)**
- **Open-Loop Differential Voltage Amplification . . . 100 V/mV Typ**
- **Internal Frequency Compensation**

LM124 . . . D, J, OR W PACKAGE
LM124A . . . J PACKAGE
LM224, LM224A, LM224K, LM224KA . . . D OR N PACKAGE
LM324, LM324K . . . D, N, NS, OR PW PACKAGE
LM324A . . . D, DB, N, NS, OR PW PACKAGE
LM324KA . . . D, N, NS, OR PW PACKAGE
LM2902 . . . D, N, NS, OR PW PACKAGE
LM2902K . . . D, DB, N, NS, OR PW PACKAGE
LM2902KV, LM2902KAV . . . D OR PW PACKAGE
(TOP VIEW)



LM124, LM124A . . . FK PACKAGE
(TOP VIEW)



NC − No internal connection

description/ordering information

These devices consist of four independent high-gain frequency-compensated operational amplifiers that are designed specifically to operate from a single supply over a wide range of voltages. Operation from split supplies also is possible if the difference between the two supplies is 3 V to 32 V (3 V to 26 V for the LM2902), and V_{CC} is at least 1.5 V more positive than the input common-mode voltage. The low supply-current drain is independent of the magnitude of the supply voltage.

Applications include transducer amplifiers, dc amplification blocks, and all the conventional operational-amplifier circuits that now can be more easily implemented in single-supply-voltage systems. For example, the LM124 can be operated directly from the standard 5-V supply that is used in digital systems and provides the required interface electronics, without requiring additional ±15-V supplies.

description/ordering information (continued)

ORDERING INFORMATION

T_A	V_{IO}max AT 25°C	MAX TESTED V_{CC}	PACKAGE†		ORDERABLE PART NUMBER	TOP-SIDE MARKING
0°C to 70°C	7 mV	30 V	PDIP (N)	Tube of 25	LM324N	LM324N
					LM324KN	LM324KN
			SOIC (D)	Tube of 50	LM324D	LM324
				Reel of 2500	LM324DR	
				Tube of 50	LM324KD	LM324K
				Reel of 2500	LM324KDR	
			SOP (NS)	Reel of 2000	LM324NSR	LM324
				Tube of 50	LM324KNS	LM324K
				Reel of 2000	LM324KNSR	
			TSSOP (PW)	Tube of 90	LM324PW	L324
				Reel of 2000	LM324PWR	
				Tube of 90	LM324KPW	L324K
				Reel of 2000	LM324KPWR	
	3 mV	30 V	PDIP (N)	Tube of 25	LM324AN	LM324AN
				Tube of 25	LM324KAN	LM324KAN
			SOIC (D)	Tube of 50	LM324AD	LM324A
				Reel of 2500	LM324ADR	
				Tube of 50	LM324KAD	LM324KA
				Reel of 2500	LM324KADR	
			SOP (NS)	Reel of 2000	LM324ANSR	LM324A
				Tube of 50	LM324KANS	LM324KA
				Reel of 2000	LM324KANSR	
			SSOP (DB)	Reel of 2000	LM324ADBR	LM324A
			TSSOP (PW)	Tube of 90	LM324APW	L324A
				Reel of 2000	LM324APWR	
				Tube of 90	LM324KAPW	L324KA
				Reel of 2000	LM324KAPWR	
−25°C to 85°C	5 mV	30 V	PDIP (N)	Tube of 25	LM224N	LM224N
					LM224KN	LM224KN
			SOIC (D)	Tube of 50	LM224D	LM224
				Reel of 2500	LM224DR	
				Tube of 50	LM224KD	LM224K
				Reel of 2500	LM224KDR	
	3 mV	30 V	PDIP (N)	Tube of 25	LM224AN	LM224AN
				Tube of 25	LM224KAN	LM224KAN
			SOIC (D)	Tube of 50	LM224AD	LM224A
				Reel of 2500	LM224ADR	
				Tube of 50	LM224KAD	LM224KA
				Reel of 2500	LM224KADR	

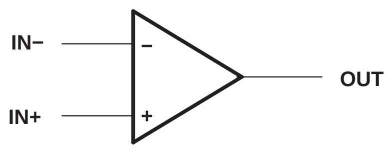
† Package drawings, standard packing quantities, thermal data, symbolization, and PCB design guidelines are available at www.ti.com/sc/package.

ORDERING INFORMATION (CONTINUED)

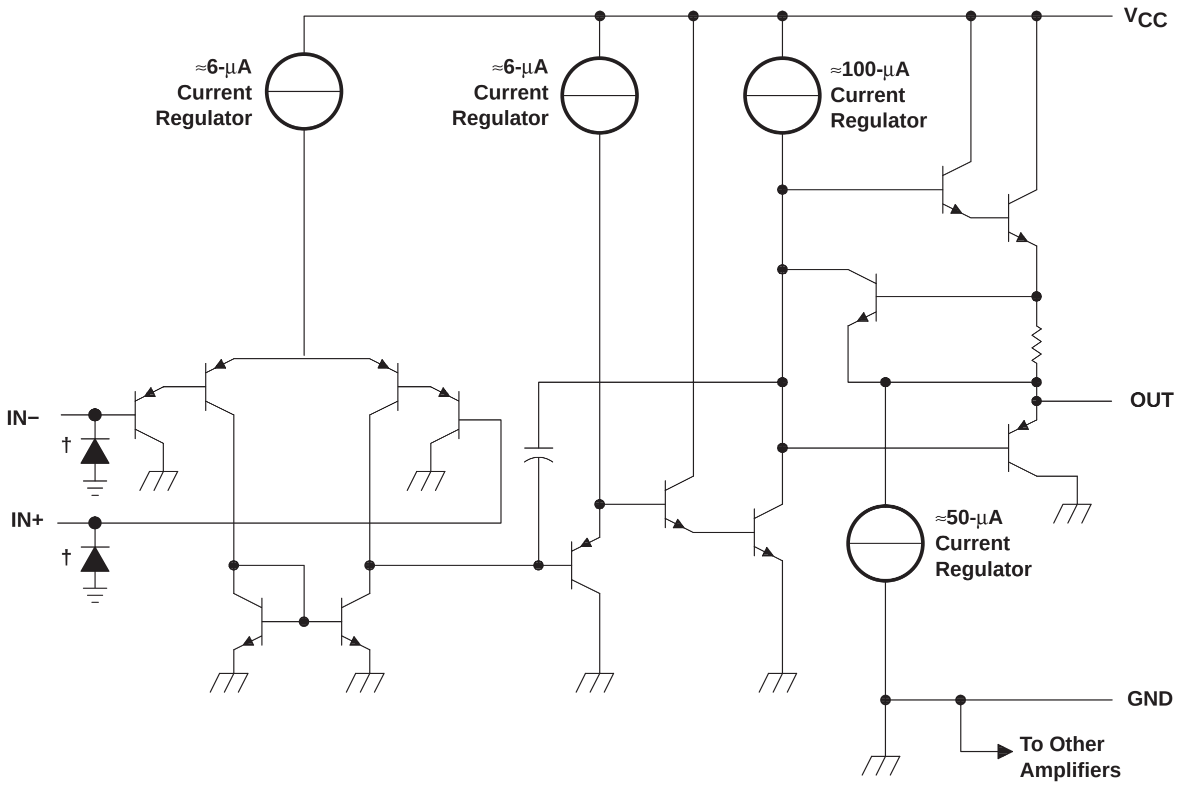
T_A	V_{IO}max AT 25°C	MAX TESTED V_{CC}	PACKAGE†		ORDERABLE PART NUMBER	TOP-SIDE MARKING
−40°C to 125°C	7 mV	26 V	PDIP (N)	Tube of 25	LM2902N	LM2902N
				Tube of 25	LM2902KN	LM2902KN
			SOIC (D)	Tube of 50	LM2902D	LM2902
				Reel of 2500	LM2902DR	
				Tube of 50	LM2902KD	LM2902K
				Reel of 2500	LM2902KDR	
			SOP (NS)	Reel of 2000	LM2902NSR	LM2902
				Tube of 50	LM2902KNS	LM2902K
				Reel of 2000	LM2902KNSR	
			SSOP (DB)	Tube of 80	LM2902KDB	L2902K
				Reel of 2000	LM2902KDBR	
			TSSOP (PW)	Tube of 90	LM2902PW	L2902
				Reel of 2000	LM2902PWR	
				Tube of 90	LM2902KPW	L2902K
				Reel of 2000	LM2902KPWR	
		32 V	SOIC (D)	Reel of 2500	LM2902KVQDR	L2902KV
			TSSOP (PW)	Reel of 2000	LM2902KVQPWR	L2902KV
	2 mV	32 V	SOIC (D)	Reel of 2500	LM2902KAVQDR	L2902KA
			TSSOP (PW)	Reel of 2000	LM2902KAVQPWR	L2902KA
−55°C to 125°C	5 mV	30 V	CDIP (J)	Tube of 25	LM124J	LM124J
			CFP (W)	Tube of 25	LM124W	LM124W
			LCCC (FK)	Tube of 55	LM124FK	LM124FK
			SOIC (D)	Tube of 50	LM124D	LM124
				Reel of 2500	LM124DR	
	2 mV	30 V	CDIP (J)	Tube of 25	LM124AJ	LM124AJ
			LCCC (FK)	Tube of 55	LM124AFK	LM124AFK

† Package drawings, standard packing quantities, thermal data, symbolization, and PCB design guidelines are available at www.ti.com/sc/package.

symbol (each amplifier)



schematic (each amplifier)



COMPONENT COUNT (total device)	
Epi-FET	1
Transistors	95
Diodes	4
Resistors	11
Capacitors	4

† ESD protection cells - available on LM324K and LM324KA only

absolute maximum ratings over operating free-air temperature range (unless otherwise noted)†

		LM2902	ALL OTHER DEVICES	UNIT
Supply voltage, V_{CC} (see Note 1)		±13 or 26	±16 or 32	V
Differential input voltage, V_{ID} (see Note 2)		±26	±32	V
Input voltage, V_I (either input)		−0.3 to 26	−0.3 to 32	V
Duration of output short circuit (one amplifier) to ground at (or below) T_A = 25°C, V_{CC} ≤ 15 V (see Note 3)		Unlimited	Unlimited	
Package thermal impedance, θ_{JA} (see Notes 4 and 5)	D package	86	86	°C/W
	DB package	96	96	
	N package	80	80	
	NS package	76	76	
	PW package	113	113	
Package thermal impedance, θ_{JC} (see Notes 6 and 7)	FK package		5.61	°C/W
	J package		15.05	
	W package		14.65	
Operating virtual junction temperature, T_J		150	150	°C
Case temperature for 60 seconds	FK package		260	°C
Lead temperature 1,6 mm (1/16 inch) from case for 60 seconds	J or W package	300	300	°C
Storage temperature range, T_{stg}		−65 to 150	−65 to 150	°C

† Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTES:
1. All voltage values (except differential voltages and V_{CC} specified for the measurement of I_{OS}) are with respect to the network GND.
2. Differential voltages are at IN+, with respect to IN−.
3. Short circuits from outputs to V_{CC} can cause excessive heating and eventual destruction.
4. Maximum power dissipation is a function of T_J(max), θ_{JA}, and T_A. The maximum allowable power dissipation at any allowable ambient temperature is $P_D = (T_J(max) - T_A)/\theta_{JA}$. Operating at the absolute maximum T_J of 150°C can affect reliability.
5. The package thermal impedance is calculated in accordance with JESD 51-7.
6. Maximum power dissipation is a function of T_J(max), θ_{JC}, and T_C. The maximum allowable power dissipation at any allowable case temperature is $P_D = (T_J(max) - T_C)/\theta_{JC}$. Operating at the absolute maximum T_J of 150°C can affect reliability.
7. The package thermal impedance is calculated in accordance with MIL-STD-883.

ESD protection

TEST CONDITIONS		TYP	UNIT
Human-Body Model	LM224K, LM224KA, LM324K, LM324KA, LM2902K, LM2902KV, LM2902KAV	±2	kV

electrical characteristics at specified free-air temperature, V_{CC} = 5 V (unless otherwise noted)

PARAMETER		TEST CONDITIONS†		T_A‡	LM124 LM224 MIN	TYP§	MAX	LM324 LM324K MIN	TYP§	MAX	UNIT
V_{IO}	Input offset voltage	V_{CC} = 5 V to MAX, V_{IC} = V_{ICR}min, V_O = 1.4 V		25°C		3	5		3	7	mV
				Full range			7			9	
I_{IO}	Input offset current	V_O = 1.4 V		25°C		2	30		2	50	nA
				Full range			100			150	
I_{IB}	Input bias current	V_O = 1.4 V		25°C		−20	−150		−20	−250	nA
				Full range			−300			−500	
V_{ICR}	Common-mode input voltage range	V_{CC} = 5 V to MAX		25°C	0 to V_{CC} − 1.5			0 to V_{CC} − 1.5			V
				Full range	0 to V_{CC} − 2			0 to V_{CC} − 2			
V_{OH}	High-level output voltage	R_L = 2 kΩ		25°C	V_{CC} − 1.5			V_{CC} − 1.5			V
		R_L = 10 kΩ		25°C							
		V_{CC} = MAX	R_L = 2 kΩ	Full range	26			26			
			R_L ≥ 10 kΩ	Full range	27	28		27	28		
V_{OL}	Low-level output voltage	R_L ≤ 10 kΩ		Full range		5	20		5	20	mV
A_{VD}	Large-signal differential voltage amplification	V_{CC} = 15 V, V_O = 1 V to 11 V, R_L ≥ 2 kΩ		25°C	50	100		25	100		V/mV
				Full range	25			15			
CMRR	Common-mode rejection ratio	V_{IC} = V_{ICR}min		25°C	70	80		65	80		dB
k_{SVR}	Supply-voltage rejection ratio ($\Delta V_{CC}/\Delta V_{IO}$)			25°C	65	100		65	100		dB
V_{O1}/V_{O2}	Crosstalk attenuation	f = 1 kHz to 20 kHz		25°C		120			120		dB
I_O	Output current	V_{CC} = 15 V, V_{ID} = 1 V, V_O = 0	Source	25°C	−20	−30	−60	−20	−30	−60	mA
				Full range	−10			−10			
		V_{CC} = 15 V, V_{ID} = −1 V, V_O = 15 V	Sink	25°C	10	20		10	20		
				Full range	5			5			
		V_{ID} = −1 V,	V_O = 200 mV	25°C	12	30		12	30		μA
I_{OS}	Short-circuit output current	V_{CC} at 5 V, GND at −5 V	V_O = 0,	25°C		±40	±60		±40	±60	mA
I_{CC}	Supply current (four amplifiers)	V_O = 2.5 V,	No load	Full range		0.7	1.2		0.7	1.2	mA
		V_{CC} = MAX, V_O = 0.5 V_{CC},	No load	Full range		1.4	3		1.4	3	

† All characteristics are measured under open-loop conditions, with zero common-mode input voltage, unless otherwise specified. MAX V_{CC} for testing purposes is 26 V for LM2902 and 30 V for the others.
‡ Full range is −55°C to 125°C for LM124, −25°C to 85°C for LM224, and 0°C to 70°C for LM324.
§ All typical values are at T_A = 25°C.

electrical characteristics at specified free-air temperature, V_{CC} = 5 V (unless otherwise noted)

PARAMETER		TEST CONDITIONS†		T_A‡	LM2902			LM2902V			UNIT
					MIN	TYP§	MAX	MIN	TYP§	MAX	
V_{IO}	Input offset voltage	V_{CC} = 5 V to MAX, $V_{IC} = V_{ICR}$min, V_O = 1.4 V	Non-A-suffix devices	25°C		3	7		3	7	mV
				Full range			10			10	
			A-suffix devices	25°C					1	2	
				Full range						4	
$\Delta V_{IO}/\Delta T$	Input offset voltage temperature drift	R_S = 0 Ω		Full range					7		µV/°C
I_{IO}	Input offset current	V_O = 1.4 V		25°C		2	50		2	50	nA
				Full range			300			150	
$\Delta I_{IO}/\Delta T$	Input offset current temperature drift			Full range					10		pA/°C
I_{IB}	Input bias current	V_O = 1.4 V		25°C		−20	−250		−20	−250	nA
				Full range			−500			−500	
V_{ICR}	Common-mode input voltage range	V_{CC} = 5 V to MAX		25°C	0 to V_{CC} − 1.5			0 to V_{CC} − 1.5			V
				Full range	0 to V_{CC} − 2			0 to V_{CC} − 2			
V_{OH}	High-level output voltage	R_L = 2 kΩ		25°C							V
		R_L = 10 kΩ		25°C	V_{CC} − 1.5			V_{CC} − 1.5			
		V_{CC} = MAX	R_L = 2 kΩ	Full range	22			26			
			R_L ≥ 10 kΩ	Full range	23	24		27			
V_{OL}	Low-level output voltage	R_L ≤ 10 kΩ		Full range		5	20		5	20	mV
A_{VD}	Large-signal differential voltage amplification	V_{CC} = 15 V, V_O = 1 V to 11 V, R_L ≥ 2 kΩ		25°C	25	100		25	100		V/mV
				Full range	15			15			
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}$min		25°C	50	80		60	80		dB
k_{SVR}	Supply-voltage rejection ratio ($\Delta V_{CC}/\Delta V_{IO}$)			25°C	50	100		60	100		dB
V_{O1}/V_{O2}	Crosstalk attenuation	f = 1 kHz to 20 kHz		25°C		120			120		dB
I_O	Output current	V_{CC} = 15 V, V_{ID} = 1 V, V_O = 0	Source	25°C	−20	−30	−60	−20	−30	−60	mA
				Full range	−10			−10			
		V_{CC} = 15 V, V_{ID} = −1 V, V_O = 15 V	Sink	25°C	10	20		10	20		
				Full range	5			5			
		V_{ID} = −1 V,	V_O = 200 mV	25°C		30		12	40		µA
I_{OS}	Short-circuit output current	V_{CC} at 5 V, GND at −5 V	V_O = 0,	25°C		±40	±60		±40	±60	mA
I_{CC}	Supply current (four amplifiers)	V_O = 2.5 V,	No load	Full range		0.7	1.2		0.7	1.2	mA
		V_{CC} = MAX, V_O = 0.5 V_{CC},	No load	Full range		1.4	3		1.4	3	

† All characteristics are measured under open-loop conditions, with zero common-mode input voltage, unless otherwise specified. MAX V_{CC} for testing purposes is 26 V for LM2902 and 32 V for LM2902V.
‡ Full range is −40°C to 125°C for LM2902.
§ All typical values are at T_A = 25°C.

electrical characteristics at specified free-air temperature, V_{CC} = 5 V (unless otherwise noted)

PARAMETER		TEST CONDITIONS†	T_A‡	LM124A MIN	LM124A TYP§	LM124A MAX	LM224A MIN	LM224A TYP§	LM224A MAX	LM324A, LM324KA MIN	LM324A, LM324KA TYP§	LM324A, LM324KA MAX	UNIT
V_{IO}	Input offset voltage	V_{CC} = 5 V to 30 V, $V_{IC} = V_{ICR}$min, V_O = 1.4 V	25°C			2		2	3		2	3	mV
			Full range			4			4			5	
I_{IO}	Input offset current	V_O = 1.4 V	25°C			10		2	15		2	30	nA
			Full range			30			30			75	
I_{IB}	Input bias current	V_O = 1.4 V	25°C			−50		−15	−80		−15	−100	nA
			Full range			−100			−100			−200	
V_{ICR}	Common-mode input voltage range	V_{CC} = 30 V	25°C	0 to V_{CC} − 1.5			0 to V_{CC} − 1.5			0 to V_{CC} − 1.5			V
			Full range	0 to V_{CC} − 2			0 to V_{CC} − 2			0 to V_{CC} − 2			
V_{OH}	High-level output voltage	R_L = 2 kΩ	25°C	V_{CC} − 1.5			V_{CC} − 1.5			V_{CC} − 1.5			V
		V_{CC} = 30 V, R_L = 2 kΩ	Full range	26			26			26			
		V_{CC} = 30 V, R_L ≥ 10 kΩ	Full range	27			27	28		27	28		
V_{OL}	Low-level output voltage	R_L ≤ 10 kΩ	Full range			20		5	20		5	20	mV
A_{VD}	Large-signal differential voltage amplification	V_{CC} = 15 V, V_O = 1 V to 11 V, R_L ≥ 2 kΩ	25°C	50	100		50	100		25	100		V/mV
			Full range	25			25			15			
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}$min	25°C	70			70	80		65	80		dB
k_{SVR}	Supply-voltage rejection ratio ($\Delta V_{CC}/\Delta V_{IO}$)		25°C	65			65	100		65	100		dB
V_{O1}/V_{O2}	Crosstalk attenuation	f = 1 kHz to 20 kHz	25°C		120			120			120		dB
I_O	Output current	V_{CC} = 15 V, V_{ID} = 1 V, V_O = 0, Source	25°C	−20			−20	−30	−60	−20	−30	−60	mA
			Full range	−10			−10			−10			
		V_{CC} = 15 V, V_{ID} = −1 V, V_O = 15 V, Sink	25°C	10			10	20		10	20		
			Full range	5			5			5			
		V_{ID} = −1 V, V_O = 200 mV	25°C	12			12	30		12	30		μA
I_{OS}	Short-circuit output current	V_{CC} at 5 V, GND at −5 V, V_O = 0	25°C		±40	±60		±40	±60		±40	±60	mA
I_{CC}	Supply current (four amplifiers)	V_O = 2.5 V, No load	Full range		0.7	1.2		0.7	1.2		0.7	1.2	mA
		V_{CC} = 30 V, V_O = 15 V, No load	Full range		1.4	3		1.4	3		1.4	3	

† All characteristics are measured under open-loop conditions, with zero common-mode input voltage, unless otherwise specified.
‡ Full range is −55°C to 125°C for LM124A, −25°C to 85°C for LM224A, and 0°C to 70°C for LM324A.
§ All typical values are at T_A = 25°C.

operating conditions, V_{CC} = ±15 V, T_A = 25°C

PARAMETER		TEST CONDITIONS	TYP	UNIT
SR	Slew rate at unity gain	R_L = 1 MΩ, C_L = 30 pF, V_I = ±10 V (see Figure 1)	0.5	V/µs
B_1	Unity-gain bandwidth	R_L = 1 MΩ, C_L = 20 pF (see Figure 1)	1.2	MHz
V_n	Equivalent input noise voltage	R_S = 100 Ω, V_I = 0 V, f = 1 kHz (see Figure 2)	35	nV/√Hz

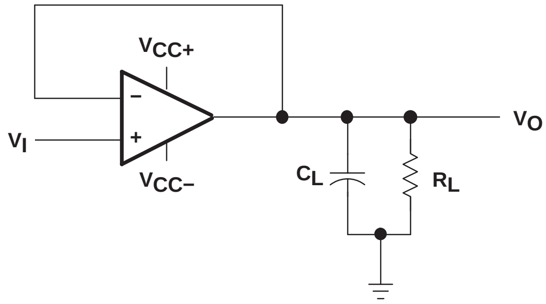


Figure 1. Unity-Gain Amplifier

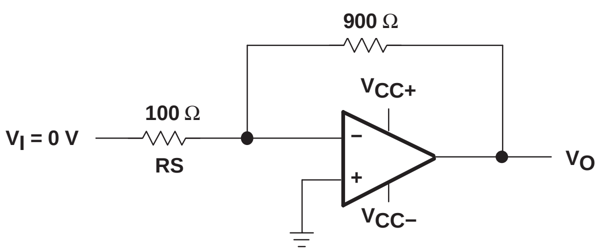
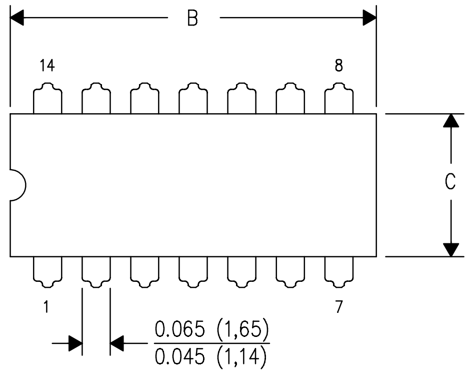


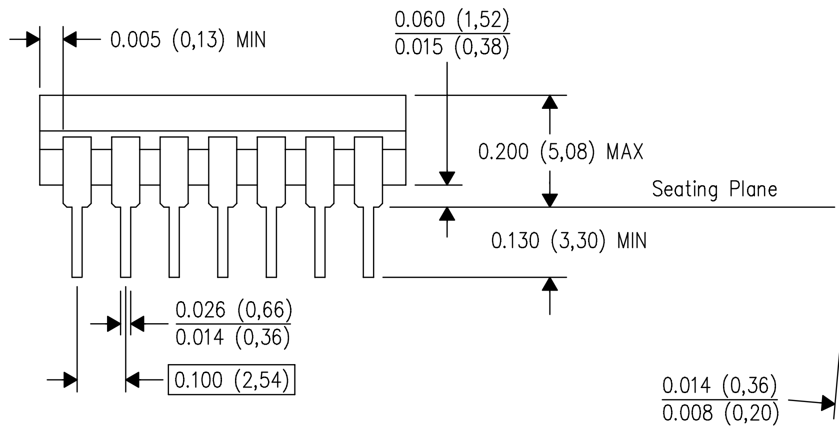
Figure 2. Noise-Test Circuit

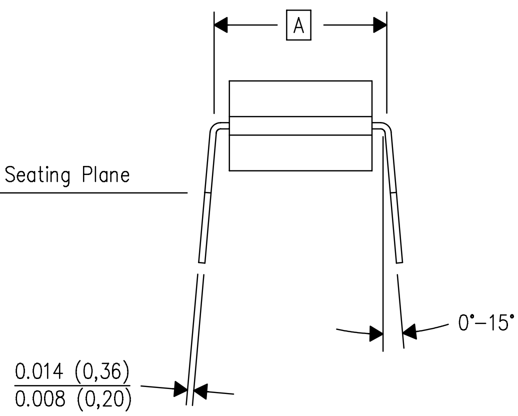
J (R–GDIP–T**)   CERAMIC DUAL IN–LINE PACKAGE

14 LEADS SHOWN



DIM \ PINS **	14	16	18	20
A	0.300 (7,62) BSC	0.300 (7,62) BSC	0.300 (7,62) BSC	0.300 (7,62) BSC
B MAX	0.785 (19,94)	.840 (21,34)	0.960 (24,38)	1.060 (26,92)
B MIN	——	——	——	——
C MAX	0.300 (7,62)	0.300 (7,62)	0.310 (7,87)	0.300 (7,62)
C MIN	0.245 (6,22)	0.245 (6,22)	0.220 (5,59)	0.245 (6,22)

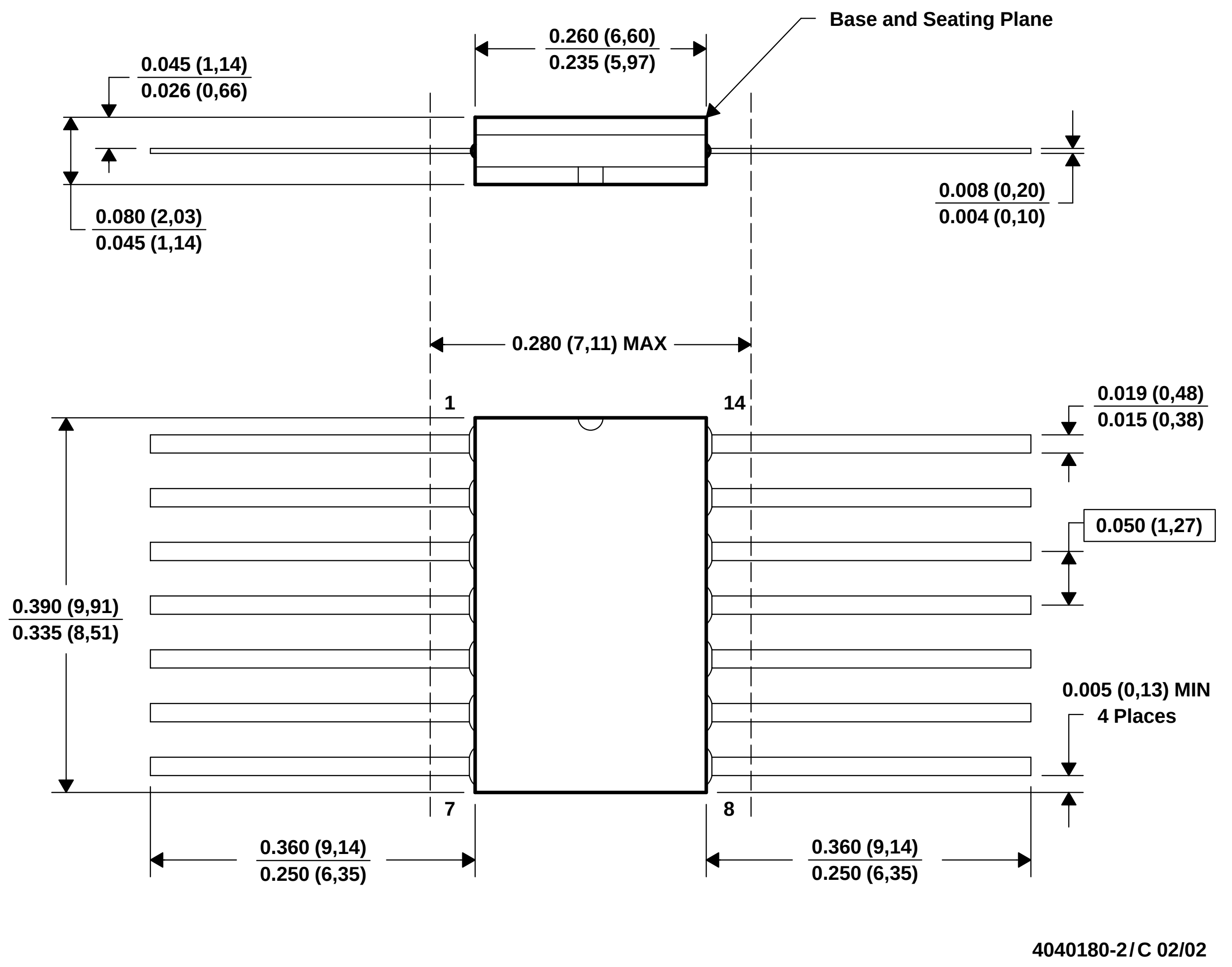




4040083/F 03/03

NOTES:
- A. All linear dimensions are in inches (millimeters).
- B. This drawing is subject to change without notice.
- C. This package is hermetically sealed with a ceramic lid using glass frit.
- D. Index point is provided on cap for terminal identification only on press ceramic glass frit seal only.
- E. Falls within MIL STD 1835 GDIP1–T14, GDIP1–T16, GDIP1–T18 and GDIP1–T20.

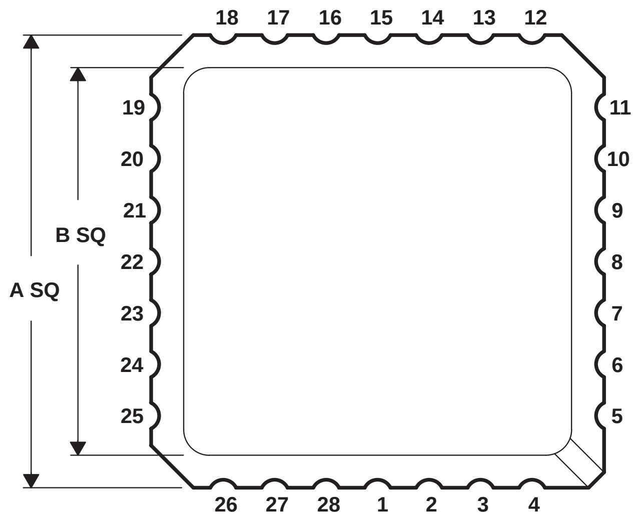
W (R-GDFP-F14) **CERAMIC DUAL FLATPACK**



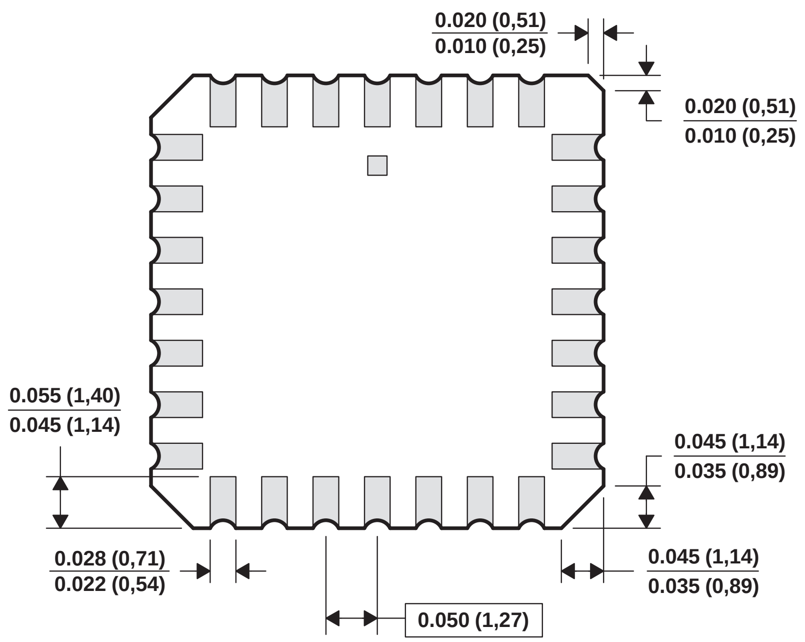
NOTES: A. All linear dimensions are in inches (millimeters).
B. This drawing is subject to change without notice.
C. This package can be hermetically sealed with a ceramic lid using glass frit.
D. Index point is provided on cap for terminal identification only.
E. Falls within MIL STD 1835 GDFP1-F14 and JEDEC MO-092AB

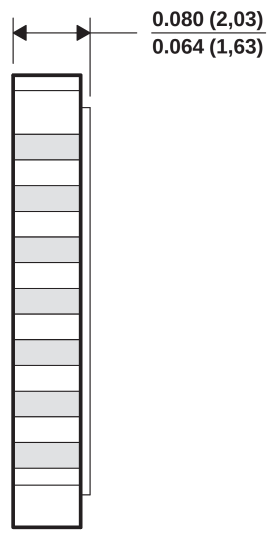
FK (S-CQCC-N)** **LEADLESS CERAMIC CHIP CARRIER**

28 TERMINAL SHOWN



NO. OF TERMINALS **	A		B	
	MIN	MAX	MIN	MAX
20	0.342 (8,69)	0.358 (9,09)	0.307 (7,80)	0.358 (9,09)
28	0.442 (11,23)	0.458 (11,63)	0.406 (10,31)	0.458 (11,63)
44	0.640 (16,26)	0.660 (16,76)	0.495 (12,58)	0.560 (14,22)
52	0.739 (18,78)	0.761 (19,32)	0.495 (12,58)	0.560 (14,22)
68	0.938 (23,83)	0.962 (24,43)	0.850 (21,6)	0.858 (21,8)
84	1.141 (28,99)	1.165 (29,59)	1.047 (26,6)	1.063 (27,0)



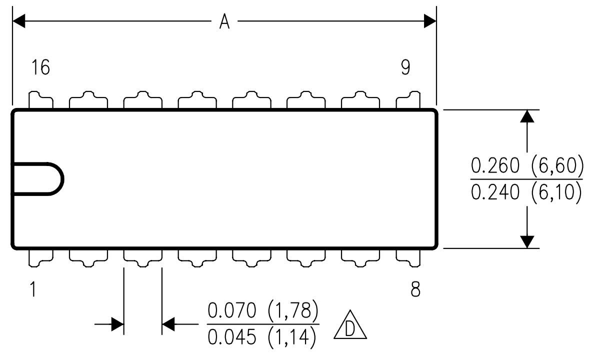


4040140 / D 10/96

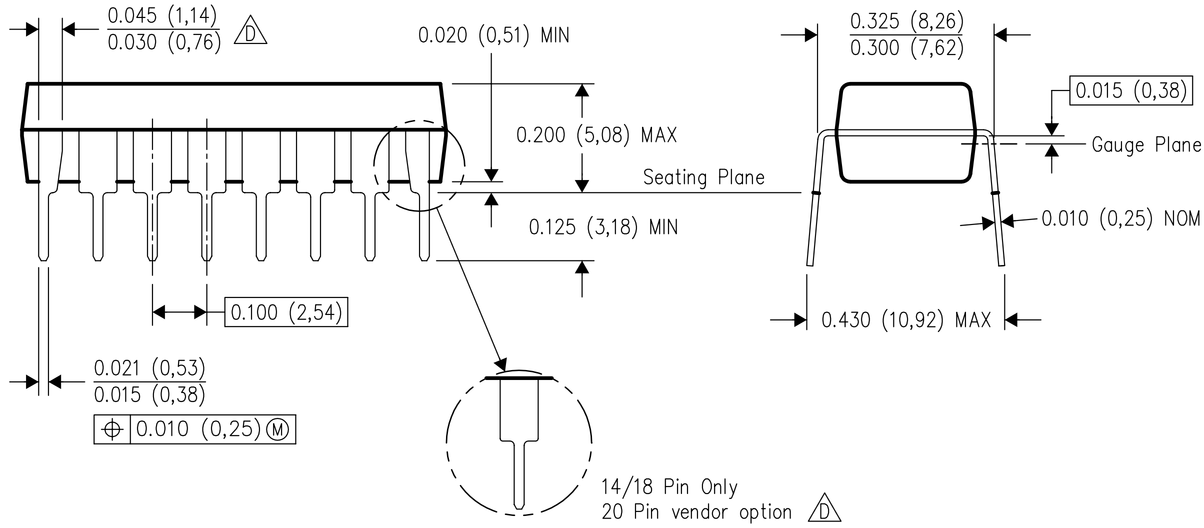
NOTES: A. All linear dimensions are in inches (millimeters).
B. This drawing is subject to change without notice.
C. This package can be hermetically sealed with a metal lid.
D. The terminals are gold plated.
E. Falls within JEDEC MS-004

N (R–PDIP–T**) PLASTIC DUAL–IN–LINE PACKAGE

16 PINS SHOWN



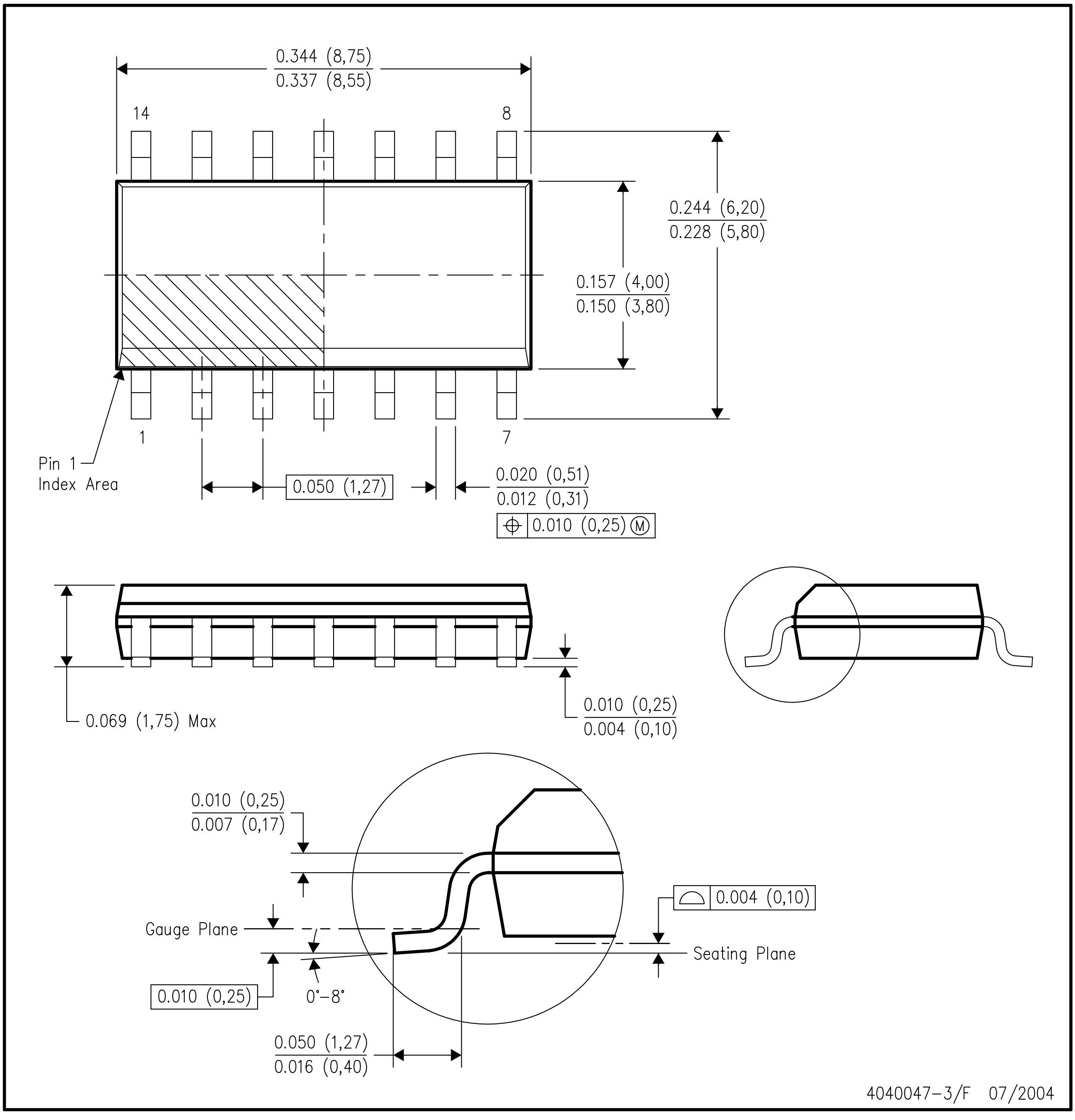
DIM \ PINS **	14	16	18	20
A MAX	0.775 (19,69)	0.775 (19,69)	0.920 (23,37)	1.060 (26,92)
A MIN	0.745 (18,92)	0.745 (18,92)	0.850 (21,59)	0.940 (23,88)
(C) MS–001 VARIATION	AA	BB	AC	AD



4040049/E 12/2002

NOTES:
- A. All linear dimensions are in inches (millimeters).
- B. This drawing is subject to change without notice.
- (C) Falls within JEDEC MS–001, except 18 and 20 pin minimum body length (Dim A).
- (D) The 20 pin end lead shoulder width is a vendor option, either half or full width.

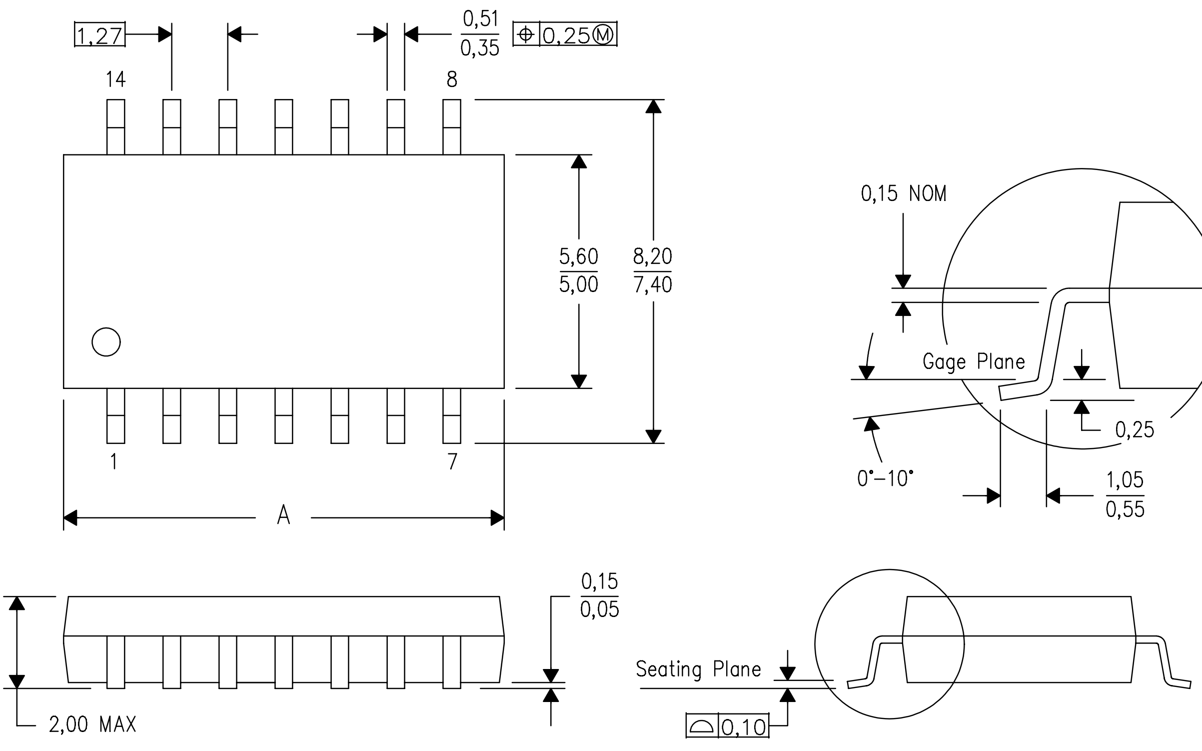
D (R–PDSO–G14) PLASTIC SMALL–OUTLINE PACKAGE



NOTES:
A. All linear dimensions are in inches (millimeters).
B. This drawing is subject to change without notice.
C. Body dimensions do not include mold flash or protrusion not to exceed 0.006 (0,15).
D. Falls within JEDEC MS–012 variation AB.

NS (R-PDSO-G)** **PLASTIC SMALL-OUTLINE PACKAGE**

14-PINS SHOWN



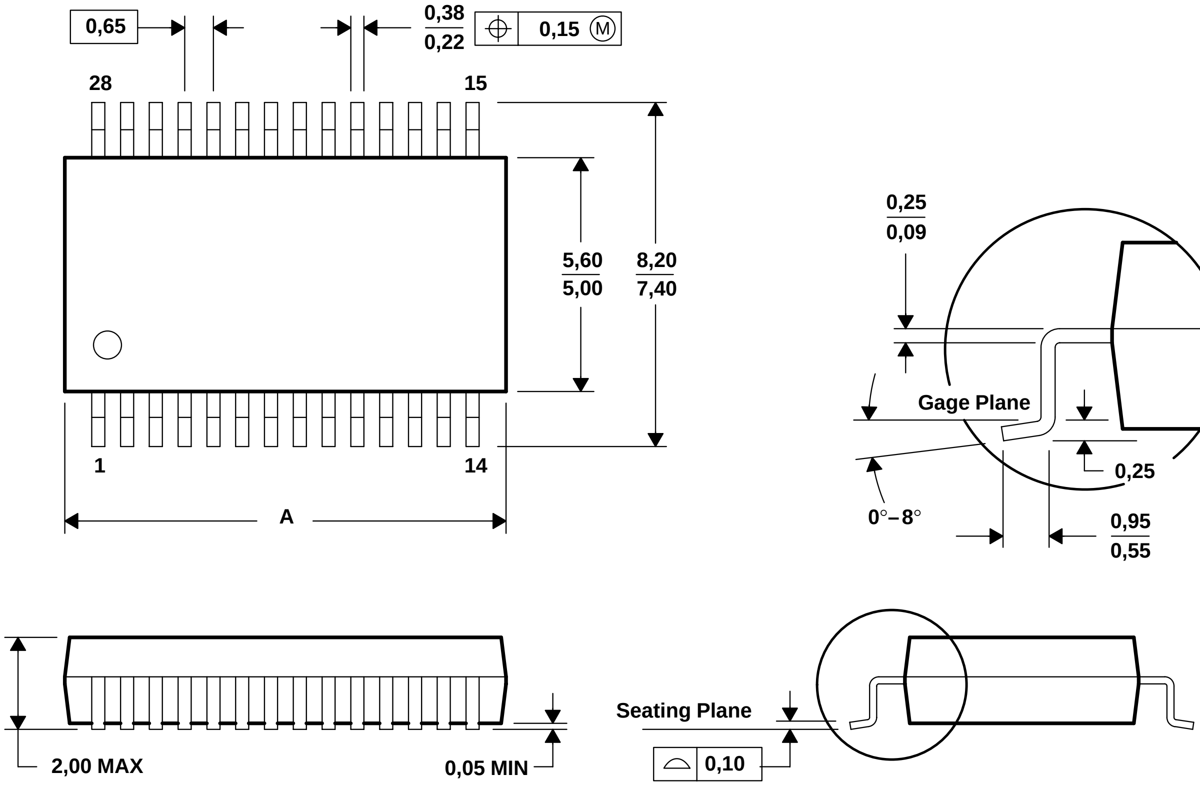
PINS ** / DIM	14	16	20	24
A MAX	10,50	10,50	12,90	15,30
A MIN	9,90	9,90	12,30	14,70

4040062/C 03/03

NOTES:
A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Body dimensions do not include mold flash or protrusion, not to exceed 0,15.

DB (R-PDSO-G)** **PLASTIC SMALL-OUTLINE**

28 PINS SHOWN



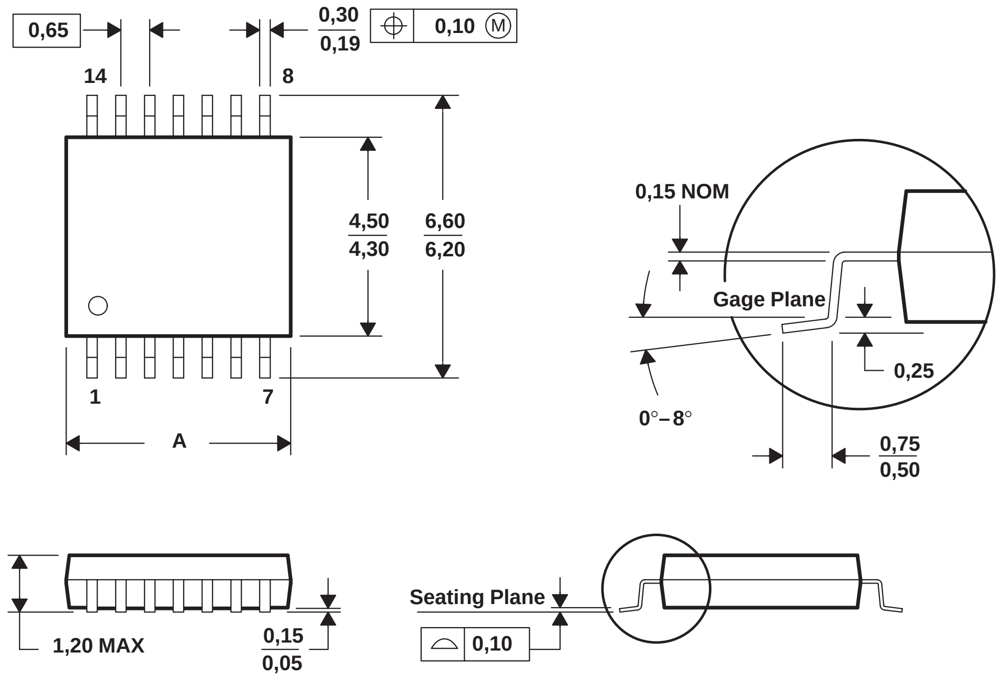
DIM \ PINS **	14	16	20	24	28	30	38
A MAX	6,50	6,50	7,50	8,50	10,50	10,50	12,90
A MIN	5,90	5,90	6,90	7,90	9,90	9,90	12,30

4040065 /E 12/01

NOTES:
A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Body dimensions do not include mold flash or protrusion not to exceed 0,15.
D. Falls within JEDEC MO-150

PW (R-PDSO-G)** **PLASTIC SMALL-OUTLINE PACKAGE**

14 PINS SHOWN



DIM \ PINS **	8	14	16	20	24	28
A MAX	3,10	5,10	5,10	6,60	7,90	9,80
A MIN	2,90	4,90	4,90	6,40	7,70	9,60

4040064/F 01/97

NOTES: A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Body dimensions do not include mold flash or protrusion not to exceed 0,15.
D. Falls within JEDEC MO-153

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DSP	dsp.ti.com	Broadband	www.ti.com/broadband
Interface	interface.ti.com	Digital Control	www.ti.com/digitalcontrol
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
		Telephony	www.ti.com/telephony
		Video & Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

Mailing Address: Texas Instruments
Post Office Box 655303 Dallas, Texas 75265

A.5 Voltage Variable Attenuator ZX73-2500+

Coaxial

Voltage Variable Attenuator

ZX73-2500+

50Ω 10 to 2500 MHz

FEMALE SMA shown

CASE STYLE: GD958

SMA INPUT	Connectors OUTPUT	Model	Price	Qty.	Case
FEMALE	**FEMALE**	ZX73-2500-S+	$49.95	(1-9)	GD958
MALE	**FEMALE**	ZX73-2500M-S+	$49.95	(1-9)	GD1163

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-55°C to 85°C
Storage Temperature	-55°C to 85°C
Absolute Max. Supply Voltage (V+)	12V
Absolute Max. Control Voltage (Vcrtl)	20V
Absolute Max. RF Input Level	+20 dBm

Permanent damage may occur if any of these limits are exceeded.

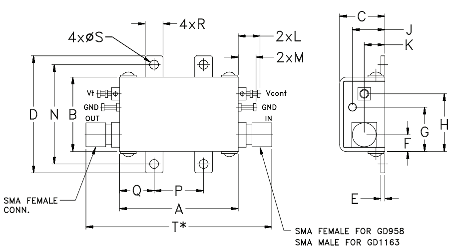
Features

- Broadband, 10-2500 MHz
- IP3, +43 dBm typ.
- 40 dB attenuation @ 1500 MHz
- Good VSWR at in /out ports over attenuation range
- No external bias and RF matching network required
- Shielded case
- Protected by US Patent 6,790,049

Applications

- Variable gain amplifier
- Power level control
- Feed-forward amplifiers
- ALC circuits

Outline Drawing (GD958)



Electrical Specifications (T_{AMB}= 25°C)

FREQ. (MHz)		MIN. INSERTION LOSS, dB (+15V)		MAX. ATTENUATION dB (0V)		INPUT POWER (dBm)	CONTROL Voltage (V)	CONTROL Current (mA)	IP3 (dBm)	RETURN LOSS[1] (dB)	POWER SUPPLY Voltage (V)	POWER SUPPLY Current (mA)
Min.	Max.	Typ.	Max.	Typ.	Min.	Max.		Max.	Typ.	Typ.		Max.
10	500	3.0	4.6	55	41	+20	0 - 17	30	43	20	+3 to +5	5
500	1500	3.3	5.0	40	30	+20	0 - 17	30	43	20	+3 to +5	5
1500	2500	4.0	6.2	37	25	+20	0 - 17	30	44	20	+3 to +5	5

Notes:
Rise/Fall time: 14μSec/25μSec Typ.
Switching Time, turn on/off: 14μSec/25μSec Typ.
[1] Improved R. Loss in/out performance can be achieved at certain frequencies by choosing a V+ between +3V to +5V

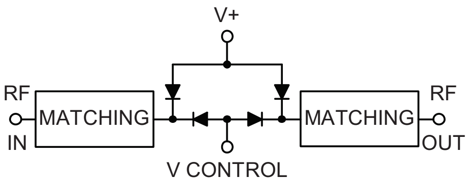
Outline Dimensions (inch/mm)

A	B	C	D	E	F	G	H	J
1.20	**.75**	**.46**	**1.18**	**.04**	**.17**	**.45**	**.59**	**.33**
30.48	19.05	11.68	29.97	1.02	4.32	11.43	14.99	8.38

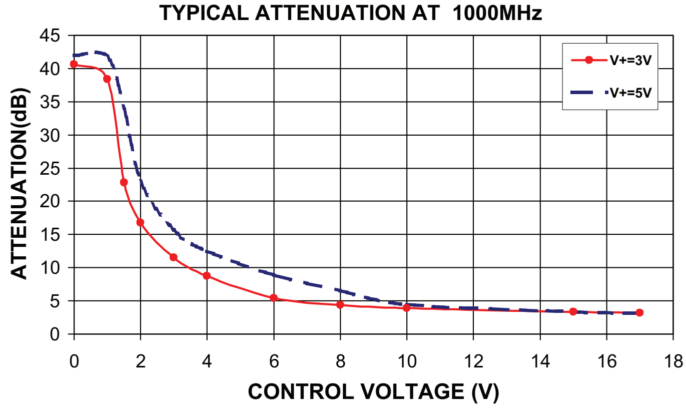
K	L	M	N	P	Q	R	S	T	wt.
.21	**.22**	**.18**	**1.00**	**.50**	**.35**	**.18**	**.106**	**1.88**	**grams**
5.33	5.59	4.57	25.40	12.70	8.89	4.57	2.69	47.75	35.0

Note:
* T dimension is 2.05 inch (52.07 mm) for GD1163 Case Style.

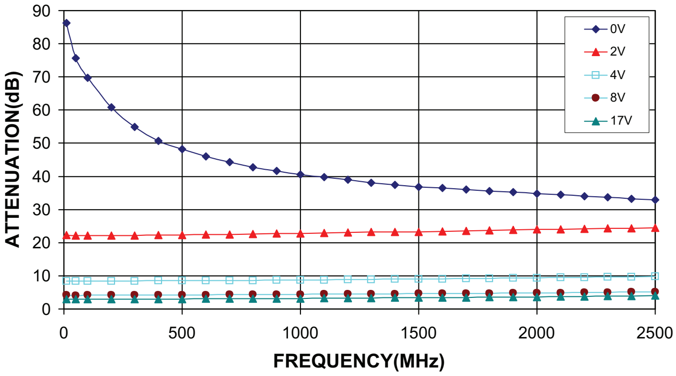
Equivalent Schematic



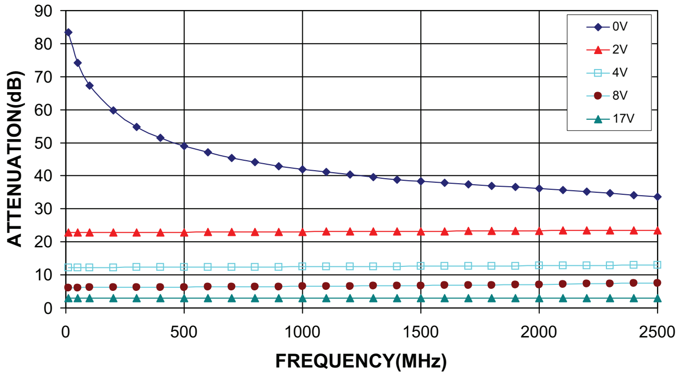
ZX73-2500+
TYPICAL ATTENUATION AT 1000MHz



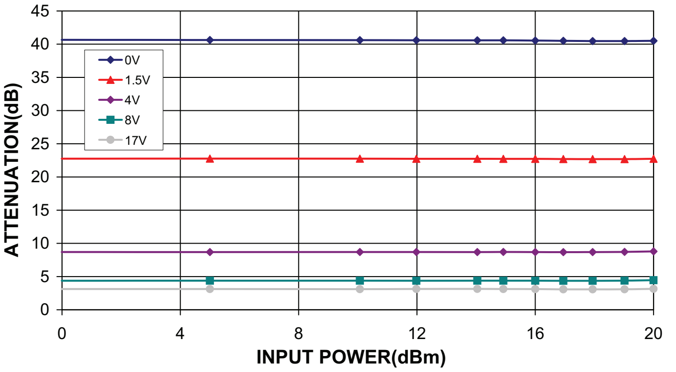
ZX73-2500+
ATTENUATION Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=3V



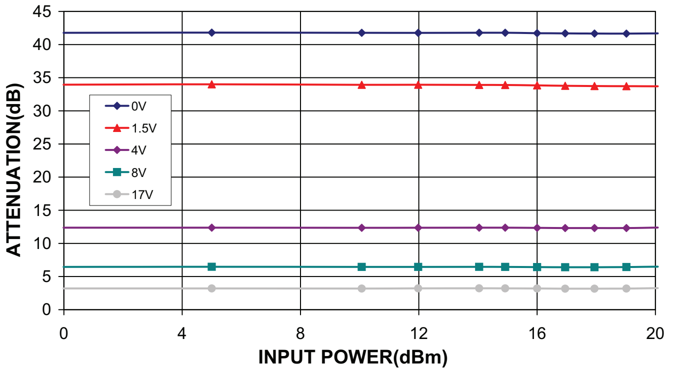
ZX73-2500+
ATTENUATION Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=5V



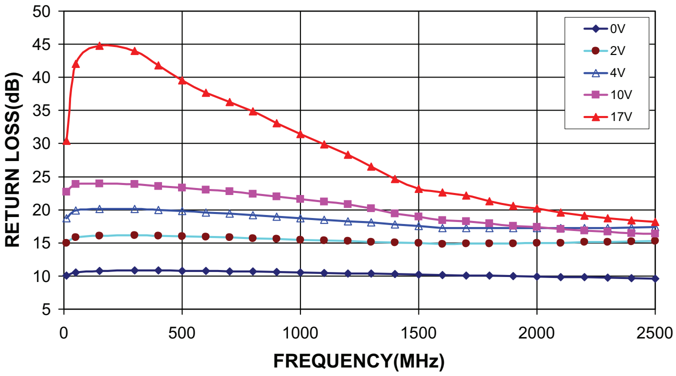
ZX73-2500+
ATTENUATION Vs. INPUT POWER
OVER CONTROL VOLTAGES AT 1000MHz @ V+=3V



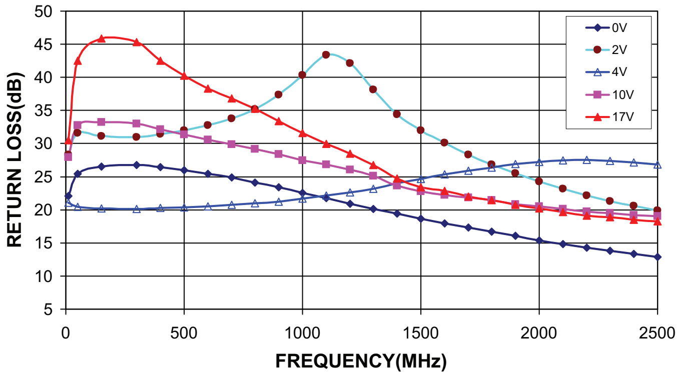
ZX73-2500+
ATTENUATION Vs. INPUT POWER
OVER CONTROL VOLTAGES AT 1000MHz @ V+=5V



ZX73-2500+
INPUT RETURN LOSS Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=3V



ZX73-2500+
INPUT RETURN LOSS Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=5V



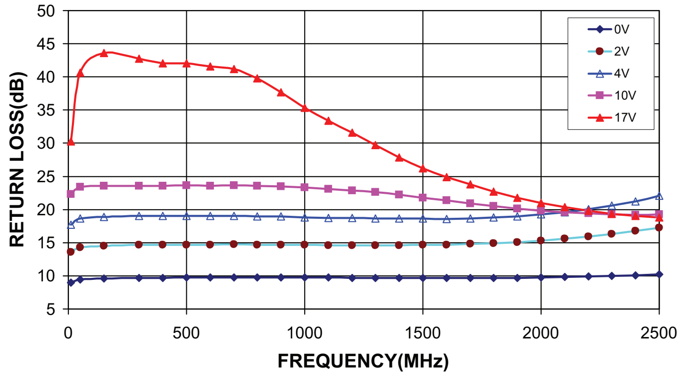
Mini-Circuits®
ISO 9001 ISO 14001 AS 9100 CERTIFIED

P.O. Box 350166, Brooklyn, New York 11235-0003 (718) 934-4500 Fax (718) 332-4661 *The Design Engineers Search Engine* Yoni2® *Provides ACTUAL Data Instantly at* **minicircuits.com**

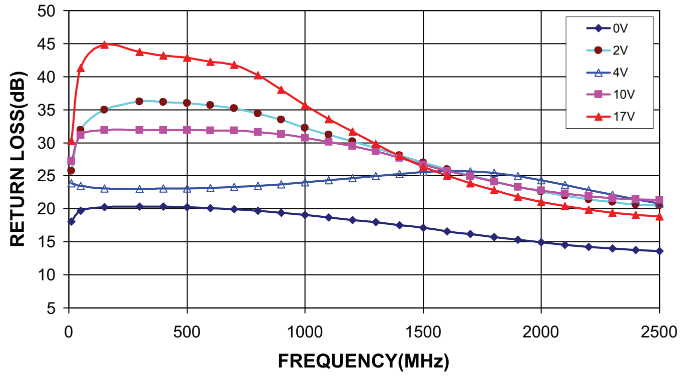
For detailed performance specs & shopping online see web site

IF/RF MICROWAVE COMPONENTS

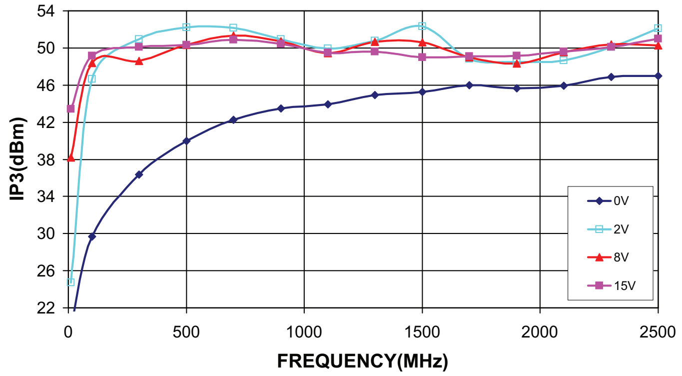
ZX73-2500+
OUTPUT RETURN LOSS Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=3V



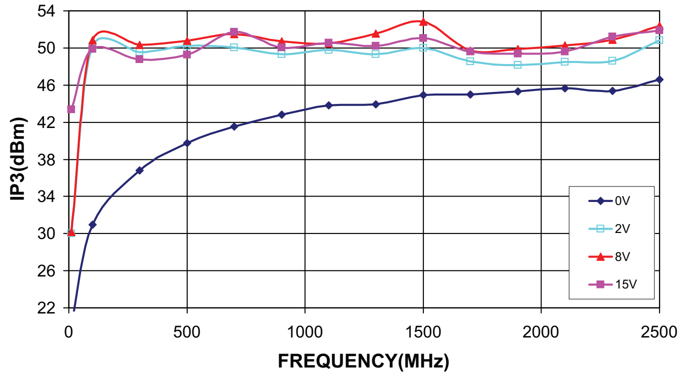
ZX73-2500+
OUTPUT RETURN LOSS Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=5V



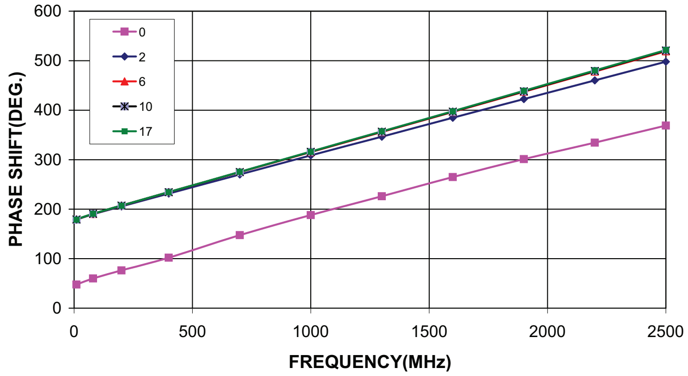
ZX73-2500+
IP3 Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=3V



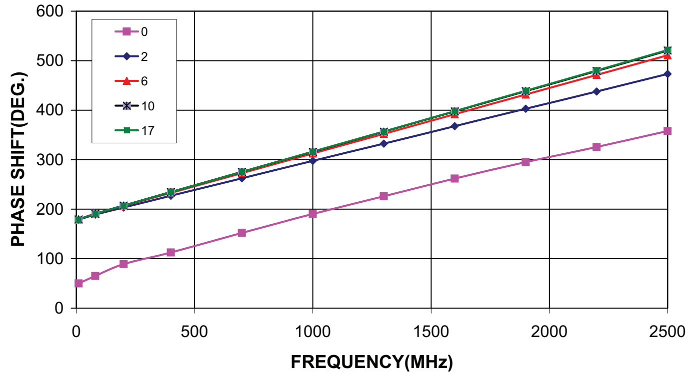
ZX73-2500+
IP3 Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=5V



ZX73-2500+
PHASE SHIFT Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=3V



ZX73-2500+
PHASE SHIFT Vs. FREQUENCY
OVER CONTROL VOLTAGES @ V+=5V



A.6 High Power Amplifier ZHL-100W-13+

Coaxial

High Power Amplifier

ZHL-100W-13+

50Ω 100W 800 to 1000 MHz

Features

- saturated power 100W typ.
- wide bandwidth, usable 750 to 1050 MHz
- high gain, 50 dB typ.
- good gain flatness, ±1dB typ.
- unconditionally stable
- self protected against excessive drive, high case temp., reverse polarity and shorting/unshorting
- can withstand short and open circuit at output while delivering 100 watts

Model No.	ZHL-100W-13+	▲ZHL-100W-13X+
Case Style	BT1689	
Connectors	IN-SMA, OUT-N-Type	
Price (Qty.)	$2195.00 ea. (1-9)	$2095.00 ea. (1-9)

+RoHS Compliant

The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Applications

- AM/FM
- multi-carrier amplification
- broadband swept signal
- linear pulse
- feed forward

Product Description

ZHL-100W-13+ is a Class-AB, unconditionally stable amplifier. It features a ruggedized case, the ability to withstand accidental open or short at output and reverse bias protection for added reliability under difficult conditions.

Electrical Specifications at 25°C

Parameter	Condition (MHz)	ZHL-100W-13+ ▲ZHL-100W-13X+			Units
		Min.	Typ.	Max.	
Frequency Range		800	—	1000	MHz
Gain[1]	800 - 1000	45	50	57	dB
Gain Flatness	800 - 1000	—	±1.0	±1.5	dB
Output Power at 1dB compression	800 - 1000	+47.5	+49	—	dBm
Output Power at 3dB compression	800 - 1000	+48.5	+50	—	dBm
Noise Figure	800 - 1000	—	7	10	dB
Output third order intercept point[2]	800 - 1000	+52	+60	—	dBm
Input VSWR	800 - 1000	—	1.3	1.6	:1
Output VSWR	800 - 1000	—	1.4	1.6	:1
DC Supply Voltage		—	28[4]	30	V
Supply Current[3]		—	10	14.5	A

1. Small signal input power -15 dBm typ.
2. Two tones, 40 dBm/tone, 1 MHz spacing.
3. Power supply should be capable of delivering 17A at start up.
4. Recommended Operating Voltage.

▲Heat sink and fan not included. Alternative heat sinking and heat removal must be provided by the user to limit maximum base-plate temperature to 60°C, in order to ensure proper performance. For reference, this requires thermal resistance of user's external heat sink to be 0.035°C/W max.

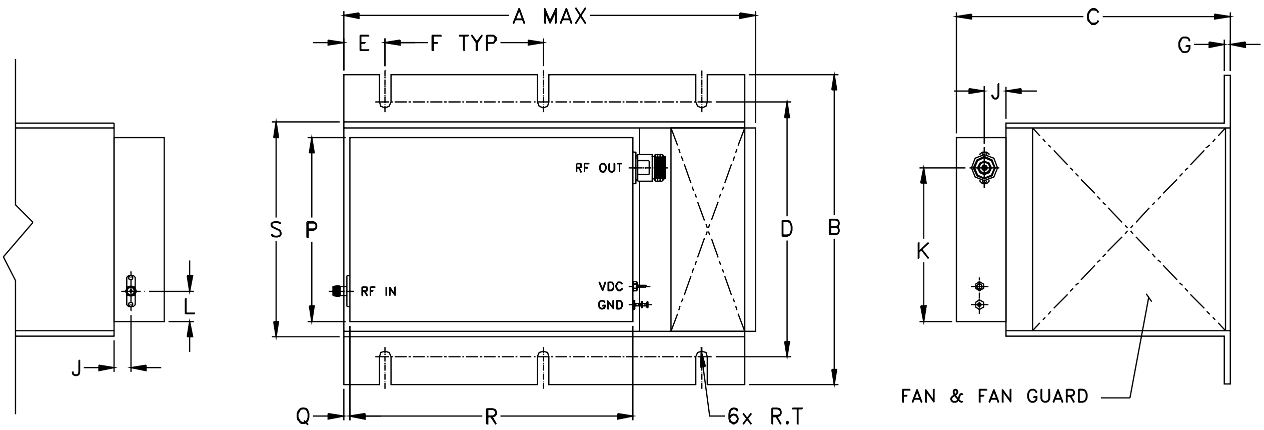
Maximum Ratings

Parameter	Ratings
Operating Temperature	-20°C to 45°C
Base Plate Temperature	60°C
Storage Temperature	-55°C to 100°C
DC Voltage	30V
Input RF Power (no damage)	+7 dBm

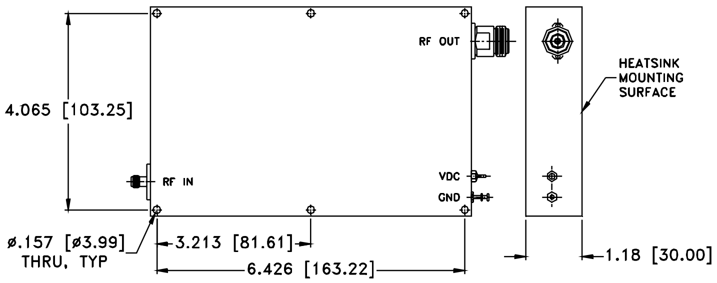
Permanent damage may occur if any of these limits are exceeded.

Notes: 1. Performance and quality attributes and conditions not expressly stated in this specification sheet are intended to be excluded and do not form a part of this specification sheet. 2. Electrical specifications and performance data contained herein are based on Mini-Circuit's applicable established test performance criteria and measurement instructions. 3. The parts covered by this specification sheet are subject to Mini-Circuits standard limited warranty and terms and conditions (collectively, "Standard Terms"); Purchasers of this part are entitled to the rights and benefits contained therein. For a full statement of the Standard Terms and the exclusive rights and remedies thereunder, please visit Mini-Circuits' website at www.minicircuits.com/MCLStore/terms.jsp.

Outline Drawing for models with heatsink



Outline Drawing for models without heatsink

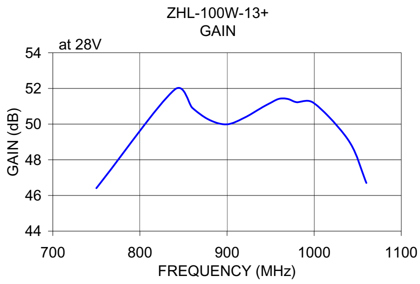


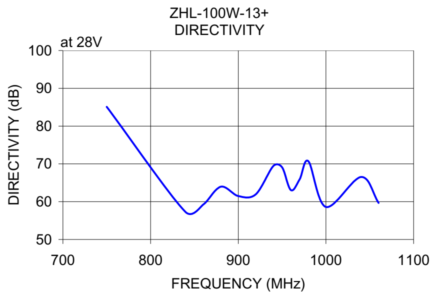
Outline Dimensions (inch / mm)

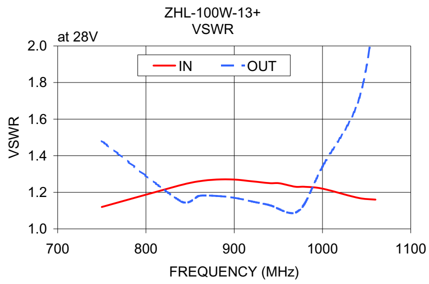
A	B	C	D	E	F	G	J	K	L	P	Q	R	S	T	wt
9.85	7.3	6.5	6.00	.98	3.75	.13	.51	3.62	.72	4.33	.2	6.69	5.1	.136	grams*
250.19	185.42	165.10	152.40	24.89	95.25	3.30	12.95	91.95	18.29	109.98	5.08	169.93	129.54	3.45	5645

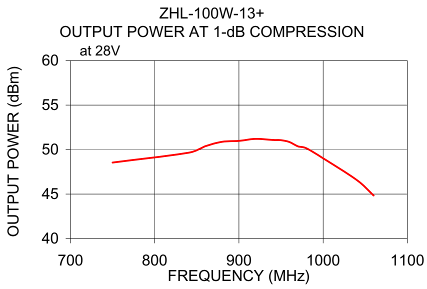
*800 grams without heatsink

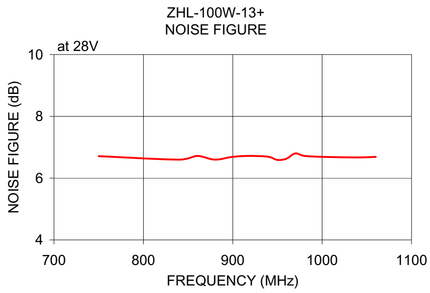
FREQUENCY (MHz)	GAIN (dB)	DIRECTIVITY (dB)	VSWR (:1)		POUT at 1 dB COMPR. (dBm)	NOISE FIGURE (dB)	IP3 (dBm)
	28V	28V	IN	OUT	28V	28V	28V
750	46.41	85.10	1.12	1.48	48.54	6.71	62.89
840	51.94	57.24	1.24	1.15	49.64	6.60	62.97
860	50.92	59.22	1.26	1.18	50.37	6.72	62.58
880	50.23	63.96	1.27	1.18	50.87	6.60	62.57
900	49.99	61.48	1.27	1.17	50.97	6.69	62.63
920	50.36	61.95	1.26	1.15	51.20	6.72	63.20
940	50.93	69.45	1.25	1.13	51.08	6.69	63.95
950	51.19	69.08	1.25	1.11	51.05	6.59	64.32
960	51.42	63.07	1.24	1.09	50.84	6.63	64.76
970	51.41	65.92	1.23	1.09	50.36	6.80	65.13
980	51.23	70.67	1.23	1.14	50.15	6.72	65.25
1000	51.17	58.60	1.22	1.34	49.02	6.69	64.51
1040	49.05	66.54	1.17	1.69	46.57	6.67	63.12
1060	46.70	59.66	1.16	2.18	44.83	6.69	63.38

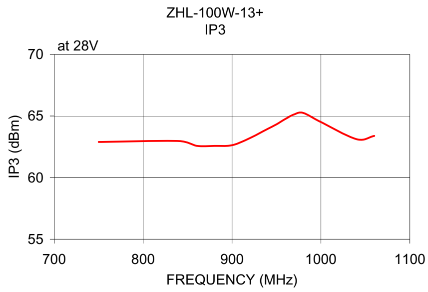








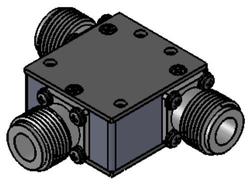


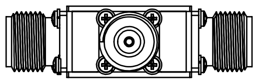


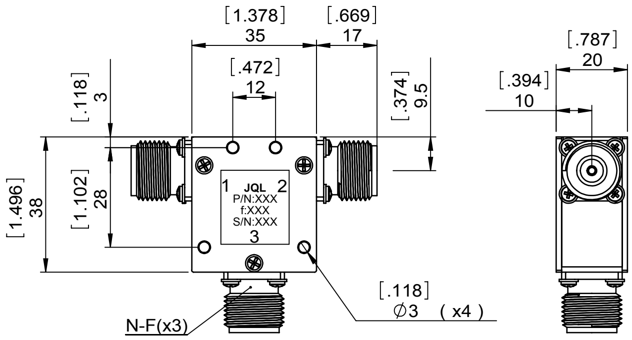
A.7 Circulator JCC0900T1000N20-HER

Document No.	QR4-700-T-003
REV.	A/0

REV.	DESCRIPTION	REVISOR	DATE	APPROVED
0		JP.Yang	07.04.2013	David







SPECIFICATIONS	
Part's Number	JCC0900T1000N20-HER
Frequency(GHz)	0.900~1.000
Direction	CW
Insertion Loss(dB)MAX	0.3dB Max at 200Watts 0.25dB Max at 0dBm power input
Isolation(dB)MIN	21.0
Return Loss(dB)MIN	21.0
3rd IMD(dBc)MAX	-
Power FWD/REV/PK(Watt)	200/200/-
Operating Temperature(°C)	-20~+85
Storage Temperature(°C)	-
2nd/3rd Harmonic(dBc)	-
Termination/Attenuator(Watt/dB)	-
Tab(W×LG×THK)(mm[Inch])	-
Additional Notes	-

JQL Electronic Inc
500 Lake Cook Road, Suite 350
Deerfield, IL 60015, USA
Tel: 1(888)236-9828
Fax: 1(888)823-2902

MATERIAL: STEEL

SURFACE TREATMENT: NICKEL PLATING

DESCRIPTION: COAX CIRCULATOR

DWG NO: JCC0900T1000N20-HER

DWG BY:	JP.Yang	07.04.2013	SACLE
CHK'D BY:			2:3
APPV'D BY:			
Unit: mm[inch]	Tolerance: Liner: ±0.25 Anguar: ±0.5°	The First:	A4

RoHS COMPLIANCE

WEIGHT:

A.8 Termination TN060M-100W

TERMINATIONS

Type N, up to 6.0 GHz, 100 Watts

A passion for performance.

SPECIFICATIONS:

RoHS Compliant

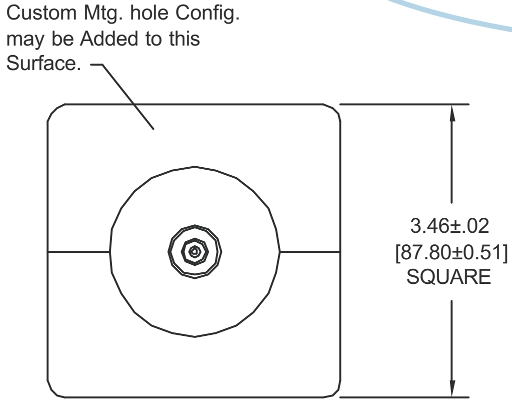
Models: TNXXXM-100W & TNXXXF-100W

Electrical:

Frequency Range	DC - 6.0 GHz
Standard Freq. Values	2.5 & 6 GHz
VSWR	
DC - 1.5 GHz	1.20:1 Max.
1.5 - 2.5 GHz	1.30:1 Max.
2.5 - 6.0 GHz	1.40:1 Max.
Input Power	100 Watts Avg. (Derated Linearly to 20 Watts @ +125°C)
Peak Power	1 kW Max. (5uSec Pulse, .05% Duty Cycle)
Impedance	50 Ohms
Operating Temp Range	-55°C to +125°C

Mechanical:

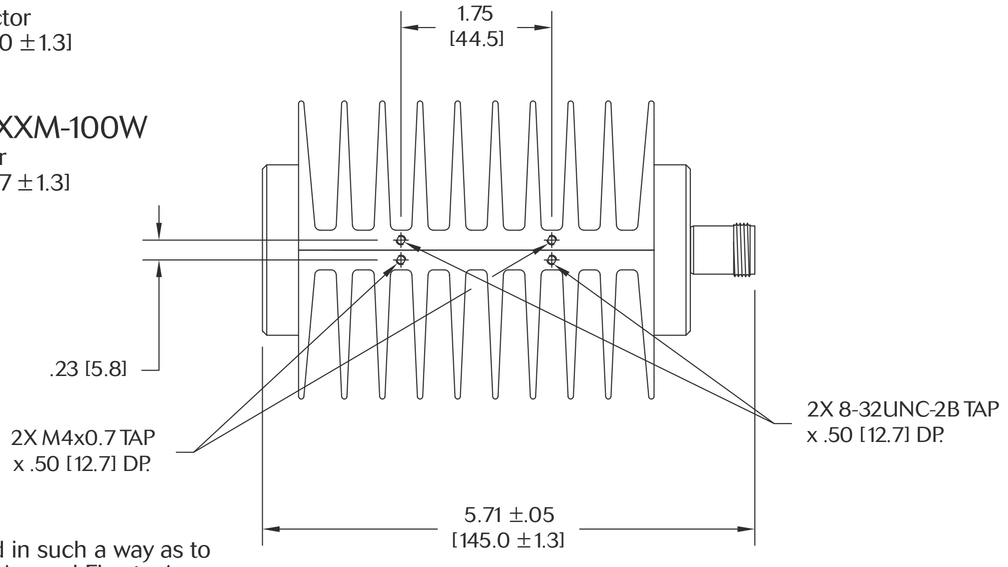
Type N Connectors (Mates with MIL-STD-348)	Passivated Stainless Steel
Conductors	Gold Plated Beryllium Copper
Housing	Anodized Aluminum



END VIEW
TYPICAL

Model Number: TNXXXF-100W
Type N Female Connector
Length: 5.71 ±.05 [145.0 ±1.3]
Pictured

Model Number: TNXXXM-100W
Type N Male Connector
Length: 5.62 ±.05 [142.7 ±1.3]



Units must be Mounted in such a way as to Allow for Free Air Flow Around Fins to Assure Performance

HOW TO ORDER:

Model Number: TNXXXY-100W

Freq. Range
020 = DC - 2.5 GHz
060 = DC - 6 GHz

Connector Configuration
F = Female
M = Male

Ordering Examples:

Model Number: **TN020M-100W**
DC - 2.5 GHz, Type N Male CONN.

Model Number: **TN060F-100W**
DC - 6 GHz, Type N Female CONN.

Note: Dimensions in Brackets are Expressed in Millimeters and are for Reference Only.
Design specifications are subject to change without notice.
Contact factory for technical specifications before purchasing or use.

TNXXXY-100W: REV F

AEROFLEX INMET

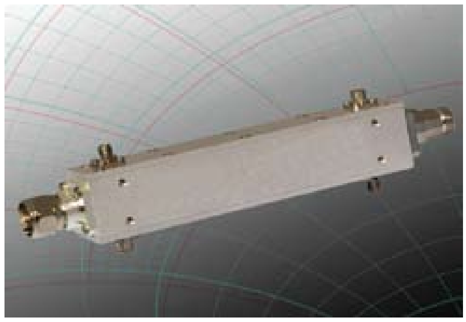
Aeroflex / Inmet, Inc. • 300 Dino Drive, Ann Arbor, MI 48103 • U.S.A.
888-244-6638 or 734-426-5553 • FAX: 734-426-5557
www.aeroflex.com/inmet • inmetsales@aeroflex.com

A.9 Dual Directional Coupler C2-A12

Dual Directional Couplers

C2-A12, 30dB Dual Directional Coupler PIM optimized
Three (3) section, dual directional airline (slabline) coupler.

Model	C2-A12	
Frequency range	380 - 3000 MHz	
	380-500 MHz	500-3000 MHz
Coupling	31 +2/-1.5 dB	30 ± 1.5 dB
Coupling Flatness	3.5 dB	± 0.75 dB
	TYP	MIN
Directivity	30 dB	20 dB
	TYP	MAX
Insertion Loss	0.12 dB	0.20 dB
VSWR and (Return Loss)	TYP	MAX
Input and Output	1.07 (30 dB)	1.12 (25 dB)
Coupled Port	1.15 (23 dB)	1.3 (17.7 dB)
Impedance	50 Ω	
Intermodulation IM3 (2 x 43 dBm carrier)	155 dBc	
Max. Power	500 W Avg, 5 KW Peak	
Termination Max. Power	3 W Avg	
Connectors	TYPE N Main Line, any combination SMA(f) Coupled Ports	
Material:		
Housing	Aluminum, Conversion Coating	
Inner Conductor & Connectors	Brass, Silver Plated	
DC continuity		
Input ↔ Output	RF and DC	
Input ↔ Coupled Port	RF only	
Weight approx	1.2 kg (2.64 lb)	



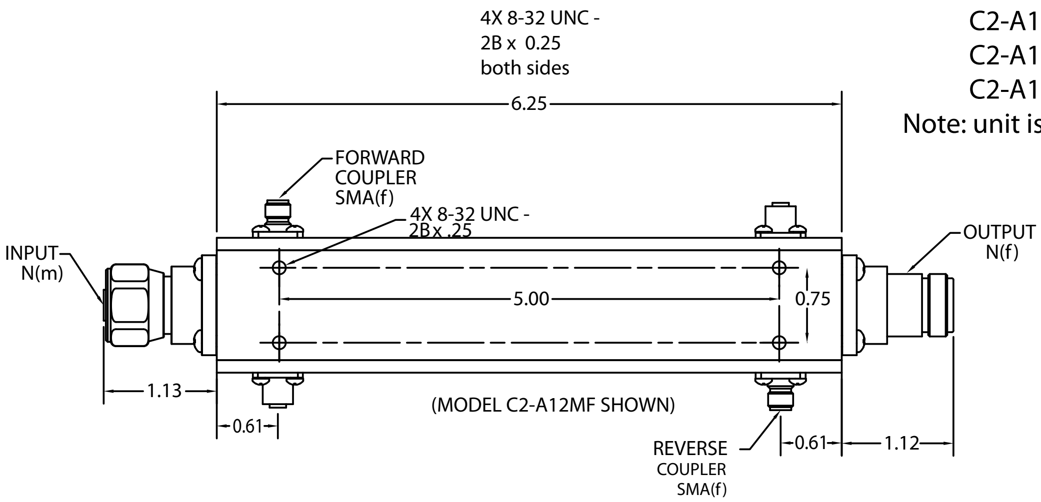
The Model C2-A12 dual directional coupler covers applications in the 380-3000MHz frequency range with high power, low insertion loss, very high directivity, and excellent PIM performance that is inherent with airline design and construction over the full 380-3000MHz frequency. The unit is designed for maximum coupling flatness over the 500-3000MHz range and the coupling will vary smoothly upward between 500 and 380 MHz. This three (3) section design dual directional coupler is supplied with two (2) terminations on the coupled ports. The unit is supplied with Type N connectors on the mainline and SMA on the coupled ports. The design may easily be modified to 7-16 DIN type connectors and other coupling values can be provided.

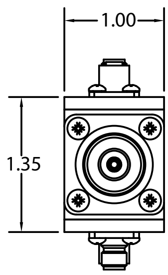
- 500 W average power
- Low VSWR and Loss
- High reliability, Low PIM
- ROHS Compliant

CONNECTOR OPTIONS

C2-A12FF
C2-A12MF
C2-A12MM

Note: unit is bi-directional



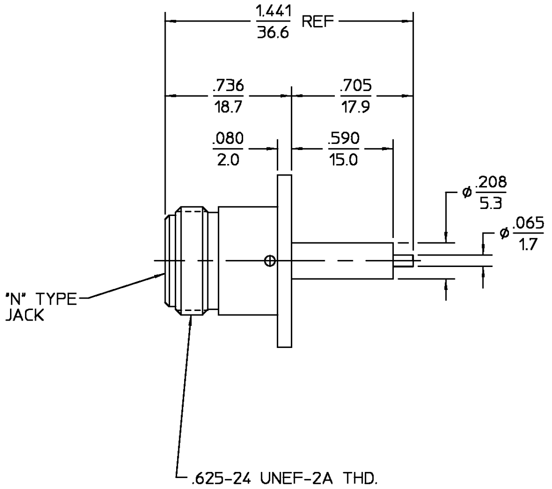


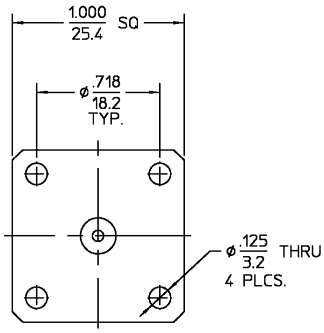
Rev 1.5
06/25/10

R&D Microwaves LLC, 11 Melanie Lane #12, East Hanover, NJ 07936 USA
Tel. 908.212.1696 www.rdmicrowaves.com
email: sales@rdmicrowaves.com

A.10 N-Type Connector

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED
02_1	REVISED	B.M.H. 7/31/96	[illegible]





COMPONENT	MATERIAL	FINISH
HOUSING	STAINLESS STEEL PER ASTM-A484 AND ASTM-A582, TYPE 303	PASSIVATE PER QQ-P-35
DIELECTRIC	TFE FLUOROCARBON PER ASTM-D-1457	N/A
CENTER CONTACT	BERYLLIUM COPPER PER ASTM-B-196 OR ASTM-B-197, ALLOY C17300, CONDITION H	GOLD PLATE PER MIL-G-45204

NOTES:

1. CAPTURED CENTER CONTACT

.XXX = in
XX.X = mm (REF)

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES FRAC. ± 1/64 DEC. ±.005 ANGLES ± 1°	DRAWN BY E.S. DATE 12/6/77 CHECKED BY KWW 12/21/77 APP'D BY BWC 12/23/77	AMP AMP Incorporated 140 Fourth Avenue Waltham, MA 02451-7599

TITLE OSN STRAIGHT 4 HOLE FLANGE MOUNT HF JACK RECEPTACLE

SIZE	CODE IDENT NO.		REV
B	26805	3652-1201-02	02_1
SCALE	3:1		SHEET 1 OF 1

CUSTOMER DRAWING

AMP PART # 1058644-1
SHEET 1 OF 1 REV A

A.11 USB Smart Power Sensor PWR-4GHS

USB *Smart* Power Sensor PWR-4GHS

50Ω -30 dBm to +20 dBm, 9 kHz to 4000 MHz

The Big Deal

- Low cost
- USB HID device compatible with 32/64 Bit operating systems
- Includes “Measurement Application” GUI (Graphical User Interface) software with an API-DLL com object
- High speed measurement capability

CASE STYLE: JL1504

Product Overview

The Mini-Circuits PWR-4GHS Smart Power Sensor is a pocket-sized, 4.89” x 1.74” x 0.95”, precision test USB HID device (no driver installation required) that turns a Windows® or Linux® PC into a power meter. All specifications provided in the data sheet apply to continuous wave (CW) signals. Each unit is shipped with our N-to-SMA adapter and a quick-locking USB cable for reliable connectivity. Native software and detailed user guides are provided on the included CD, or can be downloaded from minicircuits.com anywhere an internet connection is available, providing a full range of data analysis options.

Key Features

Feature	Advantages
USB HID (Human Interface Device)	Plug-and-Play (no need to install driver for the device).
GUI Measurement Application Software built-in	Enables the user to perform measurements on RF components such as Couplers, Filters, Amplifiers etc. and displays numerical data and graphs .
32/64 Bit operating systems	Compatible with Windows® and Linux® operating systems.
No calibration required before taking measurement	The PWR-4GHS does not require any reference signal for calibration.

Mini-Circuits®
ISO 9001 ISO 14001 AS 9100 CERTIFIED
P.O. Box 350166, Brooklyn, New York 11235-0003 (718) 934-4500 Fax (718) 332-4661

Notes: 1. Performance and quality attributes and conditions not expressly stated in this specification sheet are intended to be excluded and do not form a part of this specification sheet. **2.** Electrical specifications and performance data contained herein are based on Mini-Circuit’s applicable established test performance criteria and measurement instructions. **3.** The parts covered by this specification sheet are subject to Mini-Circuits standard limited warranty and terms and conditions (collectively, “Standard Terms”); Purchasers of this part are entitled to the rights and benefits contained therein. For a full statement of the Standard Terms and the exclusive rights and remedies thereunder, please visit Mini-Circuits’ website at www.minicircuits.com/MCLStore/terms.jsp.

USB *Smart* Power Sensor

PWR-4GHS

50Ω 9 kHz to 4000 MHz

Product Features

- Wide bandwidth, 9 kHz to 4000 MHz
- 50 dB Dynamic Range, -30 to +20 dBm
- Good VSWR, 1.1:1 typ.
- Fast measurement speed, 30 msec typ.
- Automatic frequency calibration & temperature compensation
- Multi-sensor capability (up to 24)
- Built in Application Measurement Software
- Remote operation via internet
- Effective, easy-to-use Windows® GUI
- Compatible with 32/64-bit Windows® or Linux® operating systems
- ActiveX com object and .Net class library for use with other software: C++, C#, CVI®, Delphi®, LabVIEW® 8 or newer, MATLAB® 7 or newer, Python, Agilent VEE®, Visual Basic®, Visual Studio® 6 or newer, and more[1]

Installation CD

Case Style: JL1504

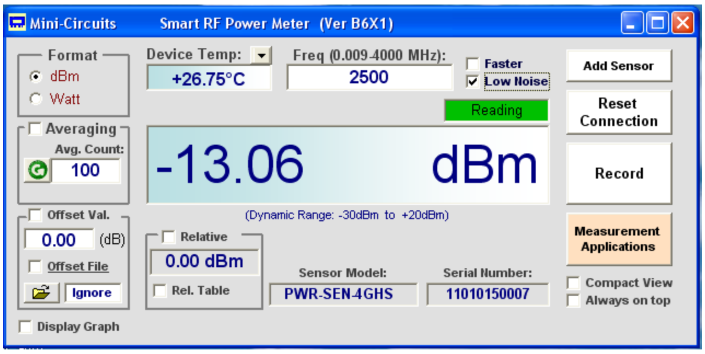
Model No.	Description	Price	Qty.
PWR-4GHS	**USB** *smart* **Power Sensor**	$795.00 ea.	(1-4)
Included Accessories			
PWR-SEN-4GHS	Power Sensor Head		
USB-CBL+	6 ft data cable (USB TYpe-A Plug)		1
NF-SM50+	N-Type (F) to SMA(M) Adapter		1
PWR-SEN-CD	Installation CD		1

Typical Applications

- Turn almost any Windows or Linux PC into a Power Meter
- Pocket-sized portability for benchtop testing anywhere
- Remote location monitoring
- Automatic, scheduled data collection
- Evaluate high-power, multi-port devices with built-in virtual couplers/attenuators & other software tools

RoHS Compliant
See our web site for RoHS Compliance methodologies and qualifications

Mini-Circuits Power Meter Program for *Smart* USB Power Sensor



[1] Windows, Visual Basic, and Visual Studio are registered trademarks of Microsoft Corporation in the United States and other countries. Linux is a registered trademark of Linus Torvalds. LabVIEW and CVI are registered trademarks of National Instruments Corp. Delphi is a registered trademark of Codegear LLC. MATLAB is a registered trademark of MathWorks, Inc. Agilent VEE is a registered trademark of Agilent Technologies, Inc. Neither Mini-Circuits nor the Mini-Circuits PWR-4GHS are affiliated with or endorsed by the owners of the above referenced trademarks.

Electrical Specifications (CW) [2], -30 dBm to +20 dBm, 9kHz to 4000 MHz

Parameter		Freq. Range (MHz)	Min.	Typ.	Max.	Units
Dynamic Range		0.009 - 4000	-30	-	+20	dBm
VSWR		0.009 - 4000	-	1.1	1.4	:1
Uncertainty of Power Measurement @ 25ºC	@ -30 to +5 dBm	0.009 - 1000	-	± 0.05	± 0.35	dB
		1000 - 4000	-	± 0.05	± 0.30	dB
	@ +5 to +12 dBm	0.009 - 1000	-	± 0.05	± 0.30	dB
		1000 - 4000	-	± 0.05	± 0.25	dB
	@ +12 to +20 dBm	0.009 - 1000	-	± 0.05	± 0.30	dB
		1000 - 4000	-	± 0.10	± 0.35	dB
Uncertainty of Power Measurement @ 0ºC to 50ºC	@ -30 to +5 dBm	0.009 - 1000	-	± 0.10	-	dB
		1000 - 4000	-	± 0.10	-	dB
	@ +5 to +12 dBm	0.009 - 1000	-	± 0.10	-	dB
		1000 - 4000	-	± 0.10	-	dB
	@ +12 to +20 dBm	0.009 - 1000	-	± 0.10	-	dB
		1000 - 4000	-	± 0.10	-	dB
Linearity @ 25ºC		0.009 - 4000	-	± 1.5	-	%
Measurement Resolution		0.009 - 4000	0.01	-	-	dB
Averaging Range		0.009 - 4000	1	-	999	-
Measurement Speed	@ Low Noise Mode	0.009 - 4000	-	100	-	mSec
	@ Faster Mode		-	30	-	
Current (via host USB)		0.009 - 4000	-	40	70	mA

Minimum System Requirements

Parameter	Requirements
Interface	USB HID
Host operating system	32 Bit operating system: Windows 98®, Windows XP®, Windows Vista®, Windows 7® 64 Bit operating system: Windows Vista®, Windows 7® Linux® support: 32/64 Bit operating system
Hardware	Pentium® II or higher, RAM 256 Mb, USB port
USB cable (supplied)	Power sensor to be used with the supplied USB cable only

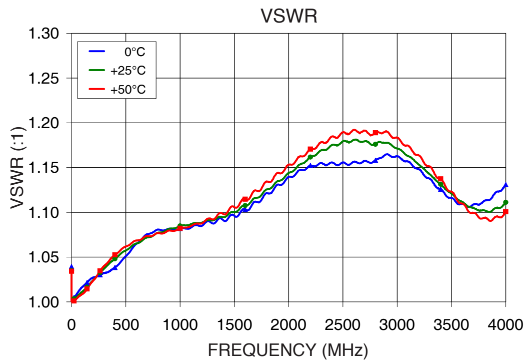
Note 2: All specifications apply to continuous wave (CW) signals.

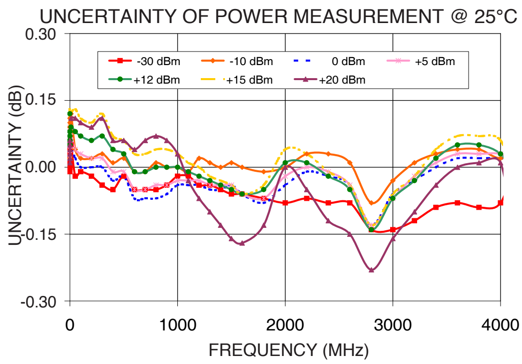
Absolute Maximum Ratings

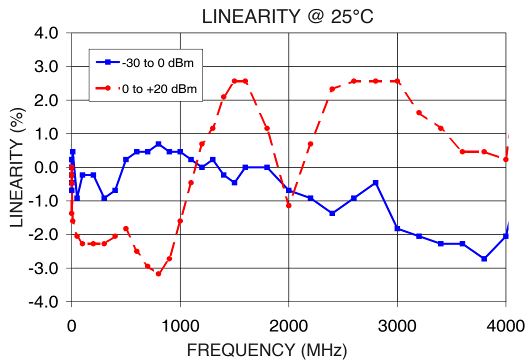
Parameter	Ratings
Operating Temperature	0°C to 50°C
Storage Temperature	-30°C to 70°C
DC Voltage at RF port	4 V
CW Power	+25 dBm

Permanent damage may occur if any of these limits are exceeded.

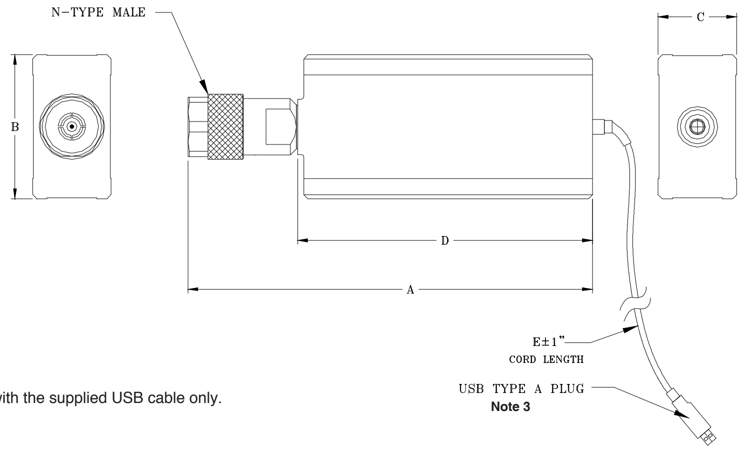
Typical Performance Curves







Outline Drawing (JL1504)



Note 3: Power sensor to be used with the supplied USB cable only.

Outline Dimensions (inch / mm)

A	B	C	D	E	WT. GRAMS
4.89 124.2	**1.74** 44.2	**.95** 24.1	**3.50** 88.9	**72.0** 1829	250

Warranty

For a full statement of the limited warranty offered by Mini-Circuits for the PWR-4GHS and the non-exclusive license for the software provided with the PWR-4GHS and the exclusive rights and remedies thereunder, together with Mini-Circuit's limitations of warranties and limitation of liability, please refer to Mini-Circuits User Guide for the PWR-4GHS and Mini-Circuits standard terms of sale found on its standard purchase order acknowledgment form, which are incorporated herein by reference. If you do not have these documents, please contact a Mini-Circuits representative and these documents will be provided promptly. Alternatively, for a copy of Mini-Circuits' standard terms of sale, visit Mini-Circuits' website at www.minicircuits.com/MCLStore/terms.jsp.

THE SOFTWARE IS PROVIDED "AS IS", "WITH ALL FAULTS", AND WITHOUT ANY EXPRESS OR IMPLIED WARRANTY OF ANY KIND, ALL OF WHICH ARE HEREBY WAIVED.

Ordering, Pricing & Availability Information see our web site

Model	Description
PWR-4GHS	USB *Smart* Power Sensor

Included Accessories	Description
PWR-SEN-4GHS	Power Sensor Head
USB-CBL+[4]	6 ft data cable with USB Type-A plug connector
NF-SM50+	N-Type Female to SMA Male Adapter.
PWR-SEN-CD	Installation CD

Note 4: Power sensor to be used with the supplied USB cable only.

Calibration

Model	Description	
CALSEN-4GHS	Calibration Service	Click Here

A.12 Coaxial Cable 086 Model Series

HAND FLEX™

Coaxial Cable

086 Model Series

50Ω   DC to 18 GHz

CASE STYLE: KP1505-XX

XX= cable length in inches

The Big Deal

- Hand Formable
- Tight Bend Radius
- Excellent Return Loss and Insertion Loss

Product Overview

The 086 Series Hand-Flex Coaxial Cables are ideal for interconnection of coaxial components or sub-systems. The construction includes a silver-plated copper-clad steel center conductor which maintains the shape after bending. The outer shield is copper braid, tin soaked, which minimizes signal leakage and at the same time flexible for easy bend. Dielectric is low loss PTFE. Connectors have passivated stainless-steel coupling nut over a gold plated connector body and gold plated, brass center conductor.

Key Features

Feature	Advantages
Hand-Formable RF Cables	The 086 Series Hand-Flex cables are hand formable making them ideal for use integrating coaxial components and sub-assemblies without the need for special cable-bending tools and alleviating the risk of damage during the bending process typical of semi-rigid coaxial cable assemblies.
Tight Bend Radius	Capable of only 6mm bend radius, the 086 Hand Flex series is able to make connections in tight spaces making these cables ideal for dense system integration
Excellent Return loss	Supporting typical return loss of 33 dB to 6 GHz and 21 dB to 18 GHz, the 086 Series Hand-Flex Cables are ideally suited for interconnecting a wide variety of RF components while minimizing VSWR ripple contribution due to mating cables & connectors.
Good Power Handling Capability: • 211W at 0.5 GHz • 35W at 18 GHz	Mini-Circuits 086 Cable series can support medium to high RF power levels enabling these cables to be used in the transmit path. NOTE: power rating is at sea-level altitudes.
Built in Anti-torque nut	Mini-Circuits 086 Series Hand Flex cables include an anti-torque feature to support the connector body during installation alleviating risk of stress to the connector/cable interface.
Jacketed and Unjacketed options	Standard 086 Series cables include a blue FEP insulator jacket reducing the risk of accidental shorting of DC power lines or active pins during installation and operation. Un-jacketed versions are available upon request.

HAND FLEX™

Coaxial Cable

086-6SM+

50Ω 6 inch DC to 18 GHz

CASE STYLE: KP1505-6

Connectors	Model	Price	Qty.
SMA-Male	086-6SM+	$9.75 ea.	(1-9)

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-55°C to 105°C
Storage Temperature	-55°C to 105°C
Power Handling at 25°C, Sea Level	211W at 0.5 GHz
	150W at 1 GHz
	104W at 2 GHz
	59W at 6 GHz
	45W at 10 GHz
	35W at 18 GHz

Permanent damage may occur if any of these limits are exceeded.

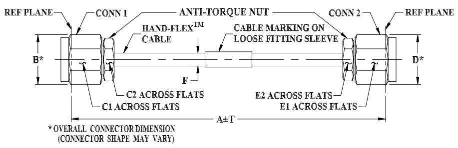
Features

- Wideband frequency coverage, DC to 18 GHz
- Low Loss, 0.7 dB at 18 GHz
- Excellent Return Loss, 24 dB at 18 GHz
- Hand formable to almost any custom shape without special bending tools
- 6mm bend radius for tight installations
- Anti-torque nut prevents cable stress during installation
- Insulated outer jacket standard[1]
- Connector interface, meets MIL-STD-348

Applications

- Replacement for custom bent 0.086" semi-rigid cables
- Communication receivers and transmitters
- Military and aerospace system
- Environmental and test chambers

Outline Drawing



Electrical Specifications at 25°C

MODEL[1] NO.	FREQ. (GHz)	LENGTH[2] (inch)	INSERTION LOSS (dB)								RETURN LOSS (dB)							
			DC - 2 GHz		2 - 6 GHz		6 - 10 GHz		10 - 18 GHz		DC - 2 GHz		2 - 6 GHz		6 - 10 GHz		10 - 18 GHz	
	f_L-f_U		Typ.	Max.	Typ.	Max.	Typ.	Max.	Typ.	Max.	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.	Min.
086-6SM+	DC-18	6	0.08	0.30	0.26	0.54	0.34	0.72	0.52	0.98	49	23	40	23	34	17	27	16

1. Unjacketed cable also available upon request.
2. Custom sizes available, consult factory.

Outline Dimensions (inch / mm)

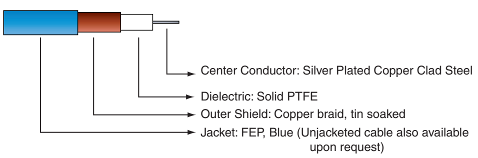
A	B	C1	C2	D
6.0	.36	.313	.250	.36
152.40	9.14	7.95	6.35	9.14

E1	E2	F	T	wt
.313	.250	.108	.05	grams
7.95	6.35	2.74	1.27	7.94

Typical Performance Data

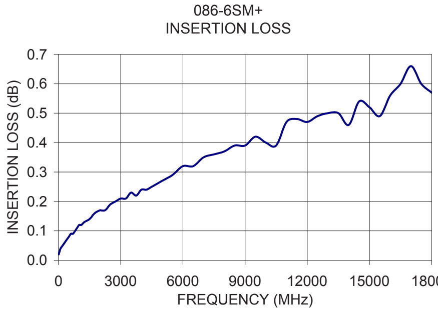
Frequency (MHz)	Insertion Loss (dB)	Return Loss (dB) SMA-MALE	Return Loss (dB) SMA-MALE
10.0	0.02	36.08	37.65
1000.0	0.12	40.43	41.62
2000.0	0.17	39.36	36.40
2500.0	0.19	38.28	36.22
4000.0	0.24	35.69	35.40
5000.0	0.27	51.99	34.92
6000.0	0.32	33.92	30.64
7000.0	0.35	52.62	37.64
8000.0	0.37	26.38	25.75
9000.0	0.39	32.60	31.47
10000.0	0.40	28.19	28.82
12000.0	0.47	27.47	29.55
13000.0	0.50	25.50	25.57
15000.0	0.52	33.60	42.08
18000.0	0.57	31.23	28.38

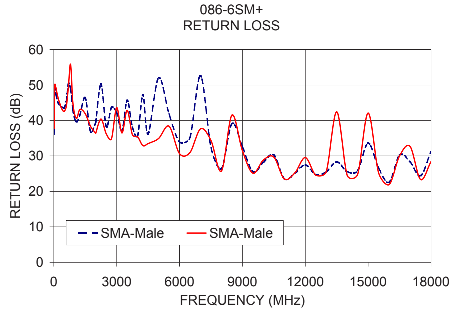
Cable Construction



Connectors: Coupling Nut: Stainless Steel Passivated
Body: Stainless Steel Gold Plated
Center Pin: Brass, Gold Plated

Typical Bending Capability





Rev. OR
M128984
086-6SM+
RS/CP/AM
130305

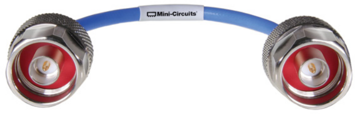
A.13 Coaxial Cable 141-6NM+

HAND FLEX™

Coaxial Cable

141-6NM+

50Ω 6 inch DC to 18 GHz



CASE STYLE: KQ1637-6

Connectors	Model	Price	Qty.
N-Male	141-6NM+	$19.61 ea.	(1-9)

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-55°C to 105°C
Storage Temperature	-55°C to 105°C
Power Handling at 25°C, Sea Level	546W at 0.5 GHz
	387W at 1 GHz
	273W at 2 GHz
	156W at 6 GHz
	121W at 10 GHz
	90W at 18 GHz

Permanent damage may occur if any of these limits are exceeded.

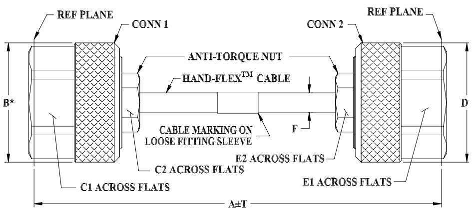
Features

- Wideband frequency coverage, DC to 18 GHz
- Low Loss, 0.31 dB at 18 GHz
- Excellent Return Loss, 27 dB at 18 GHz
- Hand formable to almost any custom shape without special bending tools
- 8mm bend radius for tight installations
- Anti-torque nut prevents cable stress during installation
- Insulated outer jacket standard[1]
- Connector interface, meets MIL-STD-348

Applications

- Replacement for custom bent 0.141" semi-rigid cables
- Communication receivers and transmitters
- Military and aerospace system
- Environmental and test chambers

Outline Drawing



* OVERALL CONNECTOR DIMENSION
(CONNECTOR SHAPE MAY VARY)

Outline Dimensions (inch / mm)

A	B	C1	C2	D
6.00	0.88	0.750	0.375	0.88
152.40	22.352	19.05	9.53	22.35

E1	E2	T	wt
0.750	0.375	0.05	grams
19.05	9.53	1.27	68.86

Electrical Specifications at 25°C

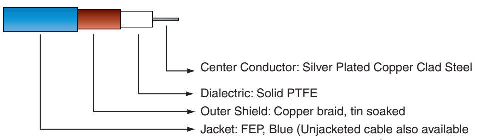
Parameter	Condition (GHz)	Min.	Typ.	Max.	Units
Frequency Range		DC		18	GHz
Length			6		Inches
Insertion Loss	DC - 2	—	0.05	0.31	dB
	2 - 6	—	0.20	0.55	
	6 - 12	—	0.30	0.73	
	12 - 18	—	0.35	1.0	
Return Loss	DC - 2	23	48	—	dB
	2 - 6	23	36	—	
	6 - 12	17	33	—	
	12 - 18	17	27	—	

1. Unjacketed cable also available upon request.
2. Custom sizes available, consult factory.

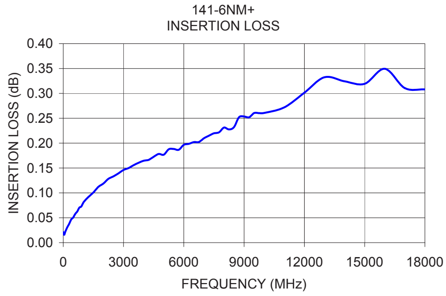
Typical Performance Data

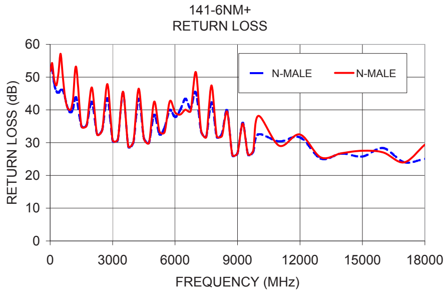
Frequency (MHz)	Insertion Loss (dB)	Return Loss (dB) N-MALE	Return Loss (dB) N-MALE
10.0	0.02	52.65	51.82
1000.0	0.08	39.25	40.21
1500.0	0.10	35.10	35.00
2500.0	0.13	33.90	33.85
4000.0	0.16	30.17	30.34
5000.0	0.18	38.51	42.53
6000.0	0.20	37.81	39.26
7000.0	0.21	45.37	51.54
8000.0	0.23	31.85	32.02
9000.0	0.25	26.78	26.81
10000.0	0.26	32.51	38.17
12000.0	0.30	31.61	32.49
14000.0	0.32	26.67	26.76
16000.0	0.35	28.35	27.02
18000.0	0.31	25.05	29.42

Cable Construction



Connectors: Coupling Nut: Stainless Steel Passivated
Body: Stainless Steel Gold Plated
Center Pin: Silver Plated Copper Clad Steel





Typical Bending Capability

Notes
A. Performance and quality attributes and conditions not expressly stated in this specification document are intended to be excluded and do not form a part of this specification document.
B. Electrical specifications and performance data contained in this specification document are based on Mini-Circuit's applicable established test performance criteria and measurement instructions.
C. The parts covered by this specification document are subject to Mini-Circuits standard limited warranty and terms and conditions (collectively, "Standard Terms"); Purchasers of this part are entitled to the rights and benefits contained therein. For a full statement of the Standard Terms and the exclusive rights and remedies thereunder, please visit Mini-Circuits' website at www.minicircuits.com/MCLStore/terms.jsp

Mini-Circuits®
www.minicircuits.com P.O. Box 35166, Brooklyn, NY 11235-0003 (718) 934-4500 sales@minicircuits.com

A.14 Coaxial Cable 141 SMNB Model Series

HAND FLEX™

Coaxial Cable

141 SMNB Model Series

50Ω DC to 12.5 GHz

CASE STYLE: KQ1669-XX

XX= cable length in inches

The Big Deal

- N-Type (F) Bulkhead Connector to SMA (M)
- Hand Formable
- Tight Bend-Radius (8mm min.)

Product Overview

141-SMNB-series Hand-Flex coaxial cables are ideal for integrating rack-mounted coaxial components and sub-assemblies in tight spaces and dense system configurations. N-Type female bulkhead connector at one end is equipped with a nickel-plated brass flange for secure connections to rack mounted equipment. SMA-connector has a passivated stainless-steel coupling nut over a gold-plated connector body. The outer shield is tin-soaked copper braid, which minimizes signal leakage with high flexibility for easy bending, and dielectric is low loss PTFE. 141-SMNB-series Hand-Flex coaxial cables are available in various lengths for different system requirements.

Key Features

Feature	Advantages
Single N-Type female bulkhead connector	Eliminates need for a bulkhead adapter and connects directly to the front panel of rack-mounted equipment, improving reliability and reducing system cost.
Hand-formable	141-SMNB-series Hand Flex cables avoid the need for cable-bending tools, alleviating the risk of damage during bending processes typical of semi-rigid cable assemblies.
8mm bend radius	Ideal for making connections in tight spaces and dense system assemblies.
Excellent return loss	Typical return loss of 21 dB to 12.5 GHz or better makes 141-SMNB series cables ideal for connecting a wide variety of RF components while minimizing VSWR ripple contribution due to mating cables & connectors.
Good power handling capability • 546W at 0.5 GHz • 110W at 12.5 GHz	141-SMNB coaxial cables can support medium to high RF power levels and can be used in the transmit path. (Power rating at sea-level).
Built-in anti-torque nut	Anti-torque feature supports the SMA connector body during installation, preventing stress to the connector/cable interface. Connector interface meets MIL-STD-348.

HAND FLEX™

Coaxial Cable

141-8SMNB+

50Ω 8 inch DC to 12.5 GHz

CASE STYLE: KQ1669-8

Connectors		Model	Price	Qty.
Conn1	Conn2			
SMA-Male	N-Female Bulkhead	141-8SMNB+	$20.61 ea.	(1-9)

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-55°C to 105°C
Storage Temperature	-55°C to 105°C
Power Handling at 25°C, Sea Level	546W at 0.5 GHz
	387W at 1 GHz
	273W at 2 GHz
	156W at 6 GHz
	121W at 10 GHz
	110W at 12.5 GHz

Permanent damage may occur if any of these limits are exceeded.

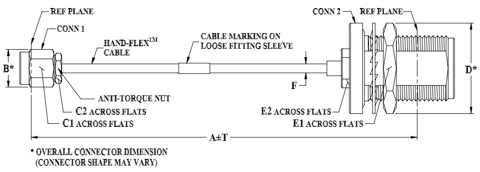
Features

- Bulkhead Female Type-N connector at one end
- Low Loss, 0.3 dB at 12.5 GHz
- Excellent Return Loss, 21 dB at 12.5 GHz
- Hand formable to almost any custom shape without special bending tools
- 8mm bend radius for tight installations
- Anti-torque nut prevents cable stress during installation
- Insulated outer jacket standard[1]
- Connector interface, meets MIL-STD-348

Applications

- Replacement for custom bent 0.141" semi-rigid cables
- Communication receivers and transmitters
- Military and aerospace system
- Environmental and test chambers

Outline Drawing

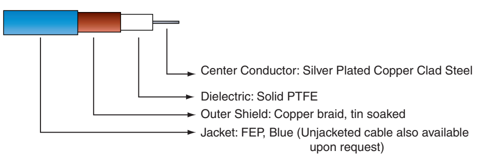


Outline Dimensions (inch / mm)

A	B	C1	C2	D
8.0	.36	.313	.250	.87
203.20	9.14	7.95	6.35	22.10

E1	E2	F	T	wt
.750	.531	.163	.10	grams
19.05	13.49	4.14	2.54	50.44

Cable Construction



SMA-Male
Connectors: Washer Nut: Stainless Steel Passivated
Body: Stainless Steel Gold Plated
Center Pin: Silver Plated Copper Clad Steel

N-Female
Washer, Nut & Body: Brass Nickel Plated.
Center Pin: BecuB, Gold Plated

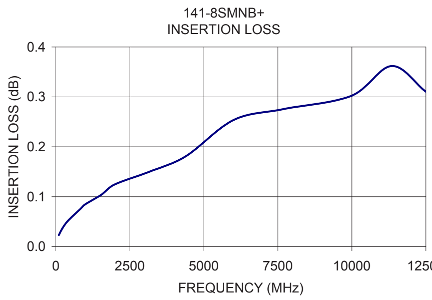
Electrical Specifications at 25°C

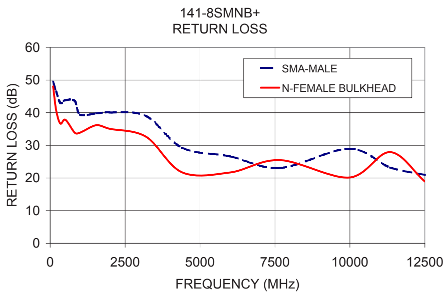
Parameter	Condition (GHz)	Min.	Typ.	Max.	Unit
Frequency Range		DC		12.5	GHz
Length[1]			8		inches
Insertion Loss	DC - 2	—	0.13	0.30	dB
	2 - 6	—	0.26	0.60	
	6 - 10	—	0.31	0.75	
	10 - 12.5	—	0.32	0.95	
Return Loss	DC - 2	22.0	32.0	—	dB
	2 - 6	17.0	19.0	—	
	6 - 10	17.0	18.0	—	
	10 - 12.5	17.0	19.0	—	

1. Custom sizes available, consult factory.

Typical Performance Data

Frequency (MHz)	Insertion Loss (dB)	Return Loss (dB) SMA-Male	Return Loss (dB) N-Female Bulkhead
100	0.02	49.5	48.1
200	0.03	46.5	40.7
340	0.05	43.0	36.7
510	0.06	43.8	37.8
820	0.07	43.6	33.9
1000	0.09	39.4	33.9
1540	0.10	39.8	36.2
2000	0.12	40.1	35.0
3200	0.15	39.0	32.6
4400	0.18	29.3	21.7
6000	0.25	26.6	21.7
7670	0.28	23.1	25.5
9970	0.30	29.0	20.1
11340	0.36	23.2	27.9
12500	0.31	20.9	18.9





Notes
A. Performance and quality attributes and conditions not expressly stated in this specification document are intended to be excluded and do not form a part of this specification document.
B. Electrical specifications and performance data contained in this specification document are based on Mini-Circuit's applicable established test performance criteria and measurement instructions.
C. The parts covered by this specification document are subject to Mini-Circuits standard limited warranty and terms and conditions (collectively, "Standard Terms"); Purchasers of this part are entitled to the rights and benefits contained therein. For a full statement of the Standard Terms and the exclusive rights and remedies thereunder, please visit Mini-Circuits' website at www.minicircuits.com/MCLStore/terms.jsp

A.15 Rohacell

Dielectric Properties

The following tables list the dielectric property values measured by various independent institutes.

For further information, please contact our experts by phone +49 6151 18 1005 or e-mail rohacell@evonik.com.

ROHACELL® IG and ROHACELL® A

Dielectric properties of ROHACELL® IG and ROHACELL® A

Properties	Unit	ROHACELL® 31 IG/ A	ROHACELL® 51 IG/A	ROHACELL® 71 IG/A	ROHACELL® 110 IG/A
ε' (f = 10 GHz)		1.05	1.071	1.09	1.12
tan δ (f = 10 GHz)		0.0017	0.0031	0.0034	0.0046

Source: Institut für Hochfrequenztechnik, Technische Universität Darmstadt, July 2004
The data of this table are representative values, but not to be used to establish specifications

Dielectric properties of ROHACELL® IG and ROHACELL® A

Properties	Unit	ROHACELL® 31 IG/ A	ROHACELL® 51 IG/A	ROHACELL® 71 IG/A	ROHACELL® 110 IG/A
ε' (f = 2.5 GHz)		1.05	1.05	1.08	TBD
tan δ (f = 2.5 GHz)		0.0003	0.0003	0.0003	TBD
ε' (f = 5 GHz)		1.06	1.07	1.1	TBD
tan δ (f = 5 GHz)		0.0011	0.0006	0.0011	TBD
ε' (f = 10 GHz)		1.06	1.07	1.08	TBD
tan δ (f = 10 GHz)		0.0039	0.0021	0.0035	TBD
ε' (f = 26.5 GHz)		1.05	1.07	1.08	TBD
tan δ (f = 26.5 GHz)		0.0034	0.0037	0.0044	TBD

Source: Seavey Engineering Ass., Report 8867-700
The data of this table are representative values, but not to be used to establish specifications

ROHACELL® HF

Dielectric properties of ROHACELL® HF

Properties	Unit	ROHACELL® 31 HF	ROHACELL® 51 HF	ROHACELL® 71 HF
ε' (f = 10 GHz)		1.04	1.08	1.10
tan δ (f = 10 GHz)		0.0017	0.0021	0.0026

Source: Institut für Hochfrequenztechnik, Technische Universität Darmstadt, July 2004
The data of this table are representative values, but not to be used to establish specifications

Dielectric properties of ROHACELL® HF

Properties	Unit	ROHACELL® 31 HF	ROHACELL® 51 HF	ROHACELL® 71 HF
ε' (f = 2.5 GHz)		1.05	1.06	1.07
tan δ (f = 2.5 GHz)		<0.0002	<0.0002	<0.0002
ε' (f = 5 GHz)		1.04	1.06	1.106
tan δ (f = 5 GHz)		0.0016	0.0008	0.0016
ε' (f = 10 GHz)		1.04	1.07	1.09
tan δ (f = 10 GHz)		0.0017	0.0041	0.0038
ε' (f = 26.5 GHz)		1.04	1.05	1.09
tan δ (f = 26.5 GHz)		0.0106	0.0135	0.0155

Source: Seavey Engineering Ass., Report 8867-700
The data of this table are representative values, but not to be used to establish specifications

ROHACELL® WF

Dielectric properties of ROHACELL® WF

Properties	Unit	ROHACELL® 51 WF	ROHACELL® 71 WF	ROHACELL® 110 WF
ε' (f = 10 GHz)		1.07	1.10	1.16
tan δ (f = 10 GHz)		0.0035	0.0041	0.0055

Source: Institut für Hochfrequenztechnik, Technische Universität Darmstadt, July 2004
The data of this table are representative values, but not to be used to establish specifications

Dielectric properties of ROHACELL® WF

Properties	Unit	ROHACELL® 51 WF	ROHACELL® 71 WF	ROHACELL® 110 WF
ε' (f = 2.5 GHz)		1.06	1.07	1.09
tan δ (f = 2.5 GHz)		0.0003	0.0003	0.003
ε' (f = 5 GHz)		1.08	1.10	1.19
tan δ (f = 5 GHz)		0.0008	0.0012	0.0014
ε' (f = 10 GHz)		1.08	1.11	1.16
tan δ (f = 10 GHz)		0.0038	0.0044	0.0056
ε' (f = 26.5 GHz)		1.07	1.08	1.12
tan δ (f = 26.5 GHz)		0.0045	0.0047	0.0059

Source: Seavey Engineering Ass., Report 8867-700
The data of this table are representative values, but not to be used to establish specifications

May 2011

Evonik Industries AG Performance Polymers 64293 Darmstadt Germany
Phone +49 6151 18-1005 E-mail rohacell@evonik.com
www.rohacell.com

EVONIK INDUSTRIES

A.16 Conductive Foam

- Vermafoam meets the surface resistance required range per EN 61340-5-1 Packaging Table 4 tested per IEC 61340-2-3
- Vermafoam low-density (FX) is polyether polyurethane foam impregnated with rigid conductive latex.
- The FX type is soft and flexible. It is used as cushion packaging.
- Corrosion prone non-ferrous metals such as Zinc, Nickel etc are not corroded when in direct or vapour contact with these conductive foams, even at elevated temperature and humidity.

Property	Value	Test Method
Density kg/m^3	24 Minimum	BS 4443 Pt 1 Method 2
Tensile Strength kPa	70 Minimum	BS 4443 Pt 1 Method 3A
Elongation @ Break %	100 Minimum	BS 4443 Pt 1 Method 3A
Loss in Tensile Strength After Heat Ageing (%)	30% Max Loss	BS 4443 Pt 1 Method 3A 140°C for 16 hours
Loss In Tensile Strength After Humidity Ageing (%)	30% Max Loss	BS 4443 Pt 1 Method 3A 105°C for 3 hours
Compression Set (50% Compression)	30% Max Loss	BS 4443 Pt 1 Method 3A
Volume Resistivity (ohms/m)	$\leq 2.5 \times 10^2$	BS 2044 Method 3 (100 Volts)
Surface Resistance (ohms)	$1 \times 10^2 \leq 1 \times 10^5$	IEC 61340-2-3
Compression Deflection at 50% Compression	3.3 Kpa (typical Value)	BS 4443 Pt1 Method 5A

"All generators of electrostatic charges, such as untreated plastic films, foams, synthetic fibres, adhesive tapes, etc., must be prohibited for use as intimate or proximity packaging material and should be kept away from EPA (ESD Protected Area)". (EN 61340-5-2 section 6)

Item	Description
815-3474	Conductive Cushioning Foam, 6mm x 1m x 1m, Sheet
815-3512	Conductive Cushioning Foam, 6mm x 305mm x 305mm, Pack of 9

Unless otherwise noted, tolerance ±10%

Specifications and procedures subject to change without notice.

Made in the United Kingdom

Conductive Cushioning Foam

RS COMPONENTS LTD.
BIRCHINGTON ROAD, CORBY,
NORTHANTS, NN17 9RS, UK

Drawing Number
RS-815-3474

DATE:
June
2014

A.17 Spectrum Analyzer

Test Equipment Solutions Datasheet

Test Equipment Solutions Ltd specialise in the second user sale, rental and distribution of quality test & measurement (T&M) equipment. We stock all major equipment types such as spectrum analyzers, signal generators, oscilloscopes, power meters, logic analysers etc from all the major suppliers such as Agilent, Tektronix, Anritsu and Rohde & Schwarz.

We are focused at the professional end of the marketplace, primarily working with customers for whom high performance, quality and service are key, whilst realising the cost savings that second user equipment offers. As such, we fully test & refurbish equipment in our in-house, traceable Lab. Items are supplied with manuals, accessories and typically a full no-quibble 2 year warranty. Our staff have extensive backgrounds in T&M, totalling over 150 years of combined experience, which enables us to deliver industry-leading service and support. We endeavour to be customer focused in every way right down to the detail, such as offering free delivery on sales, covering the cost of warranty returns BOTH ways (plus supplying a loan unit, if available) and supplying a free business tool with every order.

As well as the headline benefit of cost saving, second user offers shorter lead times, higher reliability and multivendor solutions. Rental, of course, is ideal for shorter term needs and offers fast delivery, flexibility, try-before-you-buy, zero capital expenditure, lower risk and off balance sheet accounting. Both second user and rental improve the key business measure of Return On Capital Employed.

We are based near Heathrow Airport in the UK from where we supply test equipment worldwide. Our facility incorporates Sales, Support, Admin, Logistics and our own in-house Lab.

All products supplied by Test Equipment Solutions include:

- No-quibble parts & labour warranty (we provide transport for UK mainland addresses).
- Free loan equipment during warranty repair, if available.
- Full electrical, mechanical and safety refurbishment in our in-house Lab.
- Certificate of Conformance (calibration available on request).
- Manuals and accessories required for normal operation.
- Free insured delivery to your UK mainland address (sales).
- Support from our team of seasoned Test & Measurement engineers.
- ISO9001 quality assurance.

Test equipment Solutions Ltd
Unit 8 Elder Way
Waterside Drive
Langley
Berkshire
SL3 6EP

T: +44 (0)1753 596000
F: +44 (0)1753 596001

Email: info@TestEquipmentHQ.com
Web: www.TestEquipmentHQ.com

- 40 updates/sec measurement speed
- ±1 dB amplitude accuracy
- Optional 10 Hz resolution bandwidth filter
- 99 dB third order dynamic range
- Field rugged portability
- Six-slot option card cage
- Mid-performance analyzers

ESA-E Series Spectrum Analyzers

The Agilent ESA-E series general purpose, portable spectrum analyzers offer a wide range of performance, features, and flexibility previously unavailable in this price range. Five models offer frequency ranges starting at 9 kHz and ending between 1.5 GHz and 26.5 GHz.

Fast measurement speed

The 1 ms RF sweep time and up to 40 measurements per second gives you virtual real-time measurement response. This means you spend less time testing or tuning circuits. High-speed remote measurements and data transfer of up to 40 measurements per second reduce critical test time in automatic test environments. Optional 50 ns zero-span sweep time illuminates fast changing signals in the time domain.

Highly accurate

A continuously phase-locked synthesizer operating over the entire sweep provides improved frequency accuracy, stability, and repeatability. The outstanding amplitude accuracy of ±1 dB up to 3 GHz and ±2.5 dB up to 26.5 GHz adds measurement confidence, improved yield and reduced test margins. The amplitude correction factor capability lets users remove frequency-related effects.

Automatic background alignment provides continuous calibration between sweeps, which means the full accuracy is maintained without operator intervention.

Digital resolving power

With the optional digital resolution bandwidth(RBW) filters (10 Hz to 300 Hz), you obtain finer resolving power to separate and measure closely spaced signals. A narrow shape factor (5:1) aids measurement of small signals close to the carrier. These digital RBW filters sweep up to 220 times faster than their analog equivalents, while improving sensitivity.

Wide dynamic range

99 dB maximum 3rd order dynamic range (+12 dBm TOI) and the 5 dB step attenuator let you see low-level distortion. Spur searching is enhanced with the –152 dBm sensitivity, optional built-in preamp, and the fast measurement speed. Up to 120 dB of calibrated display range allows simultaneous display of large and small signals.

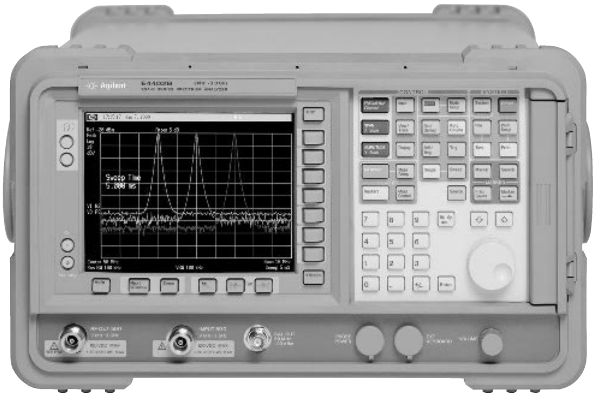
Rugged portability

Take the analyzer's lab grade performance into the field protected by rubber encased frames, rain-resistant front panel, and shielded vents. A snap on battery provides up to 1.9 hours of cordless operation and 12 Vdc capability allows operation with automotive electrical systems. Five-minute warm-up offers full measurement accuracy without waiting. And, automatic background alignment maintains the full measurement accuracy over time and varying temperatures.

Flexible platform

The ESA-E series can be configured specifically for your application as well as protect your investment into the future. The six-slot option card cage allows you to choose only the performance you need now and upgrade in the future. This scalable performance in combination with Agilent measurement personalities, downloaded into the internal memory, can transform the analyzer into an application focused solution, for example, cdmaOne or GSM measurements.

A growing number of plug-in option boards provide even more measurement capability. Most option boards are easily installed into the built-in card cage and are retrofittable.



Options include:
- Digital narrow resolution bandwidth filters of 10, 30, 100, 200 EMI and 300 Hz.
- Time-gated spectrum analysis
- FM demodulation/deviation plus tune and listen
- TV trigger with color picture on screen
- 1.5/3.0 GHz built-in tracking generators
- Pre-amplifier (1.5/3.0 GHz fully calibrated)
- 100 Hz low frequency operation
- High stability frequency reference
- Fast time-domain sweeps to 50 ns
- Battery pack/12 VDC operation
- External mixing capability to 325 GHz
- Digital demodulation communication hardware
- 75 Ω input

Features

- Segmented sweep saves measurement and setup time by viewing, in one sweep, only the frequency spans of interest. Paste together up to 32 discontinuous frequency or zero spans in one sweep. Eliminate the need for sweeping through unwanted frequencies and for multiple setups.
- Variable sweep (trace) points, ranging from 101 to 8192 points, optimize measurements for frequency resolution and accuracy versus speed.
- 16.8 cm, high-resolution color display with wide viewing angle make it easy to identify signals of interest.
- Split screen display shows wide spans while zooming in on signals of interest.
- The next generation user interface improves ease-of-use. Built-in help gives immediate assistance without manuals. When manuals are needed they are provided in printed form, on CD-ROM and on the Internet.
- One-button measurements such as ACP, Occupied BW, Emissions BW, channel power, 10 peaks table and harmonic distortion provide faster and more repeatable results.
- Multiple limit lines with margins and pass/fail messages simplify production testing. Built-in frequency counter with 1 Hz resolution precisely measures individual signals.
- 3 year global warranty lowers cost of ownership.

PC connectivity

Store up to 200 traces or states or multiple measurement personalities in the expandable user memory. Use the floppy disk drive or BenchLink XL for storing and transferring measurement results to a PC. SCPI remote control language and VXI*plug&play* drivers enhance remote program development.

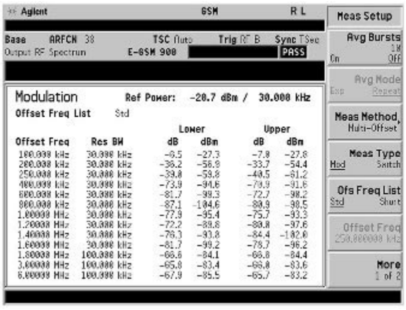
BenchLink XL PC software provides easy transfer of ESA measurement trace data directly into MS Excel spreadsheets or screen images into MS Word documents for analysis, archiving, presentations, or printing. Transfer measurement results over GPIB, RS232, or LAN (using two PCs or an E2050A GPIB/LAN adapter). Save and restore analyzer states. Unattended operation with repetitive sequence of measurement transfers by date and time. BenchLink XL is included standard with GPIB and RS232 options.

Combine the ESA-E series optional hardware configurations with downloadable measurement personalities to create application-specific solutions.

Measurement Personalities

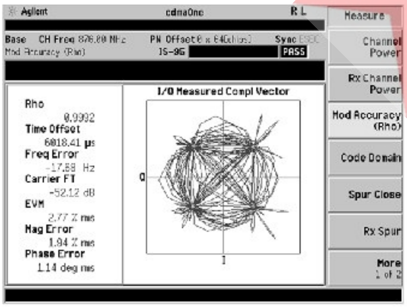
For a growing number of applications Agilent offers unique software programs (provided on 3.5-inch disks) designed specifically for the ESA-E series. Downloaded into analyzer memory, each measurement personality provides measurement setups, routines, and results specific to your application, including a user interface with application related terminology.

- Easy to use, one-button measurements
- Complex algorithms executed with a button press
- Improved accuracy and repeatability
- Operator independent results
- Decreased training time
- Improved productivity



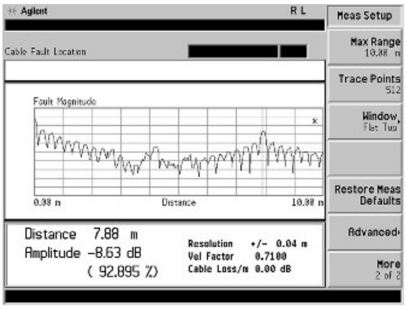
GSM

Options BAH (measurement personality) and B74 (digital demodulation hardware) combine to provide all the GSM 900, DCS1800, PCS1900 tests required to verify the performance of GSM mobile and BTS transmitters. Measurement features include mean TX power, power ramp, ORFS, phase and frequency error, distance-to-fault, and more. See page 381 for further information.



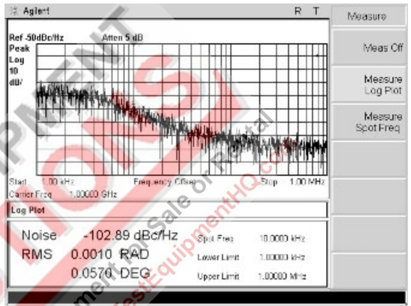
cdmaOne

Options BAC (measurement personality) and B74 (RF and digital demodulation hardware) combine to make the cdmaOne standard tests required to verify the performance of cdmaOne transmitters. Measurement features include channel power, ACPR, modulation accuracy (RHO), code domain power, occupied bandwidth, in- and out-of-band spurious, and more. See page 381 for further information.



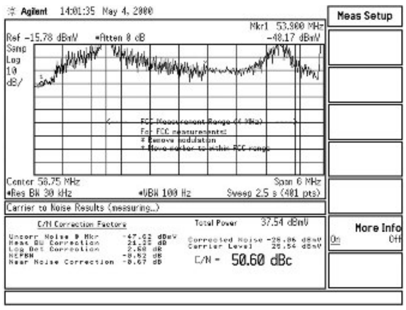
Cable Fault Location

Options 225 (measurement personality), 1DN (tracking generator), and B7K (measurment kit) combine to identify distance-to-cable discontinuities for fault location and troubleshooting of cable installation and maintenance. Includes table of common cable types with their loss and velocity factors.



Phase Noise

Option 226 (measurement personality) provides a log plot of phase noise in dBc/Hz versus offset frequency. Includes spot frequency readout and RMS phase noise integrated over a specified range, displayed in radians and degrees.



Cable TV Service and Installation

Option 227 (CATV measurement personality) provides Cable TV operators fast, accurate, and rugged spectrum analysis for field installation, ingress evaluation, and troubleshooting. One-button measurements include video carrier levels and frequencies, carrier-to-noise, CSO/CTB, hum and, with options B7B and BAA, TV trigger and picture on screen.

E4401B
E4402B
E4404B
E4405B
E4407B

ESA-E Series

Specifications

All specifications apply over 0° C to +55° C unless otherwise noted. The analyzer will meet its specifications after 2 hours of storage within the operating temperature range, 5 minutes after the analyzer is turned on, and after ALIGN NOW [RF] has been run.

Frequency Specifications

Frequency Range

E4401B		
50 Ω		9 kHz to 1.5 GHz
75 Ω		1 MHz to 1.5 GHz
E4402B		9 kHz to 3.0 GHz
Option UKB		100 Hz to 3.0 GHz
E4404B		
Band		
0		9 kHz to 3.0 GHz (dc coupled)
Option UKB		100 Hz to 3.0 GHz
0		100 kHz to 3.0 GHz (ac coupled)
1		2.85 GHz to 6.7 GHz
E4405B		
Band	LO harmonic = N	
0	1-	9 kHz to 3.0 GHz (dc coupled)
Option UKB		100 Hz to 3.0 GHz
0	1-	100 kHz to 3.0 GHz (ac coupled)
1	1-	2.85 GHz to 6.7 GHz
2	2-	6.2 GHz to 13.2 GHz
E4407B		
Band	LO harmonic = N	
0	1-	9 kHz to 3.0 GHz
Option UKB		100 Hz to 3.0 GHz
1	1-	2.85 GHz to 6.7 GHz
2	2-	6.2 GHz to 13.2 GHz
3	4-	12.8 GHz to 19.2 GHz
4	4-	18.7 GHz to 26.5 GHz
External Mixing (Opt AYZ)		18 GHz to 325 GHz

Frequency Reference

		(Opt.1D5)
Aging	$\pm 2 \times 10^{-6}$/year	$\pm 1 \times 10^{-7}$/year
Temperature Stability	$\pm 5 \times 10^{-6}$	$\pm 5 \times 10^{-8}$
Settability	$\pm 5 \times 10^{-7}$	$\pm 1 \times 10^{-8}$

Frequency Readout

Accuracy (Start, Stop, Center, Marker)	±(frequency indication x frequency reference error[1] + 0.5% of span + 15% of RBW + 10 Hz + span ÷ sweep points –1)

Marker Frequency Counter[2]

Accuracy[3]	±(marker frequency x frequency reference error[1] + counter resolution)
Counter Resolution	Selectable from 1 Hz to 100 kHz

Frequency Span

Range	0 Hz (zero span), 100 Hz to the range of the spectrum analyzer
Resolution	2 Hz x N^4
Accuracy (8192 sweep points)	±0.5% of span +2 x span ÷ sweep points –1

Frequency Sweep Time

Range	1 ms to 4000 s
Span = 0 Hz	10 µs to 4000 s
(Opt. AYX)	50 µs to 4000 s (RBW ≥ 1 kHz)
Accuracy	±1%
Sweep Trigger	Free run, Single, Line, Video, External, Offset, Delay, Gate (Opt.1D6), and TV (Opt. B7B)
Offset trigger range	± 327 ms to ±12.3 µs
Sweep (trace) point range	Span > 0Hz 101 to 8192 Span = 0Hz 2 to 8192

Resolution Bandwidth (RBW)

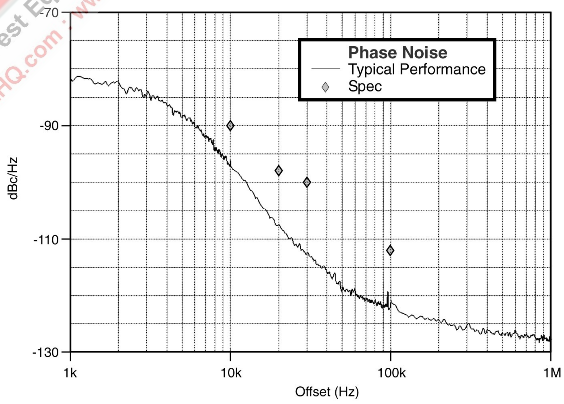
Range	1 kHz to 5 MHz (–3 dB) in 1-3-10 sequence. 9 kHz and 120 kHz (–6 dB) EMI bandwidths.
(Opt. 1DR)	Adds 10, 30, 100, and 300 Hz (–3 dB) bandwidths and 200 Hz (–6 dB) EMI bandwidth.
Accuracy	
1 kHz to 3 MHz RBW	±15%
5 MHz	±30%
10 Hz to 300 Hz RBW (Opt. 1DR)	±10%
Selectivity (Characteristic) –60 dB/-3 dB	
10 Hz to 300 Hz (Opt. 1DR)	<5:1
1 kHz to 5 MHz	<15:1

Video Bandwidth

Range	30 Hz to 3 MHz[6] in 1-3-10 sequence
(Opt. 1DR)	Adds 1, 3, 10 Hz for RBW<1kHz

Stability Noise sidebands (1 kHz RBW, 30 Hz VBW and sample detector)

≥10 kHz offset from CW signal	≤–90 dBc/Hz +(20 Log N^4 for frequencies >6.7 GHz)
≥20 kHz offset from CW signal	≤–98 dBc/Hz + (20 Log N^4 for frequencies >6.7 GHz)
≥30 kHz offset from CW signal	≤–100 dBc/Hz + (20 Log N^4 for frequencies >6.7 GHz)
≥100 kHz offset from CW signal	≤–112 dBc/Hz + (20 Log N^4 for frequencies >6.7 GHz)



Residual FM

1 kHz RBW, 1 kHz VBW	≤150 x N^4 Hz pk-pk in 100 ms
(Opt. 1D5)	≤100 x N^4 Hz pk-pk in 100 ms
(Opt. 1DR ,1DE)	≤2 x N^4 Hz pk-pk in 20 ms

System-Related Sidebands (offset from CW signal)

≥30 kHz	≤–65 dBc + (20 Log N^4 for frequencies >6.7 GHz)

Amplitude Specifications

Amplitude Range

Measurement Range	Displayed average noise level to maximum safe input level
Input Attenuator range	
E4401B	0 to 60 dB, in 5 dB steps
E4402B/04B/05B/07B	0 to 65 dB, in 5 dB steps

Maximum Safe Input Level

Average Continuous Power	(input attenuator ≥15 dB)
E4401B	+30 dBm (1 W)
E4401B (75 Ω Opt. 1DP)	+75 dBmV (0.4 W)
E4402B/04B/05B/07B	(input attenuator ≥5 dB) +30 dBm (1 W)
Peak Pulse Power	(input attenuator ≥15 dB)
E4401B	+30 dBm (1 W)
E4401B (75 Ω Opt. 1DP)	+75 dBmV (0.4 W)
E4402B/04B/05B/07B	(input attenuator ≥30 dB) +50 dBm (100 W)
dc	
E4401B (75 Ω Opt. 1DP)	100 Vdc
E4401B, E4402B	100 Vdc
E4404B, E4405B	0 Vdc (dc coupled) 50 Vdc (ac coupled)
E4407B	0 Vdc

1 dB Gain Compression (total power at input mixer[5])

≥50 MHz	0 dBm
≥6.7 GHz	–3 dBm
≥13.2 GHz	–5 dBm

Displayed Average Noise Level (dBm)
(Input terminated, 0 dB attenuation, sample-detector, 30/1 Hz VBW)

	1 kHz RBW	10 Hz RBW (Opt. 1DR)	1 kHz RBW w/ preamp (Opt. 1DS)	10 Hz RBW w/preamp (Opt. 1DR, 1DS)
E4401B				
400 kHz-10 MHz	≤–115	≤–134	≤–131	≤–150
10 MHz-500 MHz	≤–119	≤–138	≤–135	≤–153
500 MHz-1 GHz	≤–119	≤–138	≤–133	≤–152
1 GHz-1.5 GHz	≤–114	≤–133	≤–131	≤–150
E4402B				
30 Hz-9 kHz (Opt. UKB)	–	≤–85[6]	–	–
9 kHz-100 kHz	–	≤–105[6]	–	–
100 kHz-1 MHz	–	≤–131[6]	–	–
1 MHz-10 MHz	≤–117[6]	≤–136[6]	≤–134[6]	≤–152[6]
10 MHz-1 GHz	≤–117	≤–136	≤–132 (–133[14])	≤–150 (–151[14])
1 GHz-2 GHz	≤–116	≤–135	≤–132 (–133[14])	≤–151 (–152[14])
2 GHz-3 GHz	≤–114	≤–133	≤–129 (–132[14])	≤–148 (–151[14])
E4404/05/07B				
30 Hz-9 kHz (Opt. UKB)	–	≤–85[6]	–	–
9 kHz-100 kHz	–	≤–105[6]	–	–
100 kHz-1 MHz	–	≤–131[6]	–	–
1 MHz-10 MHz	≤–117[6]	≤–137[6]	≤–135[6]	≤–155[6]
10 MHz-1 GHz	≤–116	≤–136	≤–131 (–132[14])	≤–149 (–150[14])
1 GHz-2 GHz	≤–116	≤–136	≤–131 (–132[14])	≤–150 (–151[14])
2 GHz-3 GHz	≤–112	≤–132	≤–127 (–130[14])	≤–146 (–149[14])
3 GHz-6 GHz	≤–112	≤–132	–	–
6 GHz-12 GHz	≤–111	≤–131	–	–
12 GHz-22 GHz	≤–107	≤–127	–	–
22 GHz-26.5 GHz	≤–106	≤–126	–	–

Display Range

Log scale	0.1, 0.2, 0.5 dB/division and 1 to 20 dB/division in 1dB steps; ten divisions displayed.
RBW ≤300 Hz (Opt. 1DR)	0 to –120 dB from reference level is calibrated
RBW ≥1 kHz	0 to –85 dB from reference level is calibrated
Linear scale	10 divisions
Scale units	dBm, dBmV. dBμV, Volts, Watts, and Hz

Marker Readout Resolution

Log scale	0.04 dB
Linear scale	0.01% of reference level

Fast sweep times for zero span (Opt. AYX)

Log scale	
0 to –85 dB from ref. level	0.3 dB
Linear scale	0.3% of reference level

Frequency Response (10 dB input attenuation)

	Absolute[7]	Relative Flatness[8]
20˚ C to 30˚ C		
(30 Hz[6]) 100 Hz to 3.0 GHz (Opt. UKB)	±0.5 dB	±0.5 dB
9 kHz to 3.0 GHz	±0.46 dB (±0.14 db typical)	±0.5 dB
3.0 GHz to 6.7 GHz	±1.5 dB	±1.3 dB
6.7 GHz to 26.5 GHz	±2.0 dB	±1.8 dB
0˚ C to 55˚ C		
(30 Hz[6]) 100 Hz to 3.0 GHz (Opt UKB)	±1.0 dB	±1.0 dB
9 kHz to 3.0 GHz	±.76 dB	±1.0 dB
3.0 GHz to 6.7 GHz	±2.5 dB	±1.5 dB
6.7 GHz to 26.5 GHz	±3.0 dB	±2.0 dB

Input Attenuation Switching Uncertainty at 50 MHz

Attenuation setting	
0 dB to 5 dB	±0.3 dB
10 dB	Reference
15 dB	±0.3 dB
20 to 60 dB (E4401B)	±(0.1 dB + 0.01 x attenuator setting)
20 to 65 dB	±(0.1 dB + 0.01 x attenuator setting)
Overall Amplitude Accuracy[9]	± (0.54 dB + Absolute Frequency Response)
At Reference Settings[13]	±0.34 dB

RF Input VSWR (at tuned frequency) 10 dB atten.

100 kHz to 6.7 GHz	≤1.4:1[6]

Resolution Bandwidth Switching Uncertainty
(Referenced to 1 kHz RBW, at reference level)

10 Hz to 3 MHz RBW	±0.3 dB
5 MHz	±0.6 dB

Reference Level

Range	–149.9 dBm to maximum mixer level + attenuator setting
Resolution	±0.1 dB for log scale, ±0.12% of reference level for linear scale
Accuracy (reference level attenuator setting)	
–10 dBm to –60 dBm	±0.3 dB
–60 dBm to –85 dBm	±0.5 dB
–85 dBm to –90 dBm	±0.7 dB

Display Scale Fidelity

Log maximum cumulative	
0 dB to –85 dB	±(0.3 dB + 0.01 x dB from ref. level)
0 dB to –98 dB (Opt 1DR)	±(0.3 dB + 0.01 x dB from ref. level)
98 dB to –120 dB (Opt 1DR)	±(2 dB + 0.01 x dB from ref. level)[6]
Log incremental accuracy	
0 dB to –80 dB	±0.4dB/4dB form reference
Linear Accuracy	±2% of reference level
Linear to Log Switching Uncertainty	±0.15 dB at reference level
Log Scale Switching	No error

Spurious Responses

Second Harmonic Distortion

E4401B	
2 MHz to 750 MHz	<–75 dBc for –40 dBm tone at input mixer[5]. (+35 dBm SHI)
E4402/04/05/07B	
10 MHz to 500 MHz	<–65 dBc for –30 dBm tone at input mixer[5]. (+35 dBm SHI)
500 MHz to 1.5 GHz	<–75 dBc for –30 dBm tone at input mixer[5]. (+45 dBm SHI)
1.5 GHz to 2.0 GHz	<–85 dBc for –10 dBm tone at input mixer[5]. (+75 dBm SHI)
>2.0 GHz	<–100 dBc for –10 dBm tone at input mixer[5] (or below displayed average noise level). (+90 dBm SHI)

Third Order Intermodulation Distortion

E4401B	
10 MHz to 1.5 GHz	<–80 dBc for two –30 dBm tones at input mixer[5] and >50 kHz separation. (+10 dBm TOI, +15 dBm typical[14])
E4402B/04B/05B/07B	
100 MHz to 6.7 GHz	<–84 dBc for two –30 dBm tones at input mixer[5] and >50 kHz separation. (+12 dBm TOI, +16 dBm typical[14])
>6.7 GHz	<–75 dBc for two –30 dBm tones at input mixer[5] and >50 kHz separation. (+7.5 dBm TOI, + 11 dBm typical[14])

Other Input Related Spurious (in band)	
>offset 30 kHz	<–65 dBc, for –20 dBm tones at input mixer[5].

Residual Responses (input terminated and 0 dB attenuation)

150 kHz to 6.7 GHz	<–90 dBm

General Specifications

Temperature Range			
Operating	0° C to +55° C		
Disk Drive	10° C to 40° C		
Storage	–40° C to +75° C		
EMI Compatibility	Conducted and radiated interference is in compliance with CISPR Pub. 11/1990 Group 1 Class A		
Audible Noise (ISO 7779)	<40 dBa sound pressure and <4.6 Bels power		
Military Specification	Has been type tested to the environmental specifications of MIL-PRF-28800F class 3.		
Power Requirements			
On (Line 1)			
AC Operation			
Voltage, frequency	90 to 132 V rms, 47 to 440 Hz 195 to 250 V rms, 47 to 66 Hz		
Power consumption	<300 W		
Standby (Line 0)			
Power consumption	<5 W		
DC Operation			
Voltage	12 to 20 Vdc		
Power Consumption	<200 W		
Measurement Speed[6]	**E4401B**	**E4402B**	**E4404B, E4405B, E4407B**
Local measurement rate[10]	≥50/s	≥45/s	≥40/s
Remote measurement and GPIB transfer rate[11]	≥45/s	≥45/s	≥40/s
RF center frequency tuning time[15]	≤75 ms	≤75 ms	≤75 ms
Data Storage (nominal)			
Internal	200 traces or states		
External (Floppy)	200 traces or states		
Downloadable Program Memory	2 MB available		
Opt. B72	10 MB available		
Weight (without options)[6]			
E4401B	13.2 kg	(29.1 lb)	
E4402B	15.5 kg	(34.2 lb)	
E4404B/05B/07B	17.1 kg	(37.7 lb)	
Dimensions			
w/o handle	222mm H x 409mm D x 373mm W (8.88 in x 16.36 in x 14.92 in)		
w/handle (max.)	222mm H x 516mm D x 408mm W (8.88 in x 20.64 in x 16.32 in)		

Option Specifications

Option 1DN and 1DQ Tracking Generator

Frequency Range	
E4401B	
Opt. 1DN, (50 Ω)	9 kHz to 1.5 GHz
Opt. 1DQ, (75 Ω)	1 MHz to 1.5 GHz
E4402B/04B/05B/07B	
Opt. 1DN, (50 Ω)	9 kHz to 3.0 GHz
Resolution BW Range	1 KHz to 5 MHz
Output Level	
Range	
E4401B	
Opt. 1DN	0 to –70 dBm
Opt. 1DQ	+42.75 to –27.25 dBmV
E4402B/04B/05B/07B	–2 to –66 dBm
Absolute Accuracy (@ 50 MHz)	
Opt.1DN (E4401B)	±0.5 dB
Opt.1DN	±0.75 dB
Opt.1DQ (E4401B)	±1.5 dB
Dynamic Range	
Maximum output power-Displayed Average Noise Level	

[1]Frequency reference error = (aging rate x period of time since adjustment + settability + temperature stability).
[2]Not available in RBW <1kHz (Option 1DR).
[3]Marker level to DANL >25dB, Frequency offset = 0 Hz, RBW/Span ≥0.002.
[4]N = LO harmonic mixing mode
[5]Mixer Power Level (dBm) = Input Power (dBm) – Input Attenuator (dB).
[6]Characteristic
[7]Referenced to amplitude at 50 MHz
[8]Reference to midpoint between highest and lowest frequency response deviations.
[9]For reference levels 0 to –50 dBm; RBW, 1 kHz; Video BW, 1 kHz; Scale Log, Log range 0 to –50 dB; Sweep time coupled; Signal input, 0 to –50 dBm; Span, ≤20 kHz; Input attenuation 10 dB, 20° C to 30° C.

Ordering Information

E4401B ESA-E 1.5 GHz Spectrum Analyzer
E4402B ESA-E 3.0 GHz Spectrum Analyzer
E4404B ESA-E 6.7 GHz Spectrum Analyzer
E4405B ESA-E 13.2 GHz Spectrum Analyzer
E4407B ESA-E 26.5 GHz Spectrum Analyzer
- **Opt 0B0** Delete printed manual set (retains CD-ROM manual)
- **Opt 0B1** Add manual set
- **Opt 0BV** Component level service documentation
- **Opt 0BW** Assembly level service guide and CD-ROM with adjustments
- **Opt 1AX** RS-232 and Parallel printer interface (includes RS-232 cable and BenchLink XL software)
- **Opt 1CP** Rackmount and handle kit with slides
- **Opt 1D5** High stability time base
- **Opt 1D6** Time-gated spectrum analysis
- **Opt 1D7** 50 Ω/75 Ω matching pad with dc block
- **Opt 1DN** 1.5 GHz tracking generator (E4401B only)
- **Opt 1DN** 3 GHz tracking generator
- **Opt 1DP** 75 Ω input (E4401B only)
- **Opt 1DQ** 75 Ω tracking generator (E4401B only)
- **Opt 1DR** Narrow resolution bandwidths
- **Opt 1DS** 1.5 GHz Preamplifier (E4401B only)
- **Opt 1DS** 3.0 GHz Preamplifier
- **Opt A4H** GPIB and parallel printer interfaces (includes BenchLink XL software)
- **Opt A4J** IF, sweep and video ports
- **Opt A5D** 12 Vdc power cable
- **Opt AXT** Transit case
- **Opt AYT** Grey soft carrying/operating case
- **Opt AYU** Yellow soft carrying/operating case
- **Opt AYX** Fast zero-span sweeps
- **Opt B72** Increases useable memory to 10 MB
- **Opt B74** RF/Digital communication hardware
- **Opt B75** Performance Bundle (1D5+1DR+1DS)
  - E4401B only
  - E4402B, E44044B, E4405B, E4407B
- **Opt BAA** FM Demodulation/Deviation
- **Opt BAB** APC 3.5mm Connector (E4407B only)
- **Opt BAC** cdmaOne Measurement Personality
- **Opt BAH** GSM Measurement Personality
- **Opt UK6** Commerical Calibration Certificate
- **Opt UK9** Front panel cover
- **Opt B7B** TV Trigger with color picture on screen (requires Opt. BAA)
- **Opt AYZ** External Mixing (E4407B only)
- **Opt UKB** 100 Hz Low frequency extension (unavailable in E4401B)
- **Opt 042** Custom analyzer backpack (grey)
- **Opt 044** Custom analyzer backpack (yellow)
- **Opt B7K** Cable fault location measurement kit
- **Opt 225** Cable fault location measurement personality
- **Opt 226** Phase noise measurement personality
- **Opt 227** Cable TV service and installation measurement personality

E1779A Battery pack
N2717A Performance and Adjustment Software for calibration of ESA Analyzers
41800A Active Probe (5 Hz to 500 MHz)
85024A Active Probe (300 kHz to 3 GHz)
11742A dc blocking capacitor, M–F APC 3.5 mm connector (45 MHz to 26.5 GHz)
11693A Limiter, M–F Type N connector (100 MHz to 12.4 GHz)

[10]Factory preset, auto align Off, segmented sweep Off, fixed center frequency, RBW = 1 MHz, sweep points = 101, and spans >10 MHz and ≤600 MHz (>102 MHz and ≤400 MHz E4401B).
[11]Factory preset, display Off, single sweep, markers Off, auto align Off, segmented sweep Off, fixed center frequency, RBW = 1 MHz, sweep points = 101, and span = 20 MHz and stop frequency ≤3 GHz.
[12]In time domain sweeps
[13]Settings are: Reference level –20 dBm (–25 dBm E4401B); input attenuation 10 dB; center frequency 50 MHz; RBW 1 kHz; VBW 1 kHz; span 2 kHz; sweep time coupled, sample detector; signal at reference level.
[14]20° C to 30° C
[15]Factory preset, display Off, markers Off, single sweep, auto align Off, segmented sweep Off, RBW = 1 MHz, sweep points = 101, and span = 20 MHz, stop frequency ≤3 GHz, and center frequency tune step size = 50 MHz.

A.18 Paper

Closed-Loop System for Microwave-Induced Hyperthermia

María Jesús Cañavate Sánchez, Sumanth Kumar Pavuluri, Theodora Mantso, Mihalis Panagiotidis, George Goussetis
Heriot-Watt University
Edinburgh, UK

***Abstract*— Microwave technology is now widely used in a variety of medical applications such as cancer treatment and diagnostics. This paper describes the structure of a novel hyperthermia system for biomedical research. The software Ansoft HFSS was used to design a rectangular waveguide applicator. A closed-loop is presented in order to control the output power of the system by the temperature measured on the sample. Initial results from experimental testing are presented. In these results, it is shown that the water temperature can be increased from 21ºC to 40ºC in 12 minutes. As a result, it has been tested that the system works properly. The next step will be to apply the system to melanoma cancer cells.**

Keywords-superficial tumor; hyperthermia; microwave; loop; feedback; temperature; control.

I. INTRODUCTION

Hyperthermia denotes a treatment for cancer patients providing heat to body tissue (between 40-44ºC) for a specific period of time [1]. Previous evidence suggests that high temperatures such as the ones reached using this therapy can destroy cancer cells, normally with least harm to the healthy tissues [2]. Due to this fact, over the past decade most research in cancer treatment has emphasized on the use of hyperthermia combined with other therapies such us radiotherapy and chemotherapy. For instance, it has been demonstrated that tumor cells could become more vulnerable to radiation and areas not reached by radiation alone could be affected when hyperthermia is used with radiotherapy. Regarding that, a number of researches have reported that the use of these treatments together has shown a considerable diminution in tumor size. [1]-[3].

To this date three hyperthermia methods have been developed and introduced: local, regional and whole-body hyperthermia. In our study we choose local hyperthermia since one of the aims of this project is to develop a novel microwave hyperthermia system that will be used as a reference for following studies focused on melanoma cancer research and treatment [4]. The main reason why the local therapy was considered the best option to treat this disease is that local hyperthermia offers an effective way of treating tumors located in or close to the skin such as melanoma. By using this method, applicators are placed next to the affected area of the body in order to concentrate the energy on the cancer cells and increase its temperature. The way heat is induced can vary depending on the position and the magnitude of the tumor. Regarding this issue, different techniques can be applied for different situations such as infrared radiation for the whole-body, radiofrequency radiation for more profound positioned tumors or microwave radiation for skin-deep tumors. Taking into account that this study is focused on superficial hyperthermia research and treatment, a microwave applicator was selected [4], [5].

Up to the present, several hyperthermia systems have been developed. These structures usually include heavy and costly components such as a microwave generator or a power meter [5], [6]. In general, there is a demand for lighter, more compact and cheaper systems and for this reason, the main purpose of this project is to establish a new hyperthermia system for treating superficial tumors that best suits these characteristics. The system primarily targets in-vitro research although the RF chain can be used with another RF applicator more suitable for in-vivo exposures. In terms of the advantages of the system we can say that it has accurate temperature control by the use of a feedback loop, homogeneous heating of the sample and rapid temperature rise. The design of a waveguide applicator and a closed-loop to control the power levels depending on the temperature measured in real time have been presented. Finally, in order to validate the functionality of the system, a flask containing water is introduced into the applicator.

II. HYPERTHERMIA SYSTEM

A. *Identification of the components*

The frequency band chosen to operate is the ISM band of 915 MHz since it is one of the most commonly used in microwave hyperthermia [5]. For this reason, we selected components that are able to work between 0.9 and 1 GHz. In terms of the output power of the system, it was calculated that a maximum power of 50 dBm was sufficient to achieve a water temperature of 45ºC inside a flask of 0.09 m diameter and 0.02 m height in a short period of time.

As shown in Fig. 1 the hyperthermia system is composed of a voltage-controlled oscillator or VCO (ZX95-1015+, Mini-Circuits) whose signal frequency is controlled by a voltage input, an attenuator to control the power of the signal (ZX73-

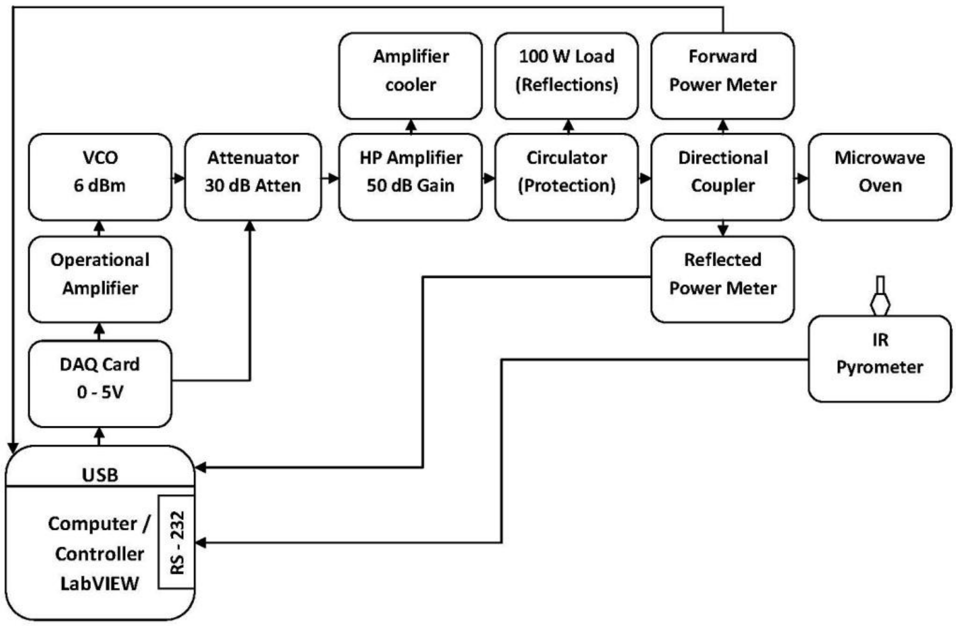


Figure 1. Block diagram of the necessary components to drive the microwave induced hyperthermia system.

2500+, Mini-Circuits), a high-power amplifier with a maximum gain of 50 dB (ZHL-100W-13+, Mini-Circuits), an isolator formed by a circulator (JCC0900T1000N20-HER, JQL Electronics) and a 100W load (TN060M-100W, RF Components) for protecting the amplifier from reflected signals, a dual directional coupler (C2-A12, RF Components) connected to two power sensors (PWR 4GHS) to calculate the forward and backward power flow and a microwave applicator, which is a rectangular waveguide [7]. The design of the cavity will be presented in the next section.

B. Closed-loop

All the system parameters such us frequency, output power and temperature can be monitored from a personal computer or PC. The software chosen for this purpose was LabVIEW (National Instruments).

First of all, in order to connect the VCO to a PC to be able to adjust the frequency from LabVIEW, a data acquisition card or DAQ was required. As the maximum output voltage value of this card is 5V (see DAQ datasheet) and the voltage necessary to choose a frequency of the ISM band of 915 MHz on the VCO is around three times greater than 5V (see VCO datasheet), the card was connected to a 3 dB gain operational amplifier (LN324AN) and the output of this one to the VCO. The DAQ card is connected to the PC via USB.

Secondly, the control of the power is accomplished by the use of the attenuator, which is connected to the PC using the same DAQ card. Additionally, the power reflection coefficient is calculated with the use of the backward and forward power flow obtained by the sensors. This coefficient will be used to further enhance control of the temperature.

Finally, the temperature is measured by a pyrometer (CT84-02, Sensortherm), which is positioned at the top of the cavity with the lens focused to the flask containing the water. This pyrometer is also connected to the PC via RS-232. As a result, the system provides real time display of the temperature at the same time that this temperature is used to control the power levels. The functionality of the closed-loop is follows: while the measured temperature is lower than requested, the attenuator should be reducing the attenuation to increase the power level until the target temperature is achieved. In the same way, when the measured temperature is higher than requested, the attenuator should increase the attenuation to reduce the power.

III. Design of the Applicator

A. Cavity shape

In the design of the applicator, several requirements were taken into account. As our aim is to validate the functionality of the hyperthermia system by heating water introduced in a flask, we decided to locate the flask inside the cavity. In order to achieve that, the applicator is formed by two rectangular aluminum waveguides that have a different width, as shown in Fig. 2, so that a rohacell layer could be placed between the two cavities. The reason why the rohacell was chosen is that its permittivity value is similar to the air permittivity. Thanks to this structure, it is possible to position the flask over the rohacell. Furthermore, the top of the shortest cavity can be removed in order to take out the flask and change the sample. there is a hole at the top of this cavity for the pyrometer to measure the temperature. Finally, an N-type connector was set

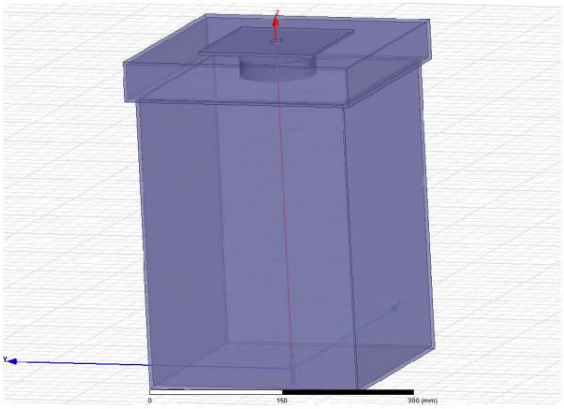


Figure 2. Microwave oven design including a cylindrical flask containing samples at the top cavity.

at the bottom of the largest cavity in order to connect the system to the applicator.

B. *Calculation of the dimensions*

The height of the applicator (d) has been obtained using the equation that calculates the resonant frequency of a TM_{mnl} mode [8] taking into account that we wanted to achieve the second transverse mode TM_{111} in correspondence of the working frequency. The value of the other two dimensions (a, b) was established as 0.25 m to be able to introduce flasks with different shapes and sizes and check the uniformity of the fields. As the cavities are filled with air, the value of the permittivity is 1. Finally, we obtained a height value of 0.37 m.

C. *Electric field distribution*

Before fabricating the applicator it was designed using the software Ansoft HFSS. Due to the fact that the inner conductor of the N-Type connector is inside the cavity, it was necessary to change the length of it in order to improve the impedance matching.

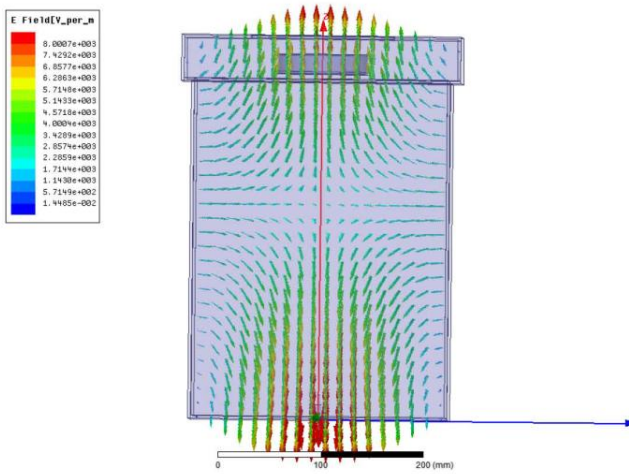


Figure 3. Simulated electric field within the oven cavity (TM mode).

In terms of the electromagnetic mode, it is shown in Fig. 3 that the TM_{111} mode was accomplished. Furthermore, it was tested that the distribution of the electric field between the two cavities was considerably uniform. Although the power is a bit stronger in the middle of the flask than at the edges.

IV. INITIAL RESULTS

Once the applicator was manufactured, the S_{11} parameter was measured by using a vector network analyzer or VNA. The comparison between the simulated and the measured S_{11} parameter is shown in Fig. 4.

Concerning the validation of the system functionality, some initial results have been obtained as shown in Fig. 5.

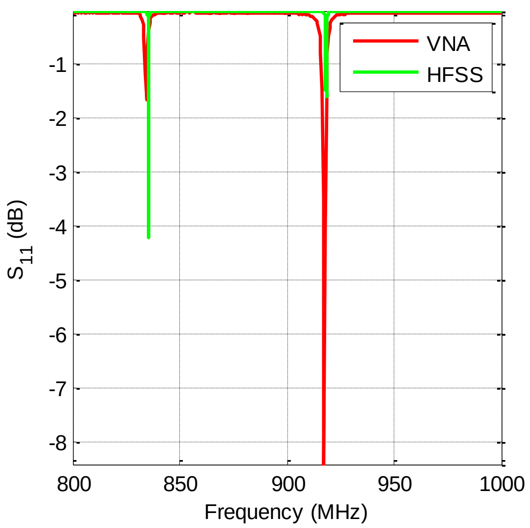


Figure 4. Comparison between the S_{11} parameter obtained by simulation (HFSS) and measurement (VNA) for the microwave oven.

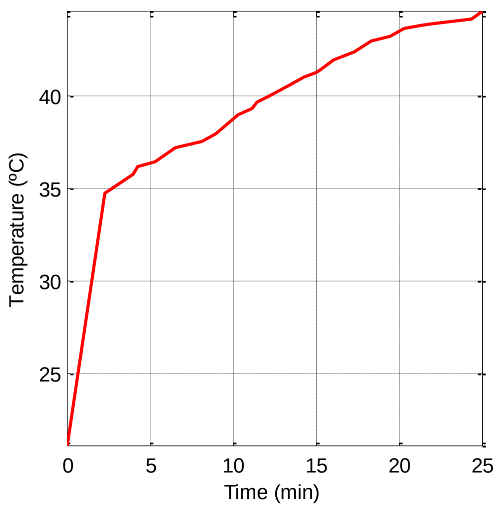


Figure 5. Measured temperature of the sample (water in this case) while the system is working at the resonance frequency (second mode).

Figure 6. System in the laboratory

V. CONCLUSION

A novel hyperthermia system has been presented in this paper. After choosing all the components that form the system, a waveguide cavity was designed with HFSS and manufactured afterwards. It has been shown in Fig. 4 that the measured resonance frequency is the same as the simulated one. The difference between them is the matching, the results measured show a better matching than the ones simulated. That could be attributed to the fact that the manufactured applicator takes into account other physical factors that the simulated one does not. Furthermore, it is shown in the same figure that two electromagnetic modes are propagating in the range from 0.8 MHz to 1 GHz. Due to the fact that the second mode (917 MHz) has a better matching than the first one (835 MHz), this was the one selected for our system.

Regarding the temperature results seen in Fig. 5, it is shown that around 12 minutes are required to increase the temperature of the water from 21ºC to 40ºC and 22 minutes to increase it up to 44ºC. As the temperature needed for the hyperthermia treatment is located between these values, a feedback loop is used in order to control the output power of the system in terms of the temperature. The functionality of this feedback loop consists of increasing the value of the power of the system if the temperature is lower than the value required for the treatment and decreasing it if the temperature is higher than required. Afterwards, the system will be used in melanoma cancer cells.

REFERENCES

[1] Hildebrandt B, Wust P, Ahlers O, et al.," The cellular and molecular basis of hyperthermia", Critical reviews in Oncology/Hematology, 43(1), pp. 33–56, 2002.

[2] Van der Zee J., "Heating the patient: a promising approach?", Annals of Oncology, 13(8), pp. 1173–1184, 2002.

[3] Wust P, Hildebrandt B, Sreenivasa G, et al., "Hyperthermia in combined treatment of cancer", The Lancest Oncology, 3(8), pp. 487–497, 2002.

[4] X. Yang, J. Du, Y. Liu, "Advances in hyperthermia technology", Engineering in Medicine and Biology 27th Annual Conference, September, 2005.

[5] P. Togni, J. Vrba, and L. Vannucci, "Microwave applicator for hyperthermia treatment on in vivo melanoma model", Med. Biol. Eng. Comput., 48, pp. 285–292, 2010.

[6] O. A. Arabe, P. F. Maccarini, E. L. Jones, G. Hanna, et al., "A 400 MHz hyperthermia system using rotating spiral antennas for uniform treatment of large superficial and sub-surface tumors", 2007.

[7] S. Kumar Pauvuluri, M. Ferenets, G. Goussetis, M. P. Y. Desmulliez, T. Tilford et al., "Encapsulation of Microelectronic Components Using Open-Ended Microwave Oven", IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 2, No. 5, May 2012.

[8] D. M. Pozar, "Microwave Engineering", Fourth Edition, chapter 6.3, p. 286, equation (6.40), 2012.

A.19 End of the Appendix