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# Microwave Amplifiers Design

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The purpose of this project was to design and construct amplifiers operating at microwave frequency of 1 GHz. Two amplifiers were to be constructed, transistor based amplifier with external matching circuits and Monolithic Microwave Integrated Circuit (MMIC) amplifier.

First step in this project was to select radio frequency transistor suitable for specified design targets. Design process was done by AWR microwave office software tool. The AWR microwave office was used to check the stability of amplifier, select operating point and design schematic and layout of the amplifier. The layout files generated by AWR microwave office were fed to the milling machine for the production of the actual amplifier circuit boards. The boards were finally tested using the network analyzer.

The results of the project were close to the specified design targets and it can be considered that the objective of the project was achieved. Both amplifiers give reasonable amplifications. Also, secondary goal of the project which was to familiarize using radio frequency equipment such as network analyzer was accomplished.

| | |
|---|---|
| Keywords | Amplifier, RF, Smith chart, gain, noise figure, stability, matching, MMIC, linearity, network analyzer |

**Contents**

# 1   Introduction

The aim of the project was to design and build two microwave amplifiers, one based on external matching circuits and second one based on internally matched Monolithic Microwave Integrated Circuit (MMIC) amplifier. The amplifiers were designed to operate at microwave frequency of 1 GHz. The target was to have a gain of at least 10 dB for the first amplifier and 20 dB for MMIC amplifier with noise figure of less than 3 dB for both amplifiers.

# 2   Overview of Amplifiers

Amplifier is an electronic device for increasing the amplitude of electrical signals. The amplifier is used to boost the voltage, current or power of an applied signal. Amplifiers are mainly used in broadcasting, wireless communications and audio equipment.
There are four basic types of amplifiers: the voltage amplifier, the current amplifier, the transconductance amplifier and the transresistance amplifier. The table 1 below summarizes gains of each type of amplifier.

Table 1. Gains of the four types of amplifiers

| Amplifier Type | Gain |
| --- | --- |
| Voltage | Voltage(out)/Voltage(in) |
| Current | Current(out)/Current(in) |
| Transconductance | Current(out)/Voltage(in) |
| Transresistance | Voltage(out)/Current(in) |

The gain of transconductance amplifier has unit of electric conductance which is siemens. The gain of transresistance amplifier is expressed in the unit of resistance, ohm.

## 2.1   Differential Amplifiers

Differential amplifier is one of the DC amplifiers which amplifies the difference between two input signal voltages. It is widely used in linear integrated circuits and is a fundamental component of many amplifiers like operational amplifiers and voltage comparators. The differential amplifier can be represented by a symbol shown in figure 1.
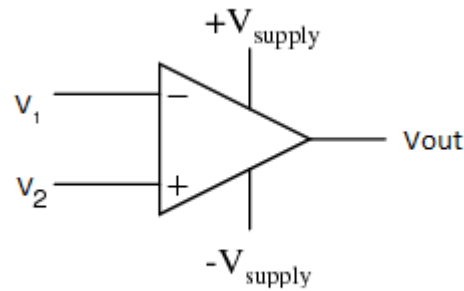
Figure 1. Symbol of differential amplifier

Gain of differential amplifier, $A_d$ is given as,

$$A_d = \frac{V_{out}}{V_2 - V_1} .$$

(1)

## 2.2 Operational Amplifiers

Operational amplifier (op-amp) is basically a differential amplifier modified by the addition of more stages to improve its performance and give it certain special features. Some of the features are high differential gain, high input impedance and low output impedance. An ideal operational amplifier has infinity voltage gain, infinity input impedance and zero output impedance. It is used to implement variety of linear and non-linear operation by connecting external elements such as resistors, capacitors and diodes. Block diagram of the operational amplifier is shown in figure 2.
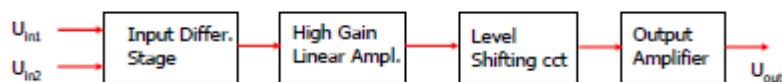


Figure 2. Block diagram of an op-Amp

Input stage is a differential amplifier. The second stage is high gain linear stage which is a multistage amplifier often using at least another differential amplifier. Level shifting stage is used to enable the output to be zero when the two inputs are equal to zero. Output stage is usually an emitter follower or a complementary symmetry configuration.

## 2.3 Power Amplifiers

Power amplifiers are large-signal amplifiers designed for good power gain. They are used in radio frequency and audio applications such as wireless communications, radar and television transmission. Power amplifiers are usually applied in the final stage of the radio frequency chain in telecommunication equipment to boost the radio signal before it is transmitted from the transmitter to the receiver. Figure 3 and figure 4 show simplified system block diagrams for receiver and transmitter systems.
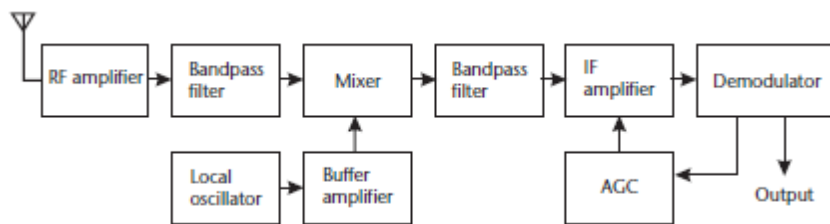


Figure 3. Block diagram for receiver system

Where AGC = Automatic Gain Control used to provide constant output signal.



Figure 4. Block diagram for transmitter system

Power amplifier stage shown in figure 4 is used to amplify the power of the carrier signal.

### 2.3.1 Classes of Power Amplifiers

Power amplifiers are classified into different classes of operations according to method of operation, efficiency and power output capability. There are several classes of power amplifiers including class A, class B, class AB and class C.

### 2.3.1.1 Class A Power Amplifiers

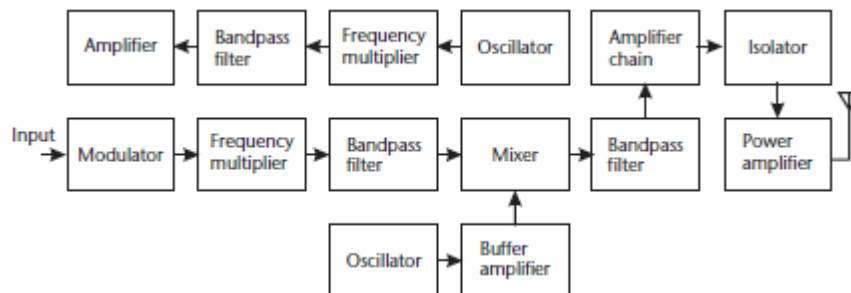Class A power amplifiers conduct for the entire cycle of the input signal (conduction angle of the transistor is 360°). The transistor operates in the linear region at all times and does not go into either saturation or cut-off. For maximum efficiency, quiescent point is centred. Efficiency of an ideal Class A power amplifier is 50%. Figure 5 shows operation of class A amplifier.
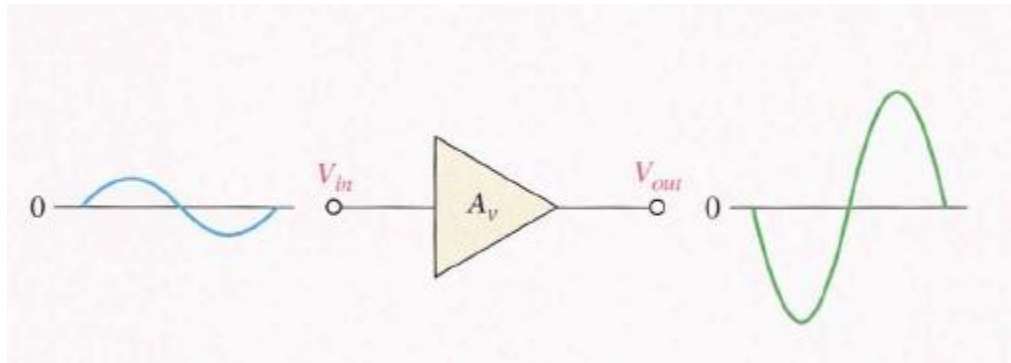


Figure 5. Basic class A amplifier operation [1, 428]

The maximum DC power of class A amplifier, $P_{DQ}$ is given as:

$$P_{DQ} = I_{CQ} * V_{CEQ} \, ,$$

(2)

where
$I_{CQ}$ = collector current when quiescent point is centred,
$V_{CEQ}$ = collector emitter voltage when quiescent point is centred.

### 2.3.1.2 Class B Power Amplifiers

Class B amplifiers conduct for only half of the cycle of the input signal (180°). The amplifier is biased at cut-off (DC current is zero). Class B amplifiers are more efficient than Class A amplifiers but it is difficult to get a linear reproduction of input waveform. Efficiency of an ideal Class B power amplifier is 78.5%. Class B amplifier operation is shown in figure 6.

Figure 6. Basic class B amplifier operation [1, 435]

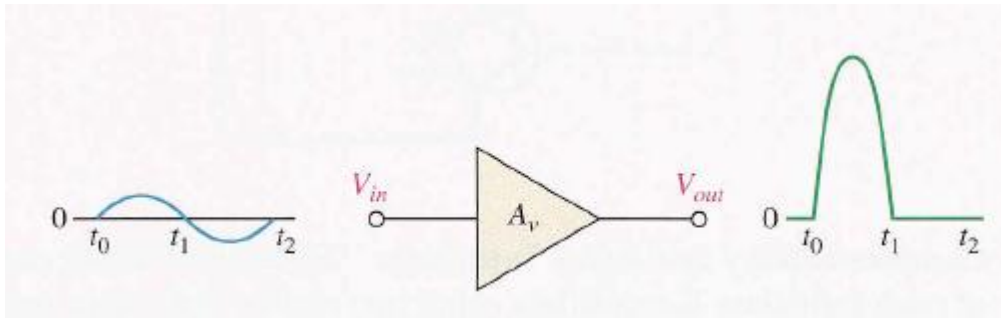In this class the transistor can be used as a switch.

2.3.1.3   Class AB Power Amplifiers

Class AB amplifiers conduct at an angle which is greater than 180° but less than 360°. Biasing is at nonzero DC current (above cut-off). Efficiency of an ideal Class AB power amplifier is between 50% and 78.5%. Class B and AB amplifiers are used as output stages of audio power amplifiers. Output signal of class B amplifier is shown in figure 7.



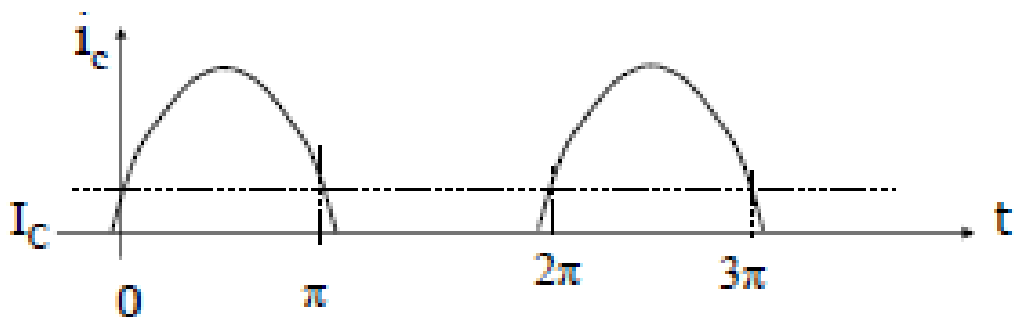Figure 7. Class AB power amplifier

When there is no input signal, transistors in class AB amplifiers must be biased slightly above cut-off to eliminate crossover distortion. The crossover distortion is common at the output stage of class B and AB amplifiers.

2.3.1.4   Class C Power Amplifiers

Class C amplifiers conduct at an angle which is less than 180°. Figure 8 shows basic operation of class C amplifier.
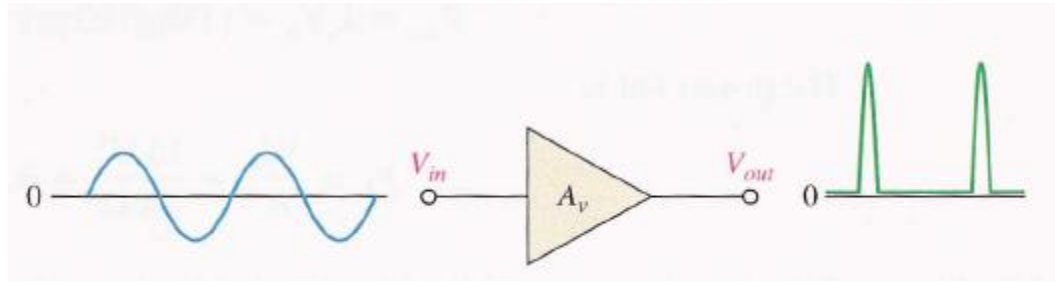
Figure 8. Basic Class C power amplifier operation [1, 448]

The efficiency of Class C amplifier is much better than either the Class B or the Class A and it can approach 85%.

### 2.3.2 Microwave Power Amplifiers

Microwave power amplifiers are amplifiers which are used at microwave frequencies. Microwaves are electromagnetic waves with frequency range of 300 MHz to 300 GHz in the electromagnetic spectrum. The microwaves have relatively short wavelengths hence their name. From frequency range of 300 MHz to 3 GHz the microwaves are designated as ultra high frequency (UHF), 3 GHz to 30 GHz are super high frequency (SHF) and 30 GHz to 300 GHz are described as extra high frequency (EHF). One advantage of microwaves is that few repeaters are needed for amplification. Microwave amplifiers are constructed with either bipolar junction transistors (BJTs) or Field-effect transistors (FETs) where class A amplifiers are used.

### 2.3.3 Monolithic Power Amplifiers

Monolithic Microwave Integrated Circuit (MMIC) is a type of integrated circuit (IC) device in which all active and passive circuit elements are fabricated on the same semiconductor substrate, such as gallium arsenide (GaAs). Other materials which can be used as substrates are alumina, ferrite and beryllium. Ideal substrates have high dielectric constant, high purity and constant thickness, low dissipation factor or loss tangent and high thermal conductivity [2, 498]. The device operates at microwave frequency range of 300 MHz to 300 GHz.

Performance of MMICs can be improved by using surface-mount device (SMD) instead of through-hole components especially at higher frequencies. Monolithic circuits use both distributed and lumped matching elements.

2.3.3.1 Advantages and Disadvantages of Monolithic Power Amplifiers

Advantages of MMICs include low cost of production, small size and light weight, elimination of circuit tweaking, reliability, good reproducibility, broadband performance and mass production capability [3, 359].

Disadvantages include limited choice of components and the circuit must be made as small as possible.

2.3.3.2 Applications of Monolithic Power Amplifiers

Monolithic Microwave Integrated Circuits (MMICs) have variety of applications including military, space and civil. Table 2 shows the major applications of MMICs.

Table 2. Applications of MMICs [4, 11]

| Military | Space | Civil |
|---|---|---|
| Phased-array radar | Communications satellites | Satellite television receive only (TVRO) |
| Electronic warfare | Synthetic aperture | VSAT earth terminals |
| | | Mobile phones |
| Smart munitions | Radiometers | Line-of-sight (LOS) communications |
| Synthetic aperture radar | Astronomy | Wireless local area networks (LANs) |
| Decoys | Low earth orbit mobile systems | Fibre-optic systems |
| | | Global positioning system (GPS) |
| Passive millimetre-wave imaging | Steerable phased-array antennas | Smart cards |
| | | Bluetooth and similar wireless systems |
| Altimeters | Remote sensing | High speed internet access |
| | | Autonomous cruise control |

| Instrumentation | | Search and rescue trans-ponders |
| | | Automatic tolling |
| Remote sensing | | Security scanners |
| | | RFID and tagging |
| | | Medical systems |

Where

VSAT = Very Small Aperture Terminal,

RFID = Radio Frequency Identification.

## 3 Transistor DC Bias Circuit

The first step in the design of amplifier was to choose a transistor which meets specified design targets. Several transistors were assessed and BFP182W was chosen. BFP182 is an NPN Silicon RF Transistor for low noise and high-gain broadband amplifiers. For Monolithic Microwave Integrated Circuit (MMIC) amplifier design MAR-8ASM+ was chosen. The MAR-8ASM+ is a wideband amplifier offering high dynamic range.

### 3.1 Safe Operating Area (SOAR)

Safe Operating Area is a region of operation of a transistor which ensures that maximum transistor ratings are not exceeded. For the transistor to operate without burning out, there are maximum limits for collector-emitter voltage ($V_{CE(max)}$) and collector current ($I_{c(max)}$). The safe operating area is also known as active or linear region. The operation of the transistor has to be within the safe operating area (SOAR). The safe operating region of the transistor can be shown graphically in figure 9.
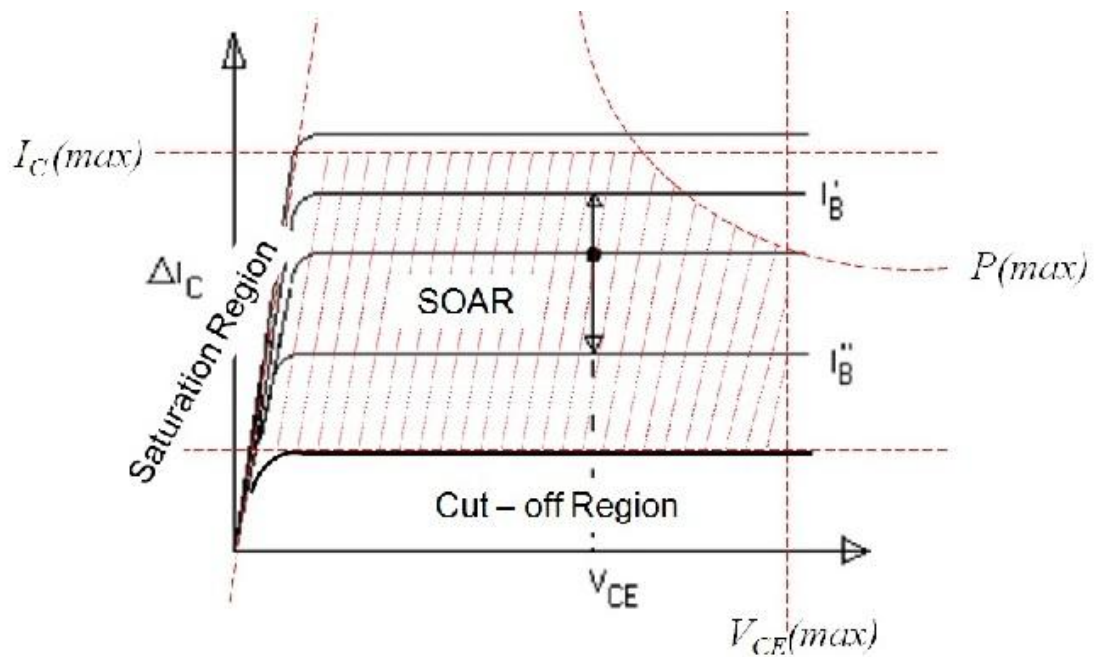
Figure 9. Safe operating region of the transistor.

Maximum power, P(max) can be calculated as,

$$P_{max} = I_{c(max)} * V_{CE(max)}.$$  (3)

## 3.2  Bias Circuit

In order to operate as an amplifier, a transistor must be properly biased to avoid signal distortion. Proper biasing and selection of DC operating point or quiescent point (Q-point) ensures that transistor operates in its active or linear region. Since DC biasing also alters AC parameters of the transistor, transistor biasing has to maintain the chosen operating point to minimize changes in the AC parameters. As long as the transistor is operated in the linear region, the output is a linear reproduction of the input. Another important purpose of transistor biasing is to prevent thermal runaway, where an increase in collector current causes increase in power dissipation and hence the transistor temperature. Thermal runaway can lead to destruction of the transistor.

In this project the design was based on Class A operation where the transistor operates in the active linear region all the time. Nonlinearity causes distortion of signals. Figure 10 illustrates the bias circuit used in the design.
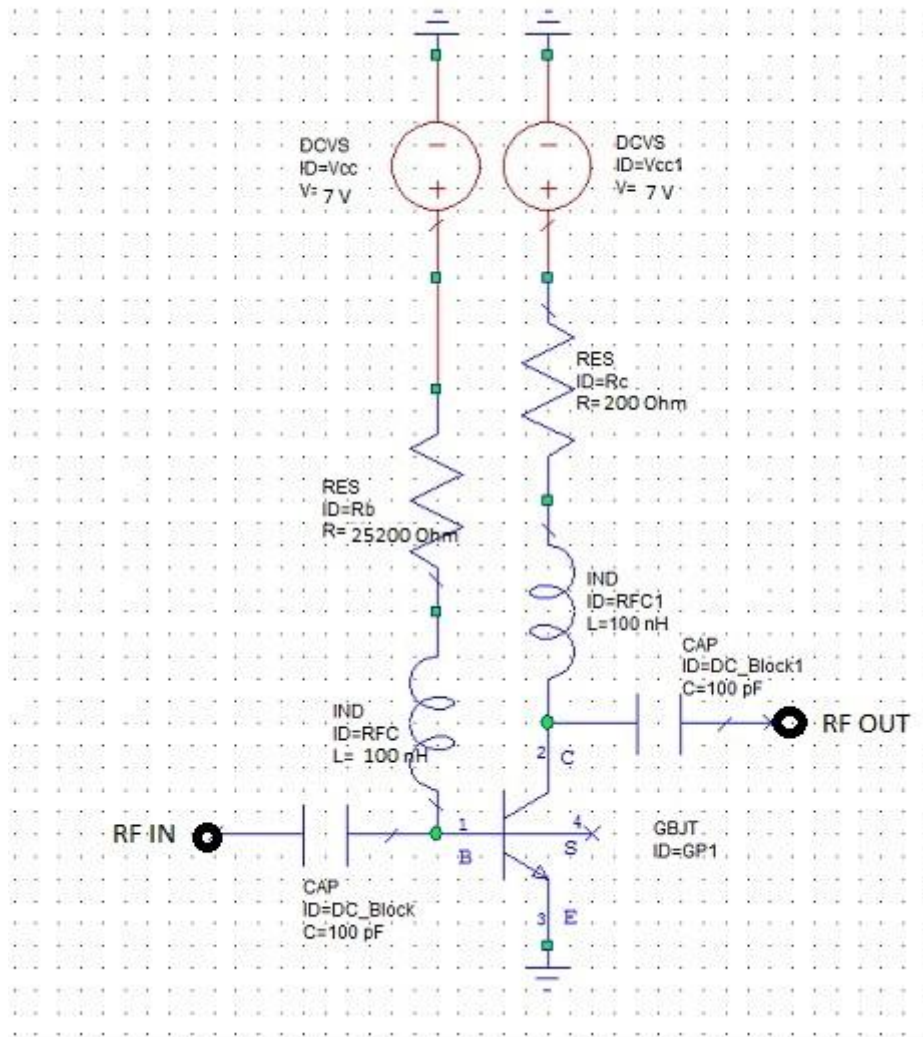
Figure 10. DC bias circuit of a transistor

$$V_{CC} = I_C R_C + V_{CE} \ , \tag{4}$$

$$V_{CC} = I_B R_B + V_{BE}, \tag{5}$$

$$I_B = \frac{I_C}{\beta} \ , \tag{6}$$

where

$V_{CC}$ = supply voltage,

$I_c$ = collector current,

$V_{CE}$ = collector-emitter voltage,

$I_B$ = base current,

$V_{BE}$ = base-emitter voltage,

β= DC current gain.

Radio Frequency Choke (RFC) inductors are fixed inductors intended to block higher-frequency alternating currents (AC), while allowing lower frequency or DC current to pass [5]. DC block capacitors are needed to block DC component of the signal. When the circuit is analyzed both the DC grounds and DC voltage supply lines are connected to ground, since they both are small signal grounds for the RF signal.

For MAR-8ASM+ amplifier design recommended bias circuit is shown in figure 11.



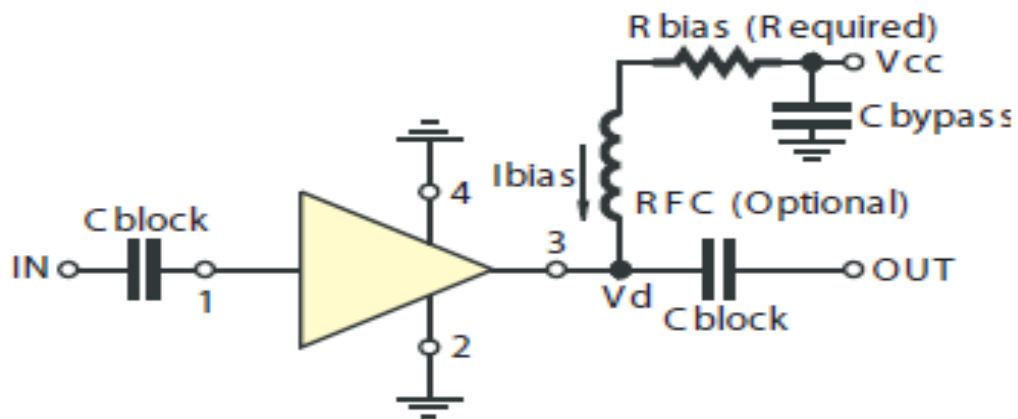Figure 11. Recommended application circuit for MAR-8ASM+ amplifier

Bypass capacitor is used to bypass AC signal to the ground to avoid self oscillations of the MMIC and to avoid possible noise to enter in the MMIC.

## 3.3   Selection of DC Operating point

Current-voltage (IV) curves of the transistor were generated using AWR microwave office. From figure 12 operating point was determined to be $V_{CE}$=2V and $I_C$=25mA.
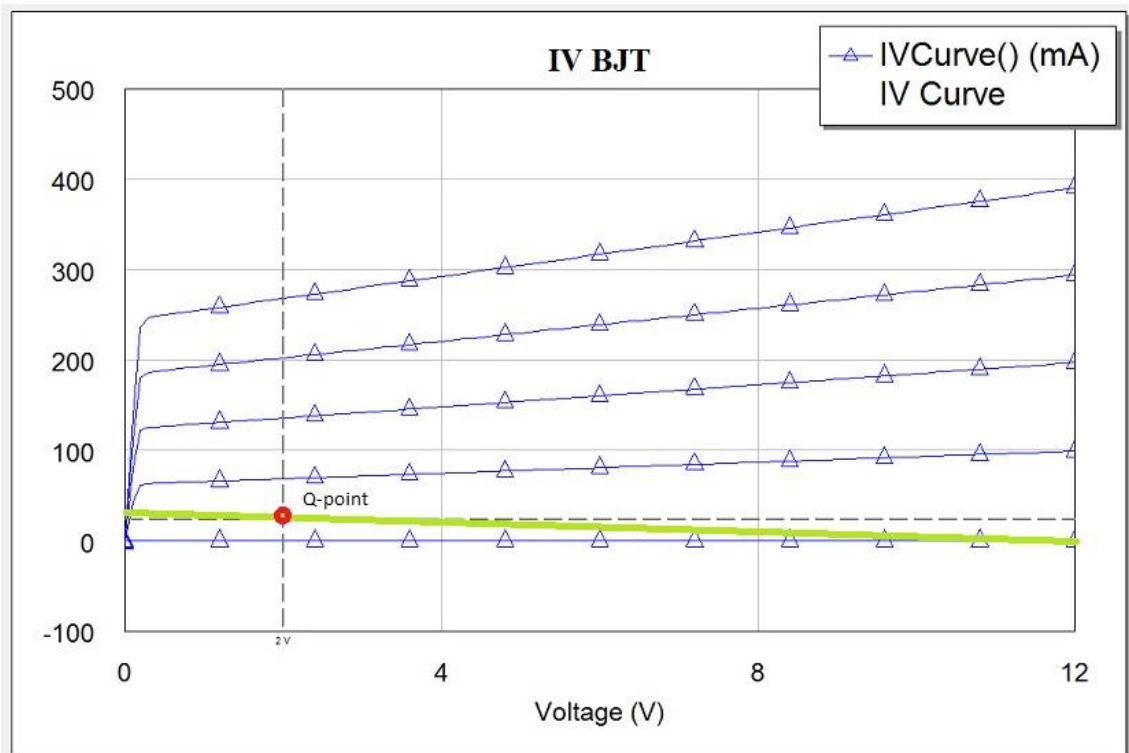
Figure 12. IV plot for a BFP182W BJT

Operating point chosen is within safe operating area of the transistor.

## 4    Smith Chart and Scattering Parameters

4.1    Smith Chart

Smith chart is a graphic tool used for solving transmission line and matching circuit problems. Smith charts can be used for amplifier design, stability circles, gain circles, noise circles, matching network design, impedance and admittance determination and finding reflection coefficients and voltage standing wave ratios (VSWR) [6, 88]. Figure 13 shows the Smith chart.
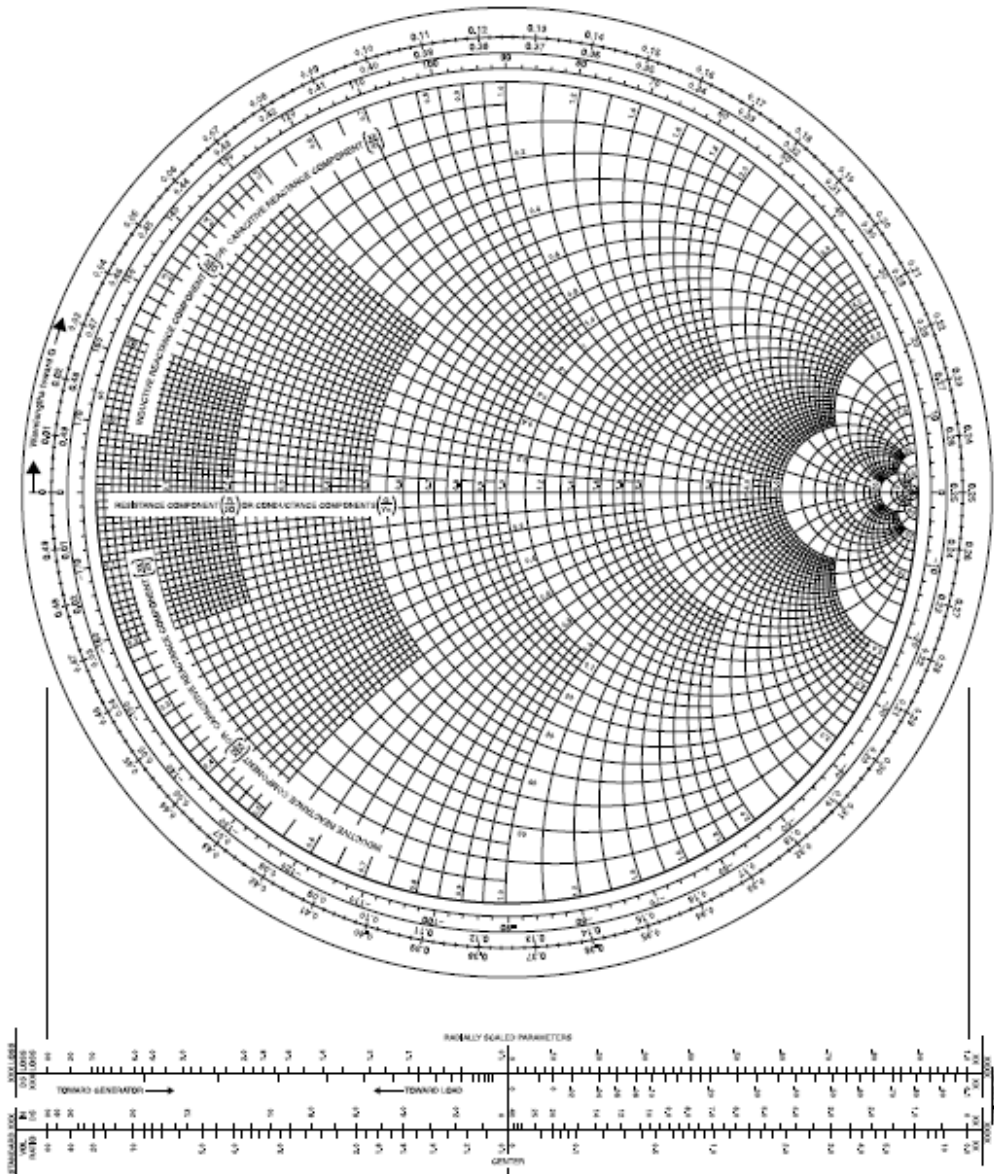
Figure 13. Smith chart.

In this project the Smith chart was used for checking the stability of amplifier and matching of input and output circuits.

## 4.2 Scattering Parameters

Scattering parameters (S-parameters) are used for circuit and system design of many items such as amplifiers, filters, matching networks and monolithic microwave inte-grated circuits [6, 88]. Scattering method is among the methods of describing the be-haviour of a two port network in terms of incident and reflected waves. Unlike Z,Y or

ABCD parameters, the values of s parameters depend not only upon the properties of the transistor but also upon the source and the load circuits used to measure them [7, 413]. Consider figure 14 below which represents a scattering parameter two port network.
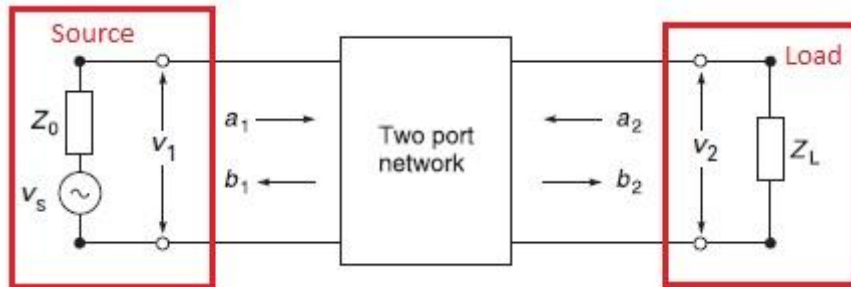


Figure 14.  Two port scattering network

$a_1$ and $a_2$ represent incident voltage waves,

$b_1$ and $b_2$ represent reflected voltage waves.

The incident and reflected voltage waves are related by the following equations:

$$b_1 = s_{11}a_1 + s_{12}a_2 \tag{7}$$

and

$$b_2 = s_{21}a_1 + s_{22}a_2 , \tag{8}$$

where

$s_{11}, s_{12}, s_{21} \text{ and } s_{22}$ are the S-parameters.

Scattering matrix from equation (7) and equation (8) can be written as,

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} . \tag{9}$$

Scattering matrix is always a square matrix.

If the input and output are connected to impedance of 50 Ω, input reflection coefficient $\rho_{in} = s_{11}$, output reflection coefficient $\rho_{out} = s_{22}$, power gain, $G = S_{21}$ and $\frac{1}{G} = S_{12}$.

Basic gain of an amplifier, G in a 50 Ω system without tuning can be calculated as follows:

$$G = 20\log\ |S_{21}|. \tag{10}$$

From table 3 in chapter 5, at frequency of 1 GHz, $S_{21}$= 4.599 then basic gain, G in dB is,

$$G = 20\log\ 4.599 = 13.25\ dB.$$

The S-parameters are used in microwave since other parameters like H, Z, Y and ABCD parameters are only useful at low frequencies.

## 5  Stability Analysis

To avoid possible oscillation of amplifier circuit, unconditional stability of amplifier must be ensured. Unconditional stability means that the amplifier remains stable for any passive source and load at the operating frequency. Two ways can be used to determine the stability of amplifier, K-Δ test or Rollet's condition test and stability circles.

### 5.1  K-Δ Test

A two-port network is said to be unconditionally stable if Rollet's condition,

$$K = \frac{1-|S_{11}|^2-|S_{22}|^2+|\Delta|^2}{2|S_{12}S_{21}|} > 1 \tag{11}$$

and

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1 \tag{12}$$

are satisfied.
Where
K = stability factor
Δ = determinant of the scattering matrix

Using scattering parameters for BFP182W transistor given in table 3, at operating frequency of 1 GHz, stability factor, K is 1.36 and determinant of the scattering matrix, Δ is 0.396. Since K>1 and Δ<1, the device is unconditionally stable.

Table 3. S-parameters of transistor BFP182W

```
! SIEMENS Small Signal Semiconductors
! BFP182W
! Si NPN RF Bipolar Junction Transistor in SOT343
! VCE = 2 V      IC = 25 mA
! Common Emitter S-Parameters:                      April 1994
# GHz  S  MA  R  50
!  f           S11              S21             S12             S22
! GHz    MAG    ANG      MAG    ANG      MAG    ANG      MAG    ANG
 0.010 0.4158  -10.4   33.968  174.8   0.0017  80.5   0.8920   -2.5
 0.020 0.4181  -20.9   33.698  171.4   0.0036  75.9   0.8872   -5.6
 0.030 0.4254  -30.7   33.513  167.2   0.0053  80.6   0.8770   -8.5
 0.050 0.4393  -49.0   32.062  158.9   0.0081  71.5   0.8476  -14.0
 0.100 0.4865  -84.8   27.487  142.0   0.0139  60.9   0.7445  -24.1
 0.150 0.5225 -108.5   22.901  129.2   0.0176  52.5   0.6443  -30.1
 0.200 0.5472 -124.5   19.113  120.4   0.0198  49.5   0.5664  -32.9
 0.250 0.5647 -135.1   16.276  113.8   0.0217  47.7   0.5103  -34.2
 0.300 0.5724 -143.1   13.992  108.8   0.0233  46.2   0.4678  -34.6
 0.400 0.5843 -154.4   10.932  101.2   0.0256  46.7   0.4156  -34.3
 0.500 0.5938 -162.3    8.935   95.7   0.0284  48.8   0.3861  -33.8
 0.600 0.5966 -167.9    7.526   91.3   0.0306  50.3   0.3681  -33.6
 0.700 0.6044 -172.8    6.535   87.7   0.0331  51.9   0.3567  -33.8
 0.800 0.6003 -176.5    5.717   84.4   0.0362  53.5   0.3488  -34.3
 0.900 0.6026 -179.9    5.106   81.5   0.0387  54.7   0.3436  -35.1
 1.000 0.6051  177.3    4.599   78.9   0.0415  56.4   0.3405  -36.1
 1.100 0.6117  174.6    4.203   76.3   0.0446  57.0   0.3378  -37.3
 1.200 0.6117  171.9    3.853   73.8   0.0476  57.9   0.3362  -38.5
 1.300 0.6131  169.6    3.565   71.3   0.0507  58.5   0.3355  -39.9
 1.400 0.6157  167.4    3.318   69.1   0.0539  59.2   0.3351  -41.5
 1.500 0.6168  165.4    3.102   66.9   0.0570  59.7   0.3347  -43.0
 1.600 0.6212  163.2    2.916   64.6   0.0600  59.7   0.3353  -44.7
 1.700 0.6235  161.0    2.750   62.5   0.0631  60.2   0.3352  -46.3
 1.800 0.6264  159.1    2.598   60.4   0.0667  60.1   0.3354  -48.1
 1.900 0.6247  157.0    2.459   58.2   0.0697  60.4   0.3364  -49.8
 2.000 0.6284  155.2    2.341   56.3   0.0730  60.4   0.3369  -51.6
 2.200 0.6344  151.7    2.136   52.3   0.0793  60.0   0.3382  -55.3
 2.400 0.6383  148.2    1.960   48.4   0.0858  59.8   0.3392  -59.2
 2.600 0.6440  144.7    1.816   44.5   0.0925  59.1   0.3411  -63.1
 2.800 0.6518  141.4    1.685   40.9   0.0992  58.5   0.3425  -67.3
 3.000 0.6617  138.2    1.574   37.3   0.1058  57.7   0.3440  -71.5
 3.200 0.6681  135.1    1.480   33.6   0.1125  56.9   0.3461  -75.9
 3.400 0.6799  131.7    1.392   30.0   0.1196  56.0   0.3491  -80.4
 3.600 0.6872  129.0    1.317   26.8   0.1261  55.1   0.3516  -84.9
 3.800 0.6942  125.8    1.240   23.3   0.1323  53.8   0.3540  -89.8
 4.000 0.7044  123.6    1.178   20.1   0.1395  52.9   0.3583  -94.7
 4.500 0.7206  117.7    1.040   12.1   0.1564  49.9   0.3743 -106.9
 5.000 0.7307  112.5    0.919    5.4   0.1733  46.9   0.3962 -118.4
 5.500 0.7400  108.5    0.824   -0.9   0.1897  43.7   0.4206 -128.2
 6.000 0.7451  104.3    0.746   -6.5   0.2064  41.0   0.4488 -136.7
!
! SIEMENS AG  Semiconductor Group, Munich
```

The blue line shows the scattering parameters at operating frequency of 1 GHz.

5.2   Stability Circles

For a transistor to be unconditionally stable, both input and output stability circles must be completely outside the Smith chart.

Using AWR microwave office stability circles were plotted to check stability at the operating frequency of 1 GHz using the frequency sweep of 0.6 GHz to 1.4 GHz. The resulted plot satisfies condition of unconditional stability as shown in figure 15.
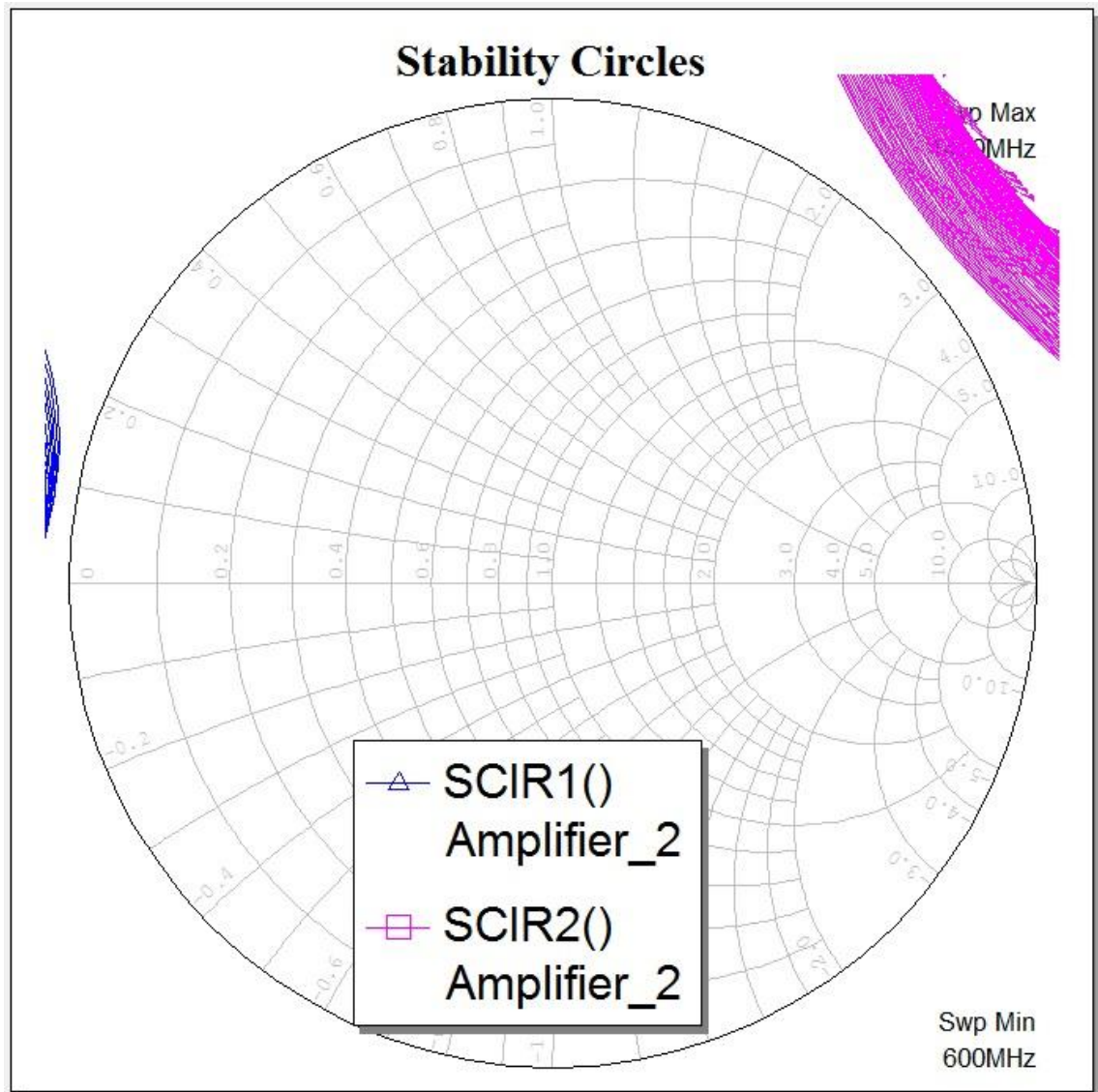


Figure 15. Stability circles

Where
SCIR1 = input stability circles,
SCIR2 = output stability circles.

# 6  Impedance Matching of Amplifier

In order for the maximum power to be delivered by a transistor, the input and output impedances of the transistor must be matched. Matching also is used to maximize signal-to-noise ratio in input stages of receivers and minimize signal distortion in transmission lines. Matching basically eliminates the reflecting wave. Selective mismatching can be used to reduce gain to the desired value. There are three basic types of matching.

## 6.1  Transmission Line Matching

In transmission line matching, matching is achieved by using a transmission line (stub) of a required length and characteristic impedance connected either in parallel or in series with the transmission feed line.

## 6.2  Transformer Matching

Matching is achieved by using RF transformers to produce very wideband impedance matching. For narrow band impedance matching, single-section transformer is enough. In transformer matching only real load impedance can be matched.

## 6.3  Lumped Elements Matching (L-Networks)

Inductors and capacitors are used to effect the impedance matching. Lumped elements matching networks are normally used by the manufacturers to determine the input and output impedance of the devices. Two ways can be used for L-Network matching, analytical method and Smith chart method. The Smith chart method was used in this project for the input and output matching of the transistor. Figure 16 shows input and output matching networks of transistor BFP182W at frequency of 1 GHz.
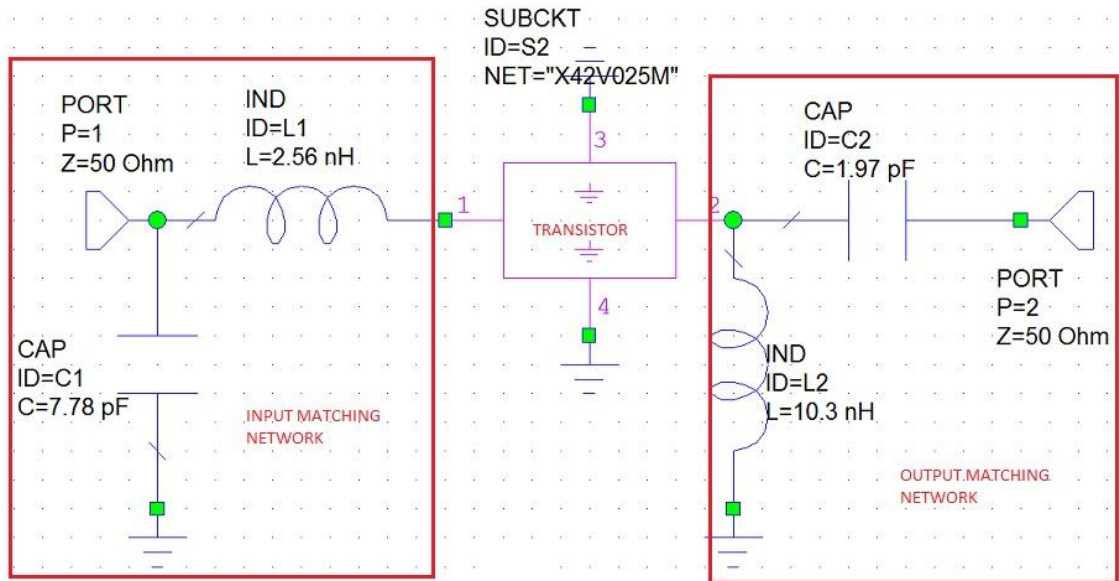
Figure 16. Input and output matching networks

Inductors and capacitors are tuned to the correct values to find the centre of the Smith chart. The Smith chart for the matching networks is given in figure 17.
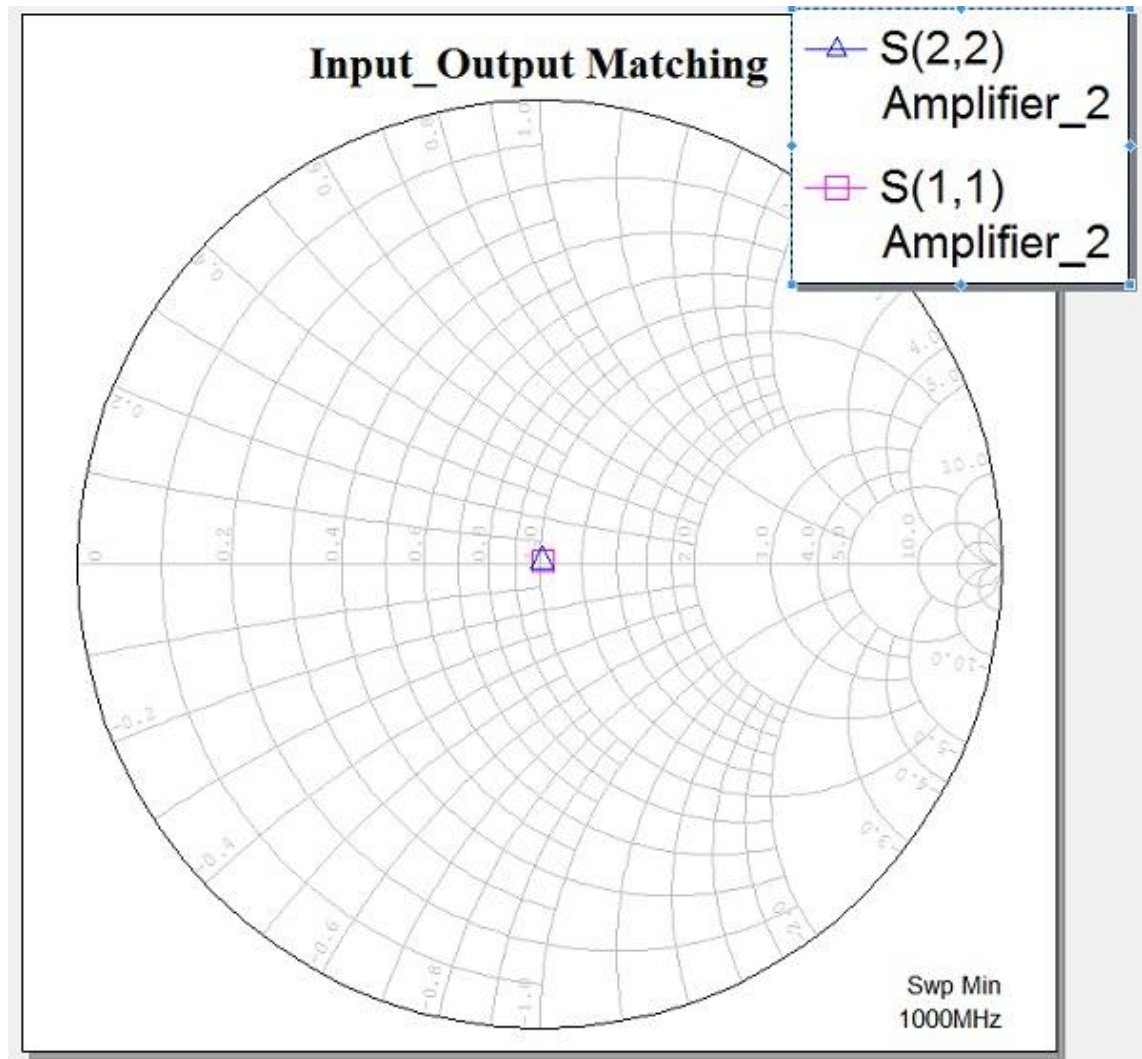
Figure 17. Smith chart for the matching networks

Where

S (1, 1) = input reflection coefficient

S(2, 2) = output reflection coefficient

## 7   Gain, Noise and Linearity

Main parameters in microwave amplifier design are power gain, noise figure and linearity. In this project the designed amplifier should have high gain, low noise figure and linear operation at operating frequency of 1 GHz.

## 7.1 Power Gain

Power gain of an amplifier is the ratio of an output power delivered to the load by the amplifier to an input power from the source [8, 747]. Maximum power gain is obtained when the input is matched to the source impedance and the load is matched to the amplifier's output impedance.

Power gain, G is expressed as,

$$G = \frac{P_{out}}{P_{in}} ,$$ (13)

where

$P_{out}$ = power delivered to the load by the amplifier,

$P_{in}$ = power input from the source.

## 7.1.1 Maximum Available Gain

Maximum available gain ($G_{MAX}$) is the ratio of available power from amplifier to the input power. It is obtained when an amplifier is conjugately matched. The maximum available gain is calculated as shown below:

$$G_{MAX} = 10\log \frac{|S_{21}|}{|S_{12}|} + 10\log |K \pm \sqrt{(K^2 - 1)},$$ (14)

where

$G_{MAX}$ = maximum available gain in dB,

K = stability factor.

The sign used before the radical (+ or -) in equation (14) is determined by the polarity of a factor called $B_1$ which is calculated as,

$$B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 ,$$ (15)

where

Δ = determinant of the scattering matrix.

If $B_1$ is positive, the negative sign is used and if it is negative, the positive sign is used.

Using the scattering parameters of the transistor BFP182W given in figure 15 in chapter 5 and the calculated values of K and Δ in chapter 5 above, maximum available gain at 1 GHz is 16.9 dB. For MAR-8ASM+ amplifier, typical maximum available gain at 1 GHz is 25 dB.

### 7.1.2 Transducer Gain

Transducer gain ($G_T$) is the ratio of power delivered to the load to the power available from source including the effects of input and output matching. It is the actual gain of an amplifier.

The transducer gain is calculated as follows:

$$G_T = \frac{|S_{21}|(1-|\rho_S|^2)(1-|\rho_L|^2)}{|(1-S_{11}\rho_S)(1-S_{22}\rho_L)-S_{12}S_{21}\rho_L\rho_S|^2} \ , \tag{16}$$

where

$\rho_s$ = source reflection coefficient,

$\rho_L$ = load reflection coefficient.

### 7.2 Noise Figure

Noise figure of a device is the measure of the degradation in the signal to noise ratio as a signal passes through the device. The noise figure, NF in dB is calculated as,

$$NF = F_{min} + \frac{4R_n}{Z_0} \frac{|\rho_S - \rho_{opt}|^2}{(1-|\rho_S|^2)|1+\rho_{opt}|^2} \ , \tag{17}$$

where

$F_{min}$ = minimum noise figure,

$\rho_{opt}$ = optimum source reflection coefficient,

$\rho_s$ = source reflection coefficient,

$R_n$ = equivalent noise resistance,

$Z_0$ = characteristic impedance of a system.

Thermal noise or Johnson–Nyquist noise is a most common source of noise in amplifiers and its power level is proportional to absolute temperature. Thermal noise is basi-

cally caused by the fluctuation of resistance in the device. Power spectral density of thermal noise does not depend on frequency over much of the electromagnetic spectrum. Voltage and current noise sources can both be used to represent the thermal noise of a resistor as follows,

$$e_n{}^2 = 4kTR\Delta f \quad , \tag{18}$$

$$i_n{}^2 = \frac{4kT\Delta f}{R}, \tag{19}$$

where

$e_n$ = voltage fluctuation,

$i_n$ = current fluctuation,

k = Boltzmann constant,

T = room temperature in Kelvin,

R = resistance of a resistor,

Δf = bandwidth in which noise source is acting.

## 7.3   Linearity

As long as the transistor is operated in the linear region, the output is a linear reproduction of the input. Nonlinearity is the main cause of signal distortion in radio frequency and microwave circuits. Other effects of nonlinearity are gain reduction in an amplifier, modulation transfer from one signal to another, phase shift caused by amplitude variation and generation of multiples of a fundamental signal.

## 8   Microstrip Transmission Lines

Microstrip transmission line is type of electrical transmission line which can be fabricated using printed circuit board technology, and is used to convey microwave-frequency signals [9]. It is necessary to connect two microwave circuit components using a microstrip transmission line.

8.1    Characteristic Impedance of Microstrip Lines

Characteristic impedance of a microstrip line depends on width and thickness of the line, distance between the line and the ground plane and the dielectric constant of the board material. Consider figure 18 which shows the microstrip line.
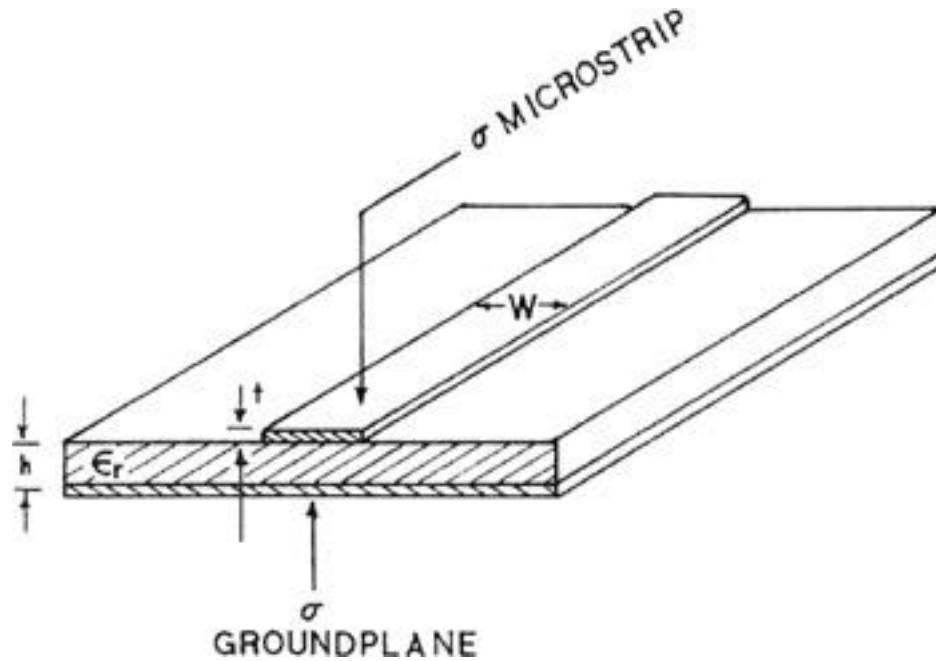


Figure 18. Microstrip line

Characteristic impedance $Z_0$ can be expressed as follows:
when w/t ≤ 1,

$$Z_0 \cong \frac{60}{\sqrt{\varepsilon_{eff}}} \ln\left(\frac{8t}{w} + \frac{w}{4t}\right) , \qquad (20)$$

$$\varepsilon_{eff} \cong \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\frac{t}{w}}} + 0.04\left(1 - \frac{w}{t}\right)^2\right] , \qquad (21)$$

when w/t ≥ 1,

$$Z_0 \cong \frac{377}{\sqrt{(\varepsilon_{eff})}\left[\frac{w}{t}+1.393+0.667\ln\left(\frac{w}{t}+1.444\right)\right]} , \qquad (22)$$

$$\varepsilon_{eff} \cong \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12\frac{t}{w}}} , \qquad (23)$$

where

w = width of the microstrip line,

t = thickness of the microstrip line,

$\varepsilon_{\text{eff}}$ = effective relative dielectric constant of the board material,

$\varepsilon_r$ = relative dielectric constant of the board material.

## 8.2 Losses in Microstrip Lines

There are three types of losses which occur in microstrip lines, conductor losses, dielectric losses and radiation losses.

## 8.2.1 Conductor Losses

Nonperfect conductors are the most common source of losses in microstrip lines at microwave frequencies. Conducting attenuation constant or conductor loss constant of a microstrip line, $\alpha_c$ is expressed as,

$$\alpha_c = \frac{R_s}{Z_0 w} \quad [\text{dB/cm}], \tag{24}$$

where

$R_s$ = surface skin resistance and is given as $R_s = \sqrt{\dfrac{\omega \mu_0}{2\sigma_m}}$ [$\Omega$/square],

$\sigma_m$ = conductivity,

$\mu_0$ = permeability of free space,

$\omega$ = angular velocity.

Conductor thickness, h must be,

$$h > 2\delta_s = 2\sqrt{\frac{2}{\omega \mu \sigma_m}} \quad , \tag{25}$$

where $\delta_s$ = skin depth.

### 8.2.2  Dielectric Losses

Dielectric loss occurs when the conductivity of a dielectric causes the electric and magnetic fields in the dielectric to be out of time phase [2, 478]. Dielectric loss constant, $\alpha_d$ is expressed as,

$$\alpha_d = \pi \frac{\varepsilon_r(\varepsilon_{eff}-1)tan\delta}{\sqrt{\varepsilon_{eff}}(\varepsilon_r-1)\lambda_0} \quad \text{[dB/cm]}, \tag{26}$$

where

$\tan\delta$ = dielectric loss tangent for the substrate,

$\lambda_0$ = wavelength in free space.

### 8.2.3  Radiation Losses

Radiation loss depends on thickness and dielectric constant of the substrate. Radiation increases with increasing frequency and can be reduced by the use of high dielectric and thin materials.

## 9   Amplifier Design

The whole amplifier design procedure was mainly guided by two books, *Microwave Engineering* by David M. Pozar [10] and *Microwave Circuit Design Using Linear and Nonlinear Techniques* by G.D. Vendelin, A.M. Pavio, & U.L. Rohde [11].

### 9.1   Monolithic Microwave Integrated Circuit (MMIC) Amplifier Design

The first step in MMIC amplifier design was to choose monolithic amplifier and MAR-8ASM+ was chosen. Since the MAR-8ASM+ is internally matched to 50 Ohms, there was no need to do matching in this design. Biasing circuit used is shown in figure 11 in chapter 3 above. The whole design process from schematic to layout design was done by AWR microwave office design software. The AWR microwave office is the software solution for designers of all types of RF and microwave circuits. The schematic was

first designed without microstrip lines and then the microstrip lines were added as shown in figure 19 and figure 20.
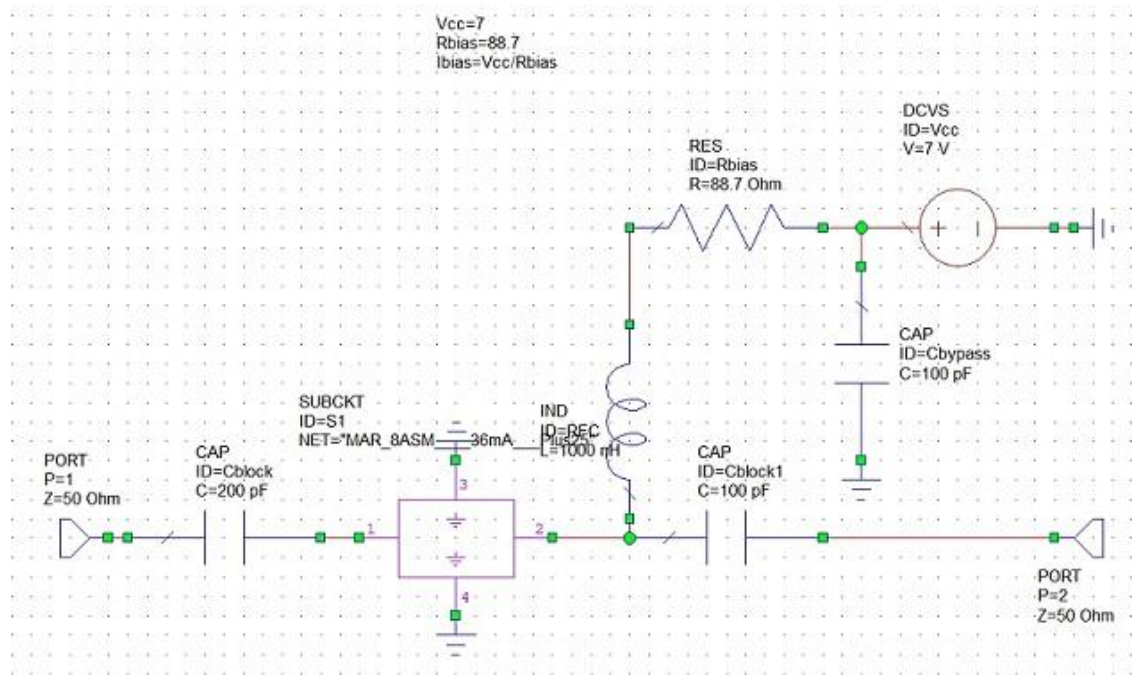


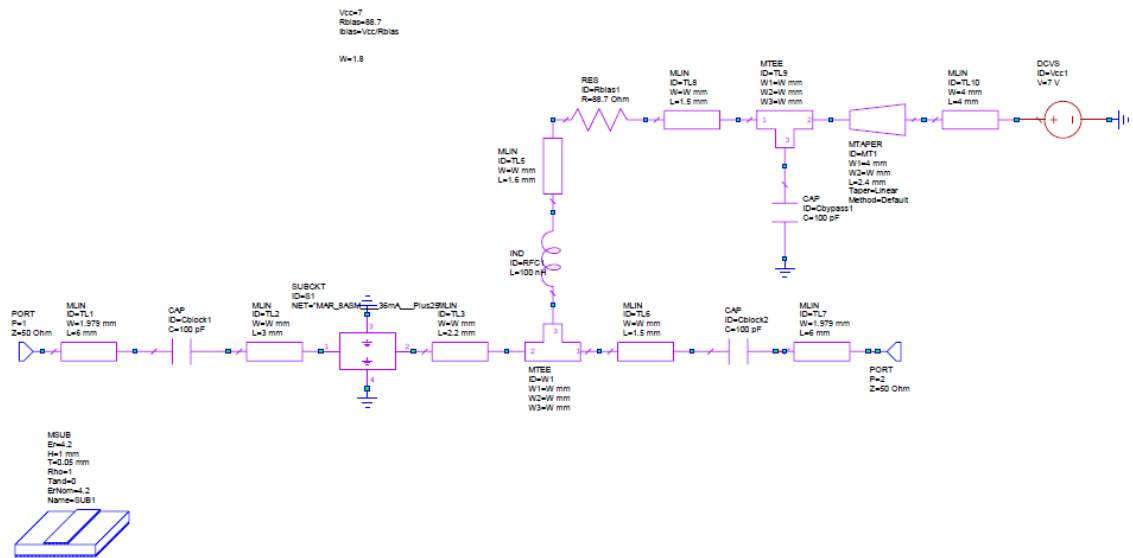Figure 19. MAR-8ASM+ amplifier schematic design without microstrip lines



Figure 20. MAR-8ASM+ amplifier schematic design with microstrip lines

Gain of the designed MAR-8ASM+ amplifier at 1 GHz was found to be 23.845 dB which is 1.155 dB lower that the typical gain of 25 dB given in its datasheet. The gain graph is shown in figure 21.
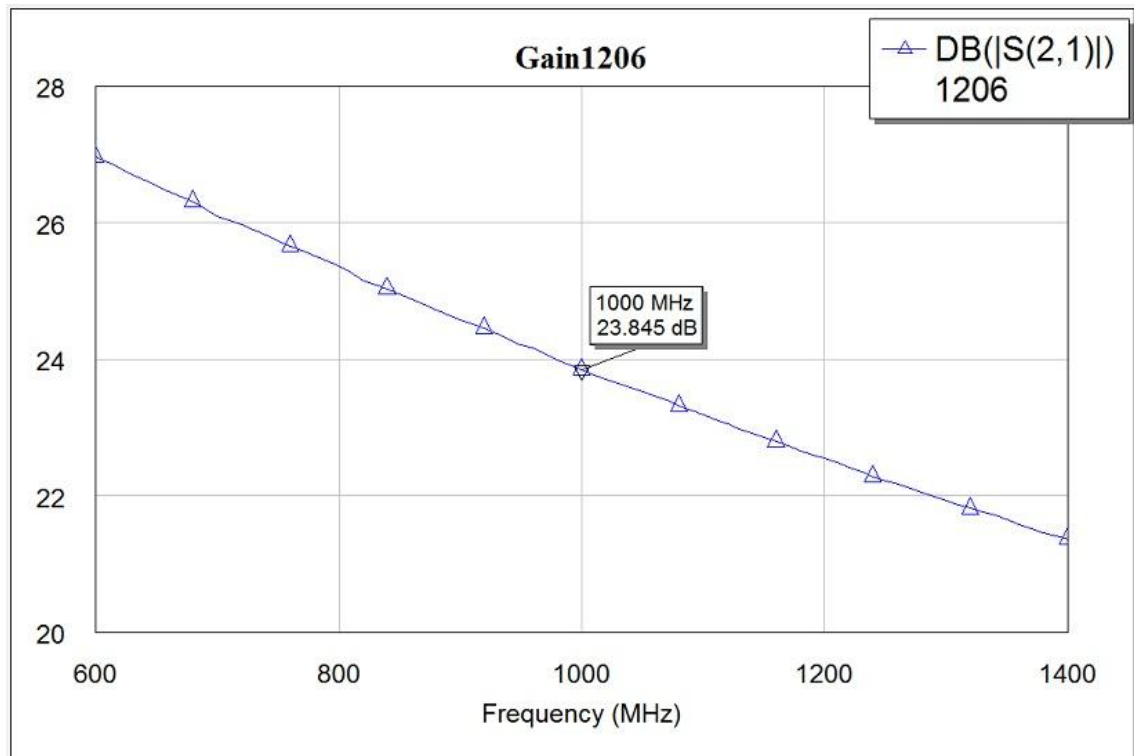
Figure 21. Gain of MAR-8ASM+ amplifier

Noise figure of the MAR-8ASM+ amplifier at 1 GHz is 0.004644 dB as shown in figure 22. This noise figure is in acceptable level as it is below the 3.1 dB noise figure specified in the MAR-8ASM+ datasheet.
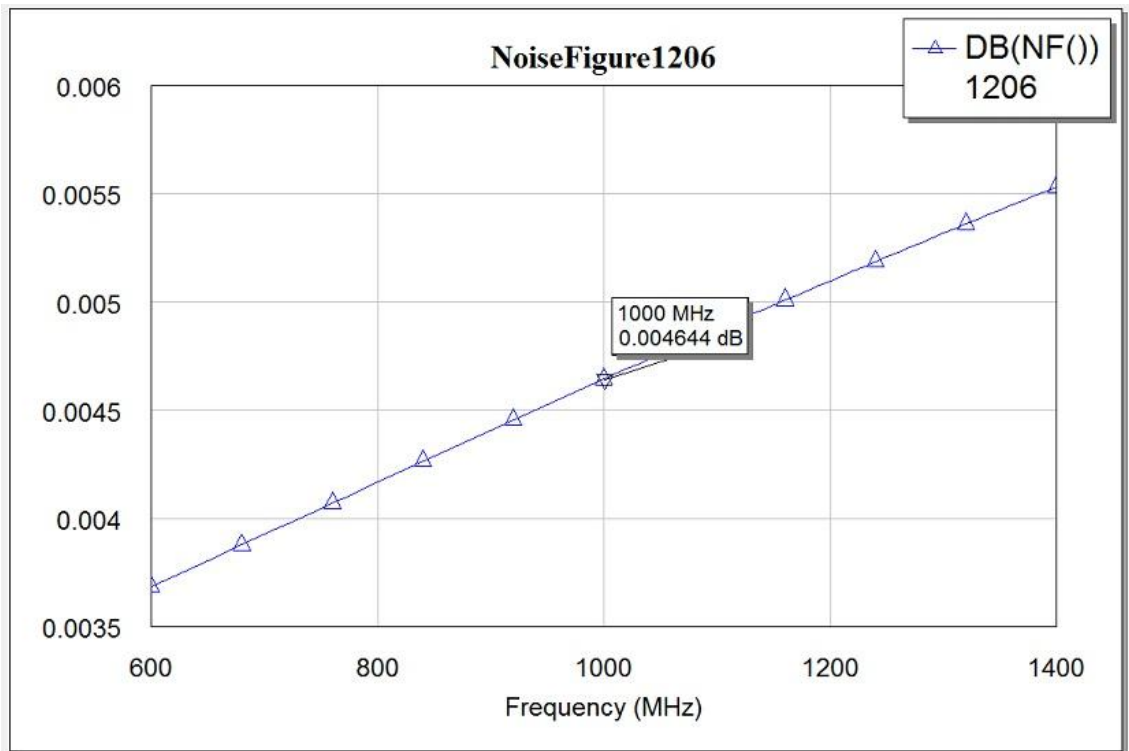
Figure 22. Noise figure of MAR-8ASM+ amplifier

The layout of the MAR-8ASM+ amplifier schematic with microstrip lines was generated as shown in figure 23. From the layout, Gerber file was produced and then fed to the milling machine.
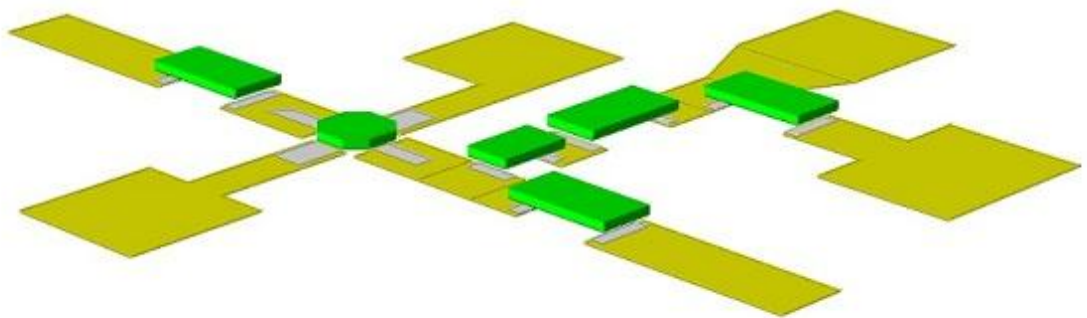


Figure 23. Layout of MAR-8ASM+ amplifier

Finally the MAR-8ASM+ amplifier circuit board was fabricated by the milling machine. The board was tested and measurement results are explained in chapter 10. Figure 24 shows the board produced by the milling machine.
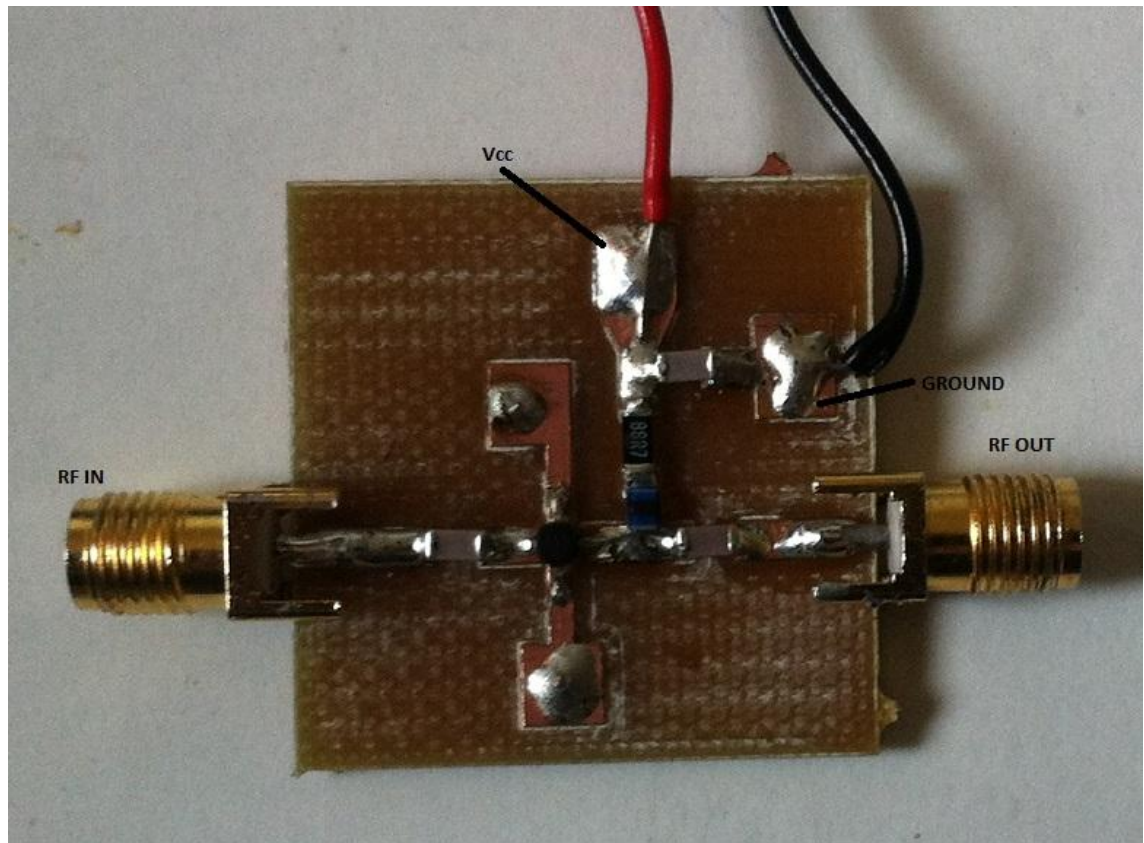
Figure 24. MAR-8ASM+ amplifier circuit board

The bottom layer of the board is ground and all the three grounds of the MAR-8ASM+ amplifier circuit were interconnected on it through vias.

## 9.2    Amplifier Based on BFP182W Transistor

The first step was to choose a transistor suitable for the specified design target and BFP182W was chosen. Operating point of the transistor was then determined and biasing circuit was made. The stability of the transistor was checked and input and output matching circuit networks were designed. The whole design process from schematic to layout design was done by AWR microwave office design software. The schematic of the amplifier was designed and microstrip lines were added. Figure 25 and figure 26 show amplifier schematic without microstrip lines and with microstrip lines.
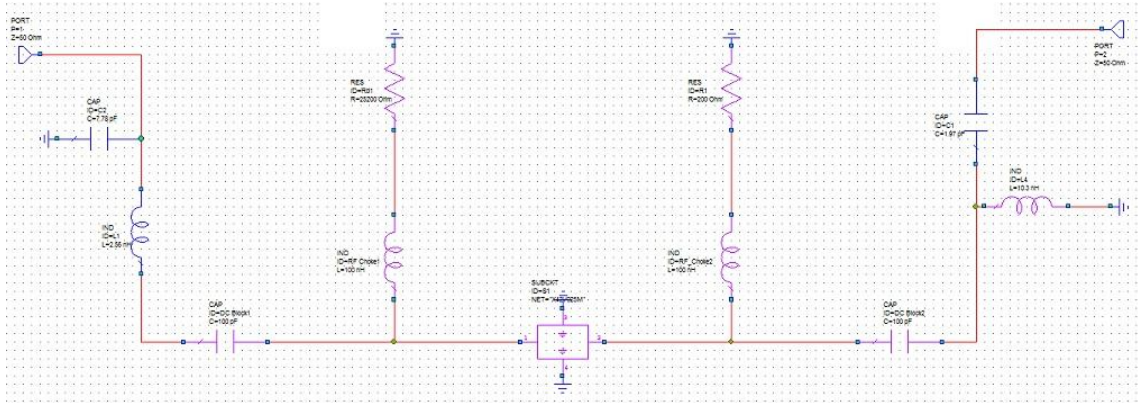
Figure 25. BFP182W transistor amplifier schematic design without microstrip lines
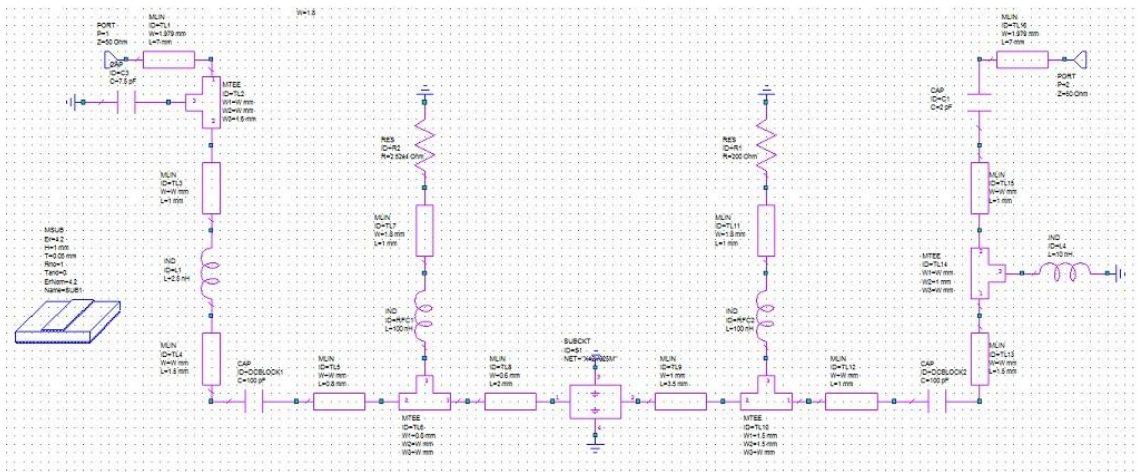


Figure 26. BFP182W transistor amplifier schematic design with microstrip lines

The gain of the BFP182W transistor amplifier after addition of microstrip lines at 1 GHz was found to be 13.31 dB. Figure 27 shows graphs of gain versus frequency at different stages of design as analyzed by AWR microwave office.
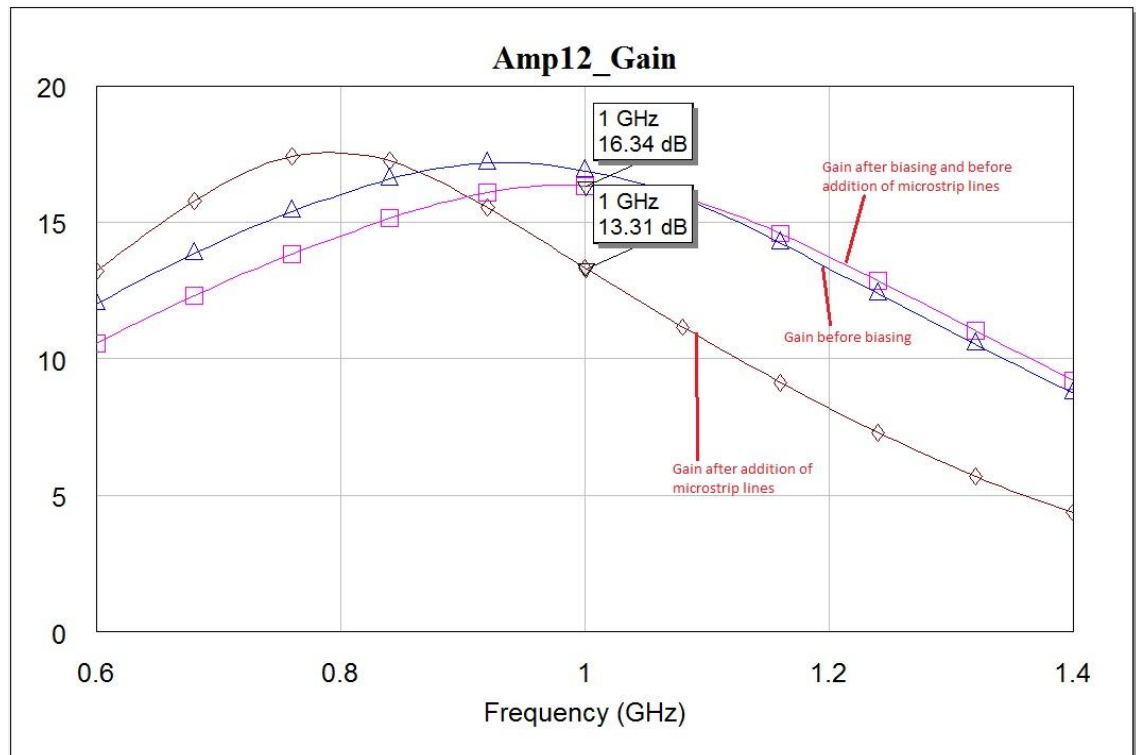
Figure 27. Gain of BFP182W transistor amplifier

The noise figure of BFP182W transistor amplifier was found to be 0.04206 dB as indicated in figure 28. The noise figure is small which means degradation in the signal to noise ratio is insignificant.
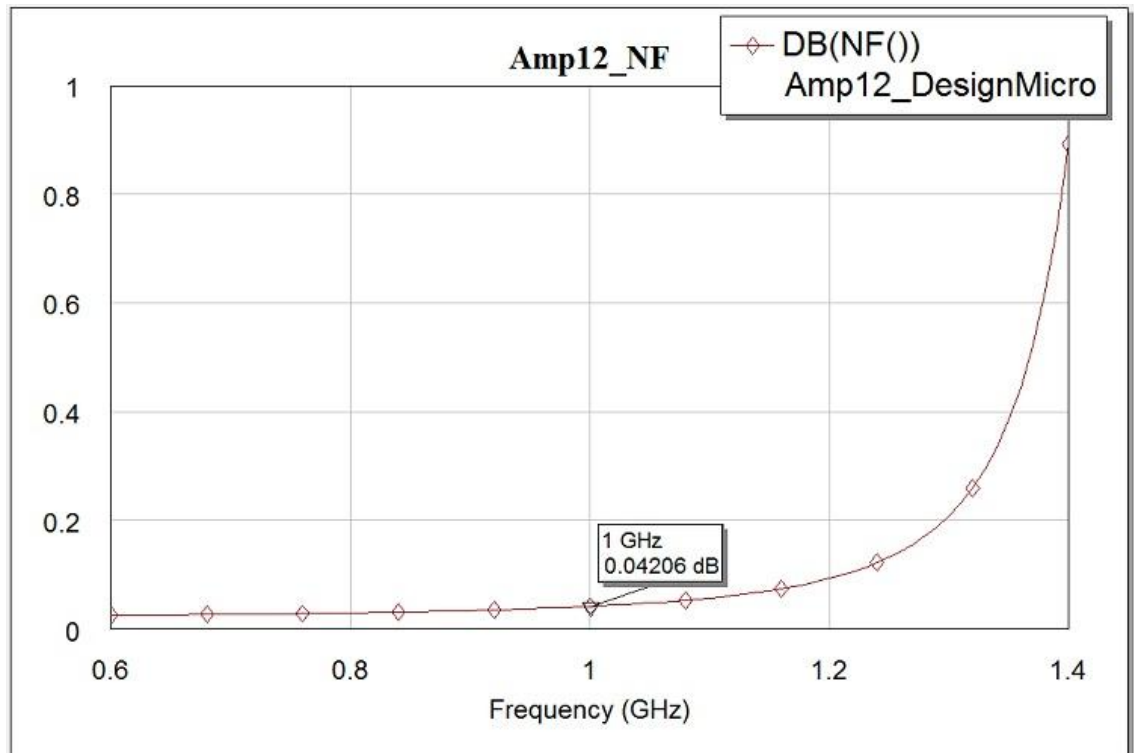
Figure 28. Noise figure of BFP182W transistor amplifier

The layout of the BFP182W transistor amplifier schematic with microstrip lines was generated and its Gerber file was produced and fed to the milling machine. Figure 29 shows the 3D layout of BFP182W transistor amplifier
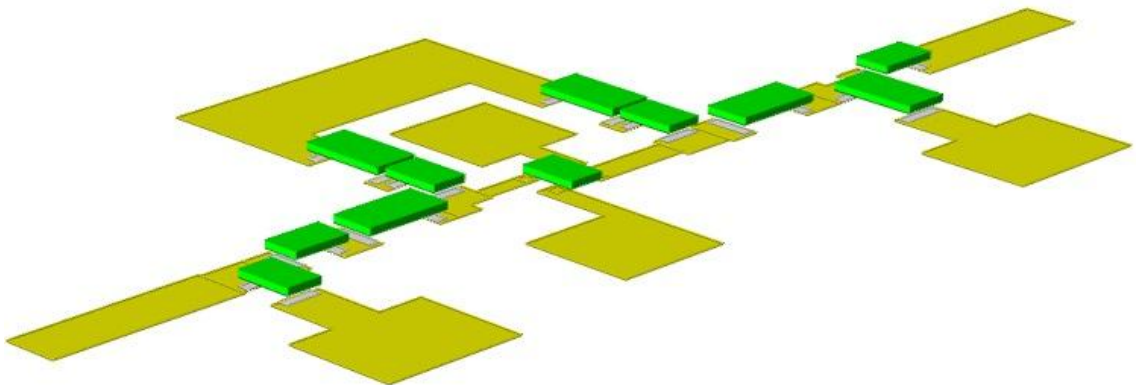


Figure 29. Layout of BFP182W transistor amplifier

The BFP182W transistor circuit board was fabricated by the milling machine. The board was tested and measurement results are explained in chapter 10. Figure 30 shows the board produced by the milling machine. The bottom layer of the board is

ground and all the four grounds of the BFP182W transistor amplifier circuit were inter-connected on it through vias.
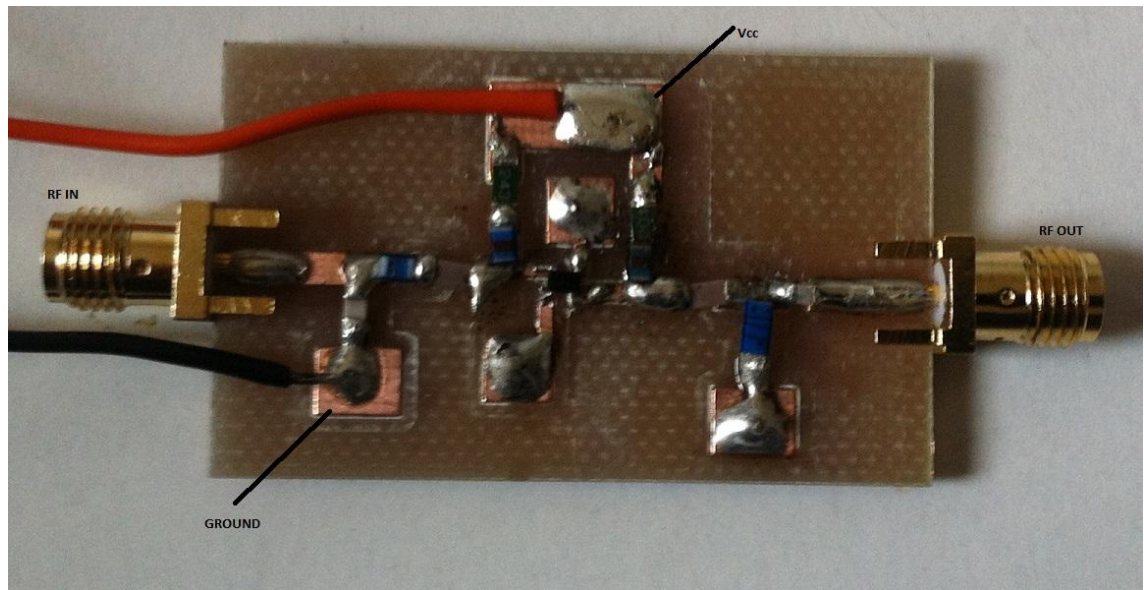


Figure 30. BFP182W transistor amplifier circuit board

Since some of capacitor and inductor values found by tuning were not commercially available, closer values to these which are commercially available were used instead. New values used caused mismatch of the amplifier circuit which affected gain and noise figure of the amplifier.

## 10  Measurements

10.1  Monolithic Microwave Integrated Circuit (MMIC) Amplifier

Measurements were done by the network analyzer where gain and reflection coefficient of the designed amplifier were measured. The measurements were done at frequency sweep of 0.6 GHz to 1.4 GHz and amplitude scale of 10 dB/division. Results of the measurements are shown in figure 31 and figure 32.

Figure 31. Gain graph as shown on the network analyzer screen

As read on the network analyzer, the gain of the amplifier at 1 GHz is 15.278 dB.
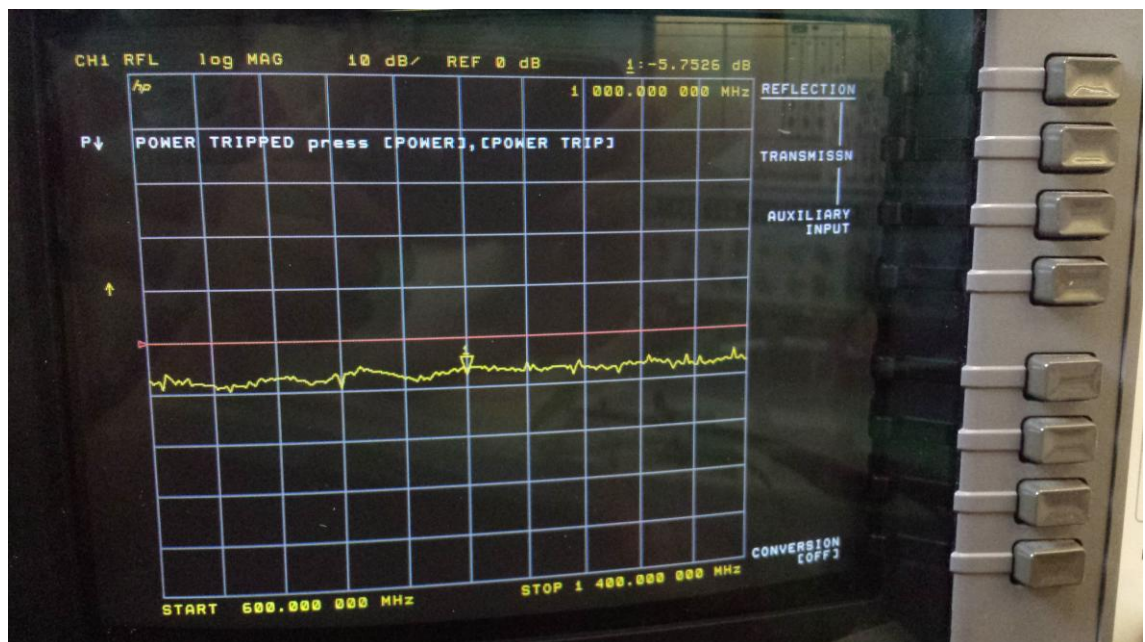


Figure 32. Reflection coefficient graph as shown on the network analyzer screen

At 1 GHz, the measured reflection coefficient is -5.7526 dB.

10.2  Amplifier Based on BFP182W Transistor

Network analyzer was used to measure gain and reflection coefficient of the amplifier. Measurements were done at frequency sweep of 0.6 GHz to 1.4 GHz with 10 dB/division amplitude scale. Figure 33 and figure 34 show measurement results.
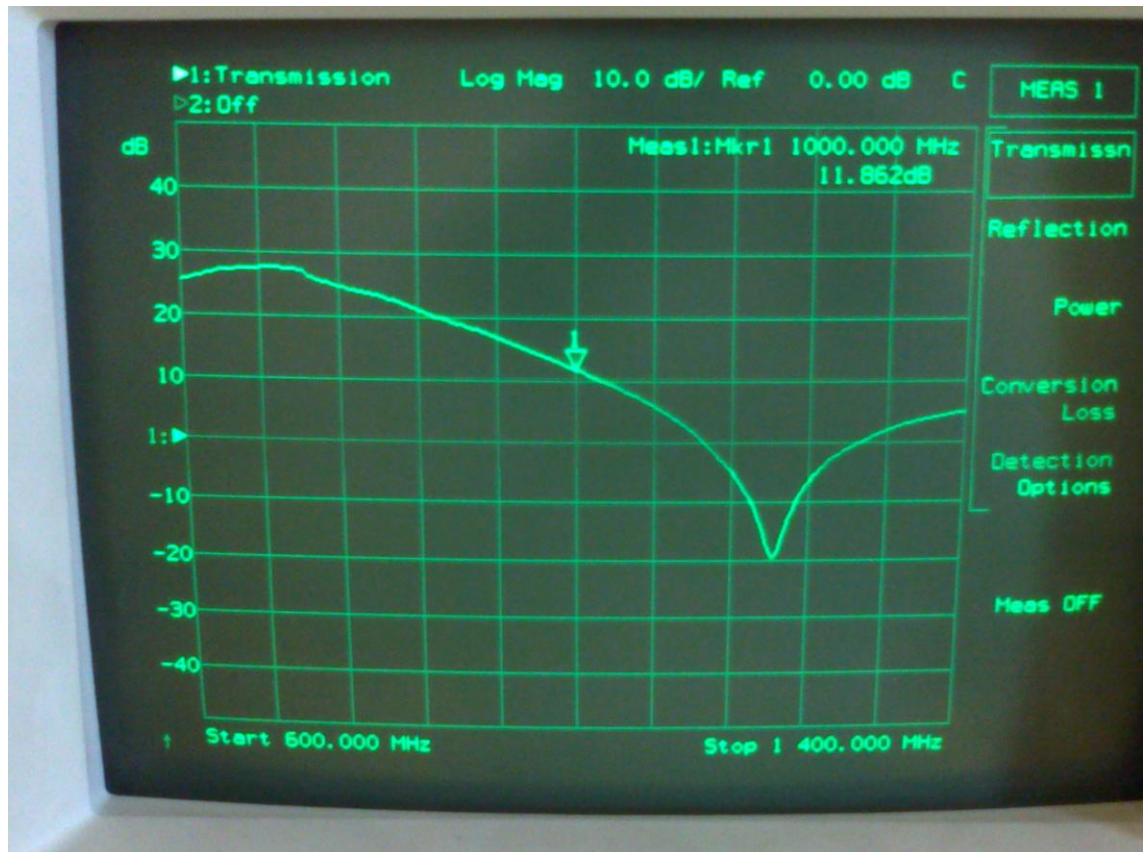


Figure 33. Gain graph of BFP182W transistor amplifier on the network analyzer screen

At operating frequency of 1 GHz, the gain is 11.862 dB. Amplifier gives amplification from 0.6 GHz to 1.15 GHz with maximum gain at 0.6 GHz. The designed amplifier was supposed to give maximum gain at 1 GHz, but the addition of microstrip lines and re-placement of ideal components values by commercially available components values caused mismatching of the amplifier circuit.
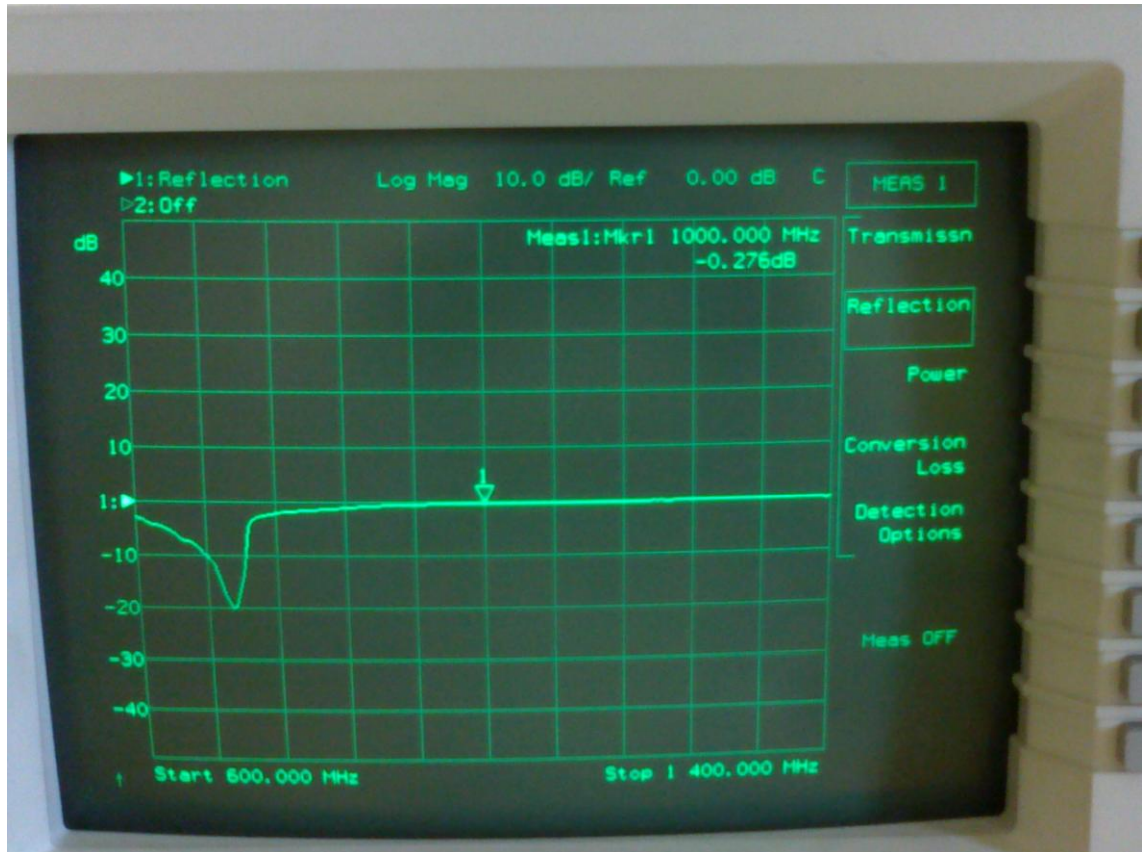
Figure 34. Reflection coefficient graph of BFP182W transistor amplifier

Reflection coefficient at 1 GHz is -0.276 dB.

## 11  Conclusion

The aim of the project was to design and build two microwave amplifiers, transistor based amplifier with external matching circuits and internally matched Monolithic Microwave Integrated Circuit (MMIC) amplifier. Operating frequency was 1 GHz. The target was to have a gain of at least 10 dB for the transistor based amplifier and 20 dB for MMIC amplifier.

The tested results show some differences between the measured and the analyzed gain. For the transistor based on BFP182W transistor the gain value measured, 11.862 dB was close to the analyzed one, 13.31 dB and was well above the specified target of 10 dB. For the MAR-8ASM+ amplifier, the measured value of the gain was 15.278 dB which is considerably below analyzed gain of 23.845 dB and less than specified target

gain of 20 dB. These discrepancies between the measured results and the simulated results were possibly caused by the signal leakage on the amplifier circuit boards and imperfections in the network analyzer and cables. Also, the gains of the amplifier were affected by the components values used which were not ideal .The results could be improved by using more sensitive network analyzer and cables.

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