

A FREQUENCY-MODULATED CONTINUOUS WAVE-BASED BOUNDARY

DETECTION SYSTEM IN A SMALL PCB PROFILE

A THESIS

by

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## ABSTRACT

A Frequency-Modulated Continuous Wave-Based Boundary Detection System in a Small PCB Profile for an Indoor Monitoring System

**Hamid Reza Asgarian**

Falls are a cause of concern for the elderly because it can make them unable to call for help. A monitoring system can detect automatically their immobility and provide help to the elderly if they fall. Ultra-wide band signals for a monitoring system is an excellent choice since it has low enough power to not interfere with other medical and household electronics as well as being able to transmit data to a central monitoring unit. One part of this monitoring system is a boundary detection system used to verify that the monitoring system is not capturing events outside the monitoring region such as an event outside the house or in a neighboring room.

The work presented in the paper, “A Frequency-Modulated Continuous Wave-Based Boundary Detection System for Determination of Monitoring Region for an Indoor Ultra-Wideband Short Range Radar-Based Eldercare Monitoring System” has determined that a frequency modulated continuous wave (FMCW) based system is an acceptable solution for boundary detection. A FMCW system can measure distance with less than 10cm accuracy if the chosen spectrum bandwidth is 1GHz or more. This thesis presents the design of a low cost approach to small PCB footprint distance detection circuitry for the boundary detection system.

Keywords: ultra-wideband, UWB, FMCW, monitoring system, boundary detection, falls

## ACKNOWLEDGEMENTS

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# CHAPTER 1

## INTRODUCTION

The eldercare monitoring system research group is working to develop a monitoring system that would enable elderly to live independently without the need for a personal caretaker [1]. The main goal for this system is to design a monitoring system to detect falls and behavior changes of the elderly and provide immediate assistance to them if necessary. The focus of this thesis is to study and to design a low cost FMCW system in a fairly small profile on a PCB board that can be used for boundary detection. Boundary detection is required for such a system so as to exclude data from area where events unrelated to the subject occur.

### 1.1 Monitoring System Outline

A monitoring system which has the capability of monitoring the health of the elderly has been a research topic of Dr. Tina Smilkstein. The purpose of the system is to offer extended independent living among the elderly and those with physical or mental challenges. This system should provide a full-time electronic monitoring to substitute need for a full time caretaker of an elderly. The system can also be installed in nursing homes, as limited employees cannot simultaneously monitor all rooms at every instant. This system is divided into different subparts. This thesis focuses on designing an improved system to define a boundary. A boundary defines the region where events should be detected. Ultra-wideband (UWB) is used to implement this system due to the

qualities of its spectrum. The total band allows for unlicensed use of 7.5 GHz of bandwidth [2]. This band of frequency is especially useful for this application because RF signal can pass through thin walls with minimum effect on its amplitude. For example, the signal passes through an 8cm brick wall with 5 to 8dB drop in power, or 2cm wood structure with 1 to 2dB drop in power [3]. This allows for a signal transceiver to cover multiple rooms to reduce cost and system complexity. In addition, the wide available bandwidth can result in a system with a reasonable accuracy of 5 to 10 cm which is enough for a system used for boundary detection.

## **1.2 Problem Definition for an UWB-based Monitoring System**

A technique to define a room boundary was studied in an earlier work [4]. An FMCW radar system with a bandwidth of 1GHz was concluded to measure distance with approximately 10cm accuracy for defining a room boundary. However, the proposed FMCW system prototype is bulky and expensive. This thesis focuses on a FMCW system in a fairly small profile which is considerably cheaper and could be commercialized. The remaining portion of this thesis discusses the approach to design this FMCW system. In Chapter 2, a brief introduction to the definition and regulations of ultra-wideband are discussed. In Chapter 3, FMCW background is discussed, and a proposed FMCW system is reviewed. Chapter 4 focuses on the design of a FMCW based prototype to measure distances.

In chapter 5, the PCB layout for the proposed FMCW system is illustrated. Finally, chapter 6 contains a brief summary, and conclusion.

# CHAPTER 2

## ULTRA-WIDEBAND BACKGROUND

UWB is the modern version of older "impulse" technologies which are generated by very short pulses (impulse waveforms). They were called "carrier-free" or "baseband" because the energy is so widespread in the frequency domain that there is no discernible carrier frequency. The legal definition of an ultra-wideband signal, as with all electromagnetic transmissions is regulated by the Federal Communications Commission (FCC). A plot of the spectrum of a narrowband and ultra-wideband signal is shown in Fig. 2.1. The power in a narrowband signal is contained within a small frequency band. If the same power of the narrowband signal is spread over a wideband, then the resulting spectral density of the signal is significantly lower [4].

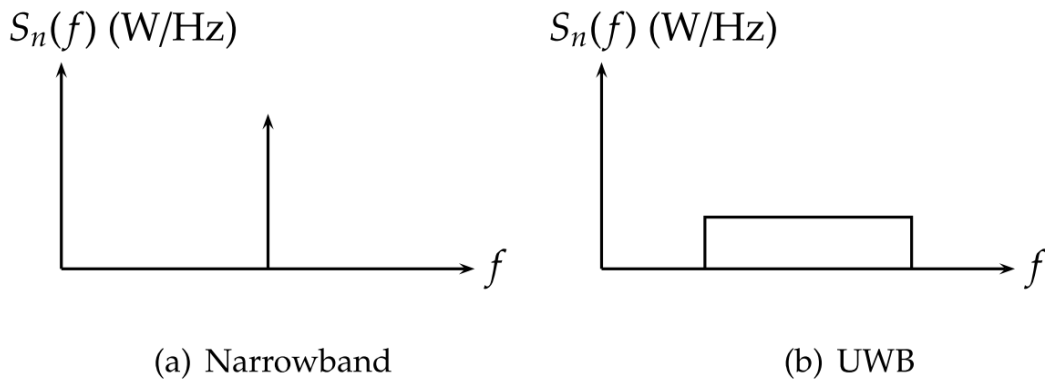


Figure 2.1: Spectral power plot of a narrowband and a UWB signal

## 2.1 UWB FCC Regulations

The FCC allows for unlicensed ultra-wideband transmissions since the year 2002. According to the FCC definition of UWB signal, it should contain at least 500MHz of bandwidth, and the bandwidth is measured at the points 10 dB below the peak power; those points are noted as  $f_L$  and  $f_H$ . The frequency the peak power occurs at is labeled as  $f_M$ . The FCC limits emissions to an average power of  $-41.3$  dBm/MHz, and the largest contiguous band is contained within 3.1 GHz to 10.6 GHz as shown in Figure 2.2 [2].

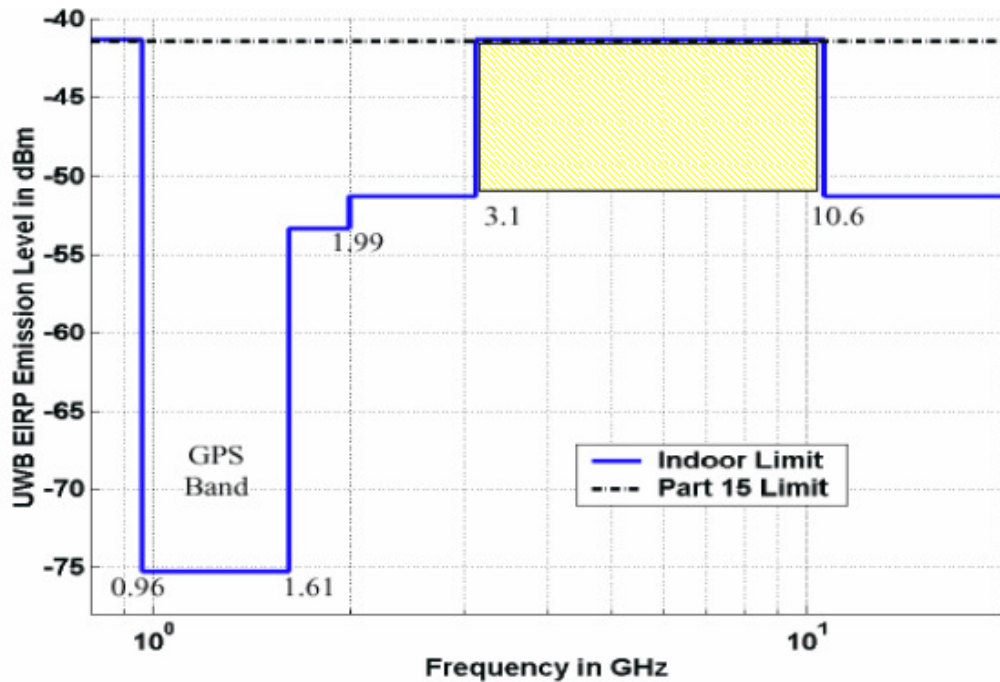


Figure 2.2: FCC mask for power limits on UWB emissions

According to FCC part 15:

“There are average power and peak power limits on UWB emissions. The average power of  $-41.3$  dB/MHz measurement is based on RMS average measurements

over a 1 MHz resolution bandwidth. The RMS average measurement is based on the use of a spectrum analyzer with a resolution bandwidth of 1 MHz, an RMS detector, and a 1 millisecond or less averaging time. In addition, there is a limit on the peak level of the emissions contained within a 50MHz bandwidth centered on the frequency at which the highest radiated emission occurs,  $f_M$ . That limit is 0 dBm EIRP, where EIRP is equivalent isotropic radiated power. EIRP is the addition of the power supplied to the antenna and antenna gain or loss' [2].

# CHAPTER 3

## FMCW THEORY AND BACKGROUND

FMCW is a radar system where a known continuous wave is swept and modulated over a certain bandwidth. The swept signal modulation can be triangular, or saw-tooth. In the next section, it is proved that the bandwidth of signal solely determines the range resolution. The larger the bandwidth, the higher is the range resolution. An FMCW radar system with a bandwidth of 1GHz presented in the paper [4] measured distance with approximately 10cm accuracy for defining a room boundary.

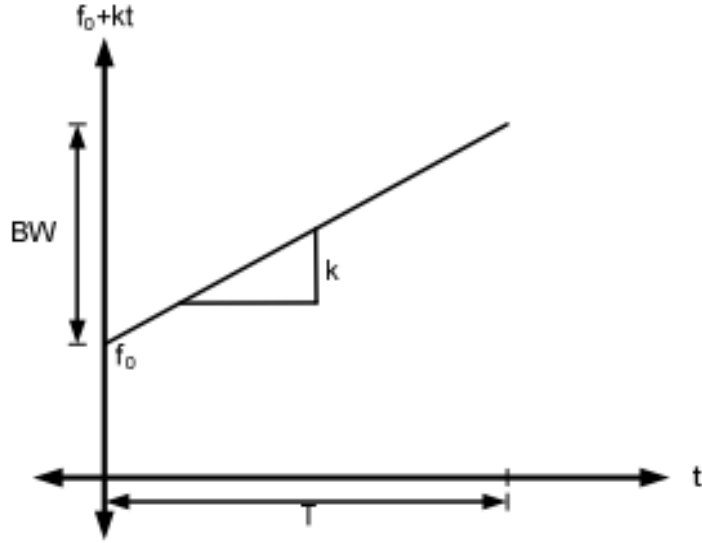
### 3.1 FMCW Radar Principles

In a FMCW radar the transmit waveform is a frequency-modulated continuous-wave given by equation 3.1 [4].

$$S(t) = \cos(2\pi(f_o + kt)t) = \cos(2\pi f_o t + 2\pi kt^2) \quad (3.1)$$

Where  $f_o$  is the start frequency and  $k$  is the chirp rate.





**Figure 3.1: FMCW radar sweep**

As shown in Figure 3.1, the frequency of the transmit signal linearly increases with time at a constant rate called chirp rate. Chirp rate can be defined as

$$k = \frac{BW}{T} \quad (3.2)$$

Where the bandwidth  $BW$  is the difference between the start and stop frequencies.  $T$  is the sweep time for the frequency range. The instantaneous frequency of the above transmit signal can be calculated by taking the derivative of the instantaneous phase

$$f_{inst} = \frac{1}{2\pi} \frac{d\phi}{dt} = \frac{1}{2\pi} (2\pi f_0 + 2\pi kt) = f_0 + kt \quad (3.3)$$

Also the maximum frequency of the transmit signal is given by

$$f_{max} = f_0 + kt \quad (3.4)$$

When the signal is transmitted, it will hit the target and gets reflected back to the antenna of radar. The received signal is attenuated, and delayed by time  $t_0$

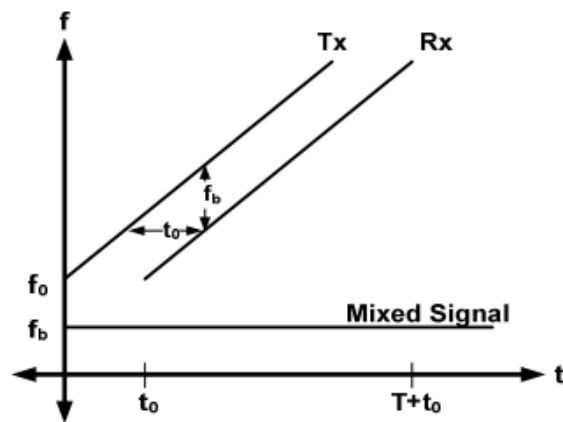
$$S(t) = \cos(2\pi f(t - t_0) + \pi k(t - t_0)^2) \quad (3.5)$$

Where  $t_0$  is the time it takes for the signal to travel to and back from the target.

$$t_0 = \frac{2R}{c} \quad (3.6)$$

Where  $R$  is the distance between radar antenna and target, and  $c$  is the speed of light.

In the FMCW radar system, the received signal goes to the RF port of mixer, and the mixer subtracts and adds the received signal frequency and the transmitted signal frequency. The subtraction value is called beat frequency, and it is proportional to the target range.



**Figure 3.2: Beat frequency**

A low pass filter can be used to remove the additive frequency from the received signal. Thus, the difference term, which is the beat signal, is given by

$$S_{beat}(t) = \cos(2\pi ft_0 + 2\pi ktt_0 - \pi kt_0^2) \quad (3.7)$$

The frequency of the beat signal can be obtained by the differentiating the phase. Thus, the frequency of the beat signal is

$$f_{beat} = \frac{1}{2\pi} \frac{d\Phi}{dt} = kt_0 = \frac{BW}{T} t_0 \quad (3.8)$$

The delay  $t_0$  is two way travel time that can be mapped to range of the target using equation

$$t_0 = \frac{2R}{c} \quad (3.9)$$

If we take FFT of the time-domain beat signal, we see the peak at the beat frequency.

This frequency can be transformed to the range of the target using the equations 3.8 and 3.9

$$R = \frac{t_0 c}{2} = \frac{c f_{beat} T}{2BW} \quad (3.10)$$

The range resolution of a FMCW system is given by

$$\Delta R = \frac{c}{2BW} \quad (3.11)$$

The range resolution is the radar's ability to discern two objects placed at a distance  $\Delta R$  apart. The range resolution of the radar system is solely determined by the systems sweep bandwidth (BW).

## 3.2 Proposed FMCW Radar

A proposed FMCW system in [6] is shown in Fig. 3.3. The system is a frequency modulated continuous wave (FMCW) based radar system with ultra-wideband support. A linear FMCW source is generated with a direct digital synthesizer (DDS) as a frequency reference to a phased-locked loop (PLL) with a wideband voltage controlled oscillator (VCO). The output is connected to a RF switch to pulse the signal, at a slow rate relative to the frequency of the FMCW source. The received signal is mixed with the local signal, sampled, and processed to determine the distance.

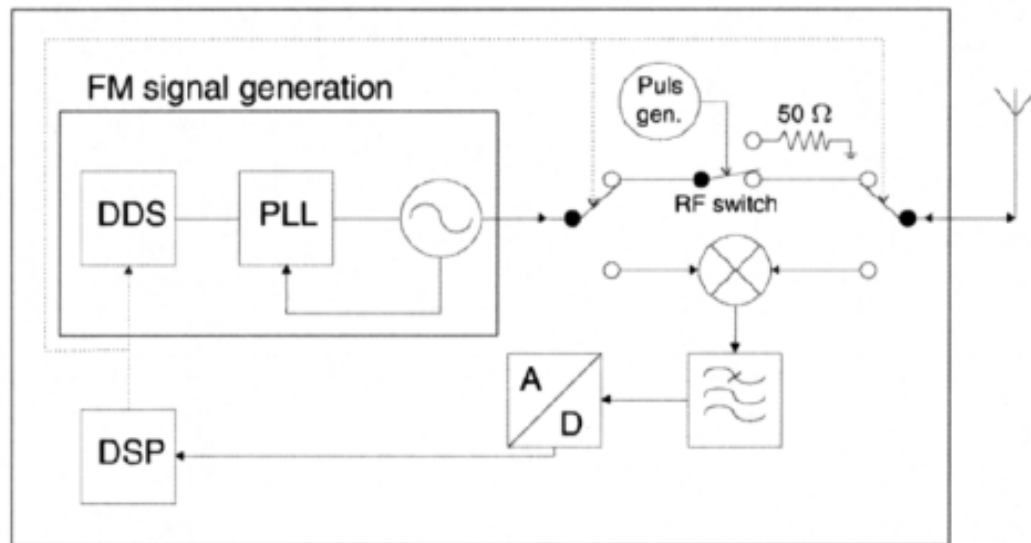
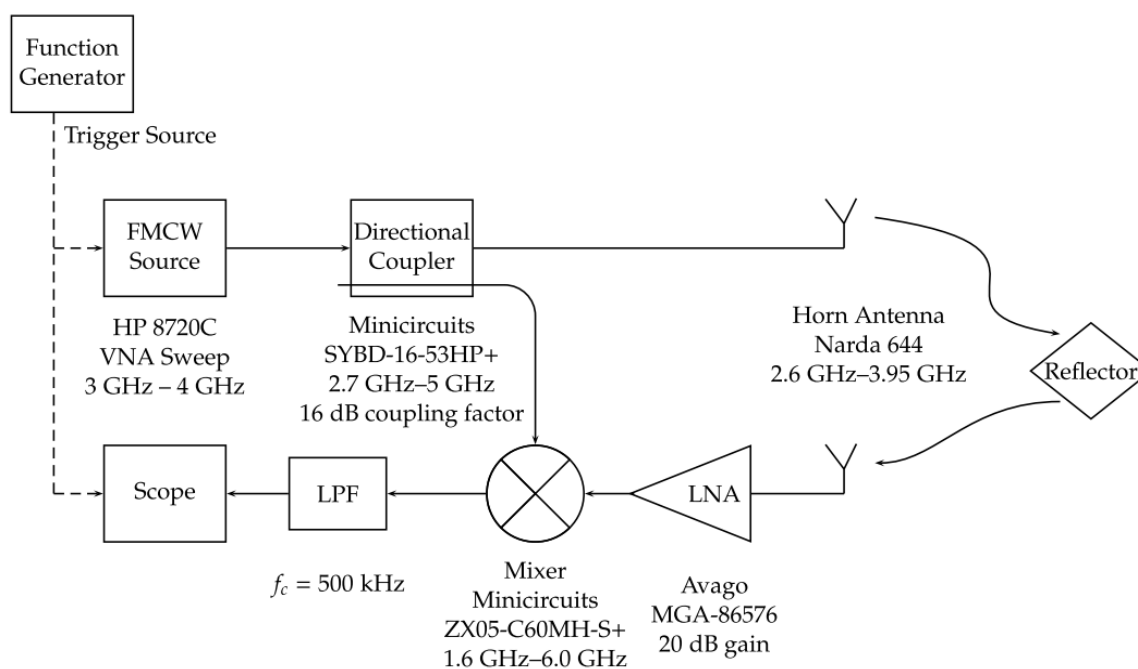


Figure 3.3: FMCW system block diagram proposed in [6]

# CHAPTER 4

## FMCW DESIGN

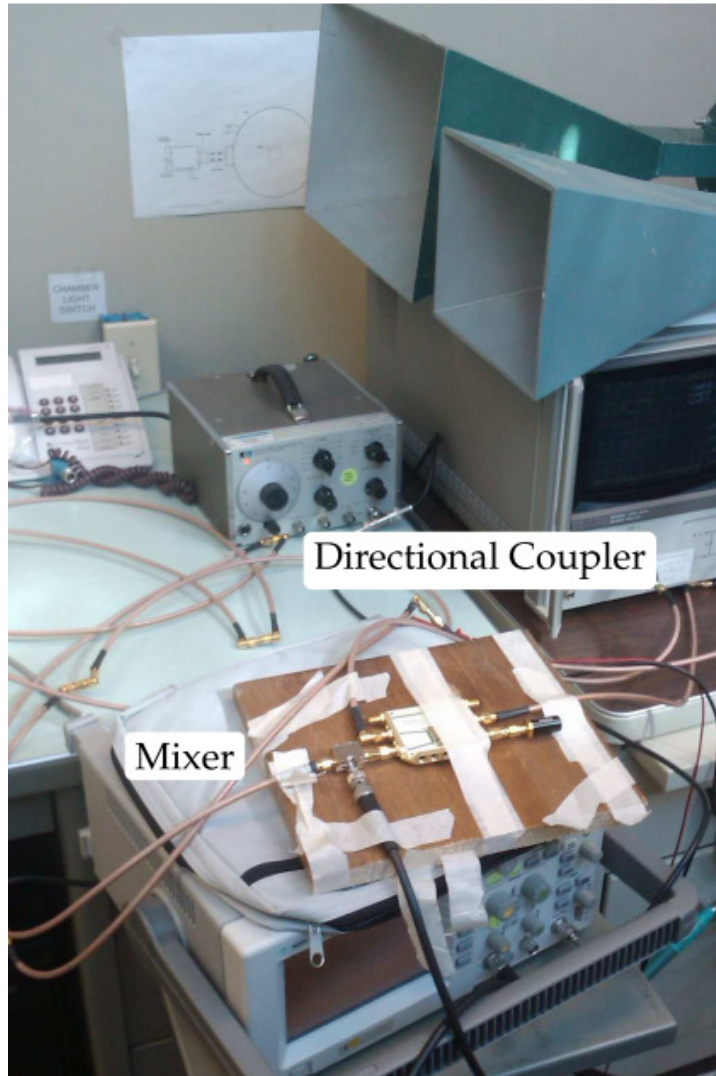
A preliminary prototype of a FMCW prototype was initially built to show the FMCW technique can be used to determine distance [4]. This system contained the minimal components needed to operate the FMCW system. Figure 4.1 shows the block diagram for the system test setup.



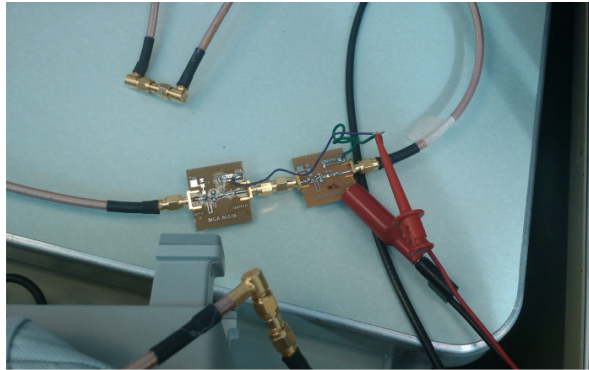
**Figure 4.1: Block diagram for system test setup**

A function generator is used to externally trigger the network analyzer to begin sweeping and the oscilloscope to trigger and capture data. The fastest sweep rate of 6 ms is used with a sweep range of 3 GHz to 4 GHz or 1 GHz of bandwidth. The bi-directional coupler divides the signal from the network analyzer where one is directed to the antenna, and the other is to drive the LO port of the mixer. When the signal is

returned to the receiving antenna, it is amplified by one (or two) using an Avago LNA MMIC amplifier and the oscilloscope is used to measure the signal. This system was composed of an LNA, directional coupler, a mixer, and a horn antenna. Figure 4.2, and 4.3 show the test setup in the lab.



**Figure 4.2: Test board containing the mixer and directional coupler [4]**



**Figure 4.3: Two stage amplifier connected between the receive antenna and mixer [4]**

Although this system is functional, and distance measurements can be done with 10cm accuracy, but it is expensive (~150 dollars). Given its high cost and fairly large dimensions (10x20x5cm), it is more reasonable to develop a system which is cheaper and comes in a smaller profile.

Figure 4.4 shows the top hierarchy of a small FMCW system, designed to fit on a small PCB board. The ideal frequency band to use for this application is 3GHz to 4GHz because it is where the reflections are most easy to differentiate between materials. Although there are a lot of RF products available for this band of frequency, it is not easy to get samples for free, or to purchase in low quantity. This FMCW system is still in the development phase; therefore, the system presented in this paper operates from 5GHz to 6GHz because there are numerous RF products available in the market for this band that can be sampled for free, or purchased in low quantity. Eventually this design can be revised to function in 3GHz to 4GHz once different phases of the monitoring system are more completed, and more budgets is allocated to this project.

## 4.1 System Top Level

In order to meet the limits of FCC, the transmit signal average EIRP (Equivalent Isotropic Radiated Power) has to be less than - 41.3 dBm/MHz. The typical gain of the antenna used for this system is 0dB. The signal loss between the external input signal and antenna is around 5dB (3B loss in power divider, 1dB in circulator, and 1dB in microstrip loss). Therefore, the input signal the average power has to be less than - 36.3dBm/MHz in order to meet the limits of FCC. As shown in figure 4.4, the board design of this FMCW system includes a power divider to divide the input signal to be directed to the antenna and the mixer LO port. Based on the datasheet of the mixer chosen for this design, the mixer LO power should be between -10 to 10dBm. Therefore, a power amplifier is used after power divider port 2 to amplify the signal which is transmitted to LO port of the mixer. The transmit signal on port 1 of the power divider is directed to port 1 of the RF circulator, and the RF Circulator routes the signal to the antenna. When the signal is received by the antenna, it goes through the RF Circulator, and comes out of its port 3. Then, the signal is amplified by three stages of Low Noise Amplifiers, and will be directed to RF port of the mixer. In the Low Noise Amplifier section on page 39, it will be discussed how much gain on the receive path is required for this system.



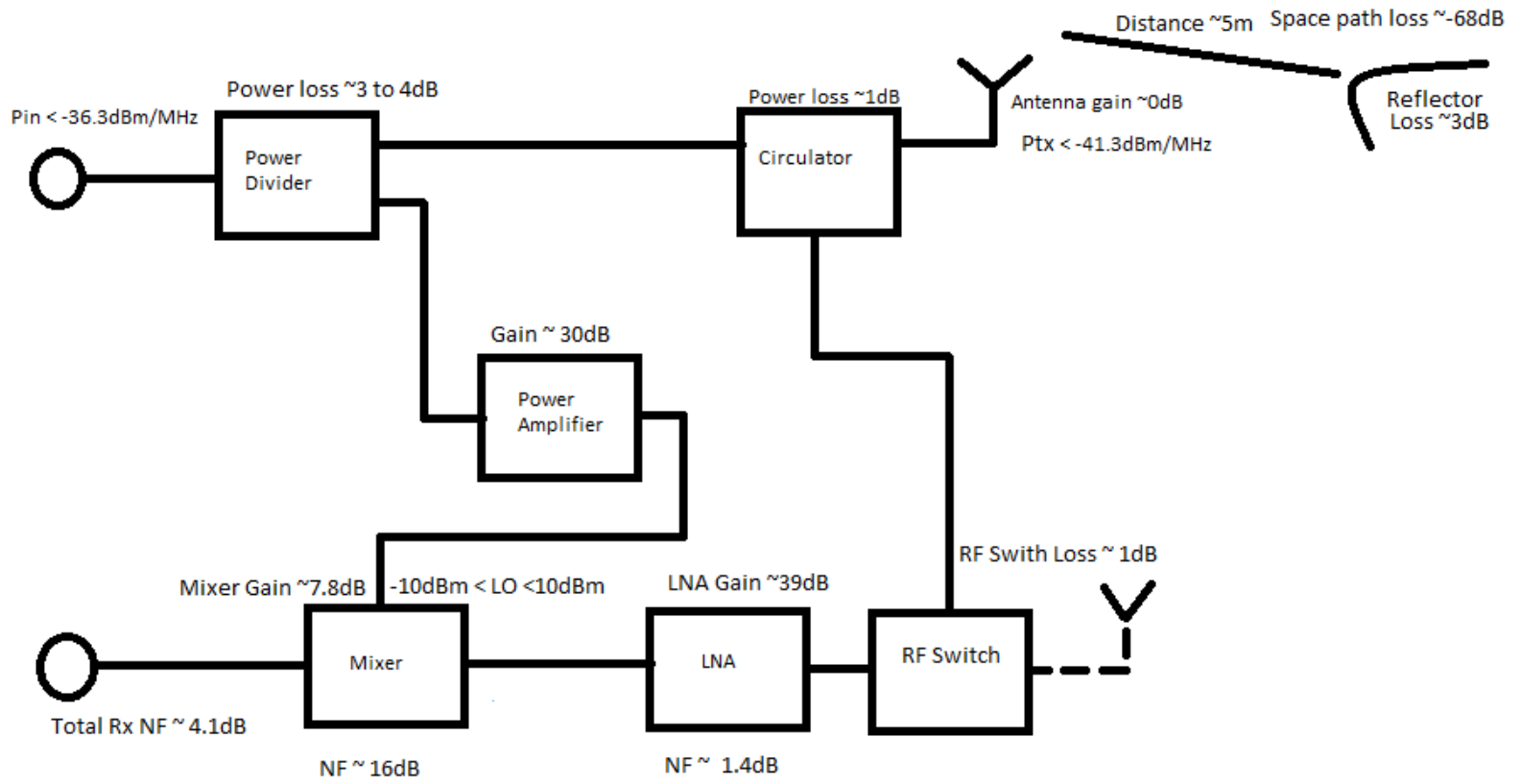


Figure 4.4: Proposed system top level block diagram

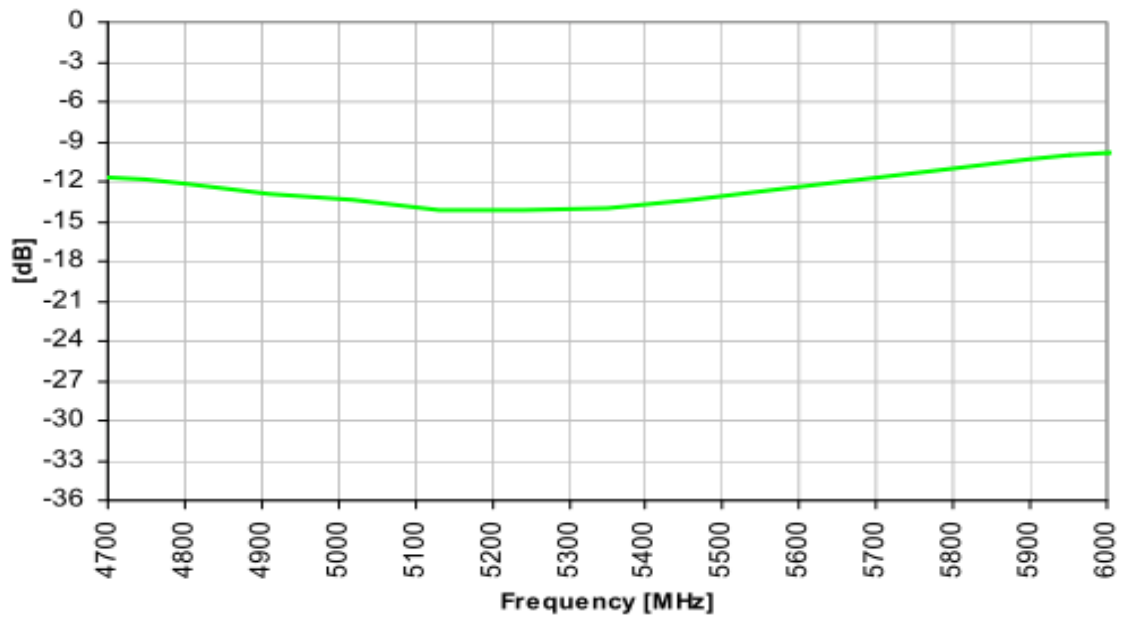


## 4.2 Component Discussion

The main components used for the design of this FMCW radar are Power Divider, Power Amplifier, Circulator, Low Noise Amplifier, RF Switch, and Antennas. An overview of each component is discussed, whether it is actually used in this design, or if it can be used as a substitute.

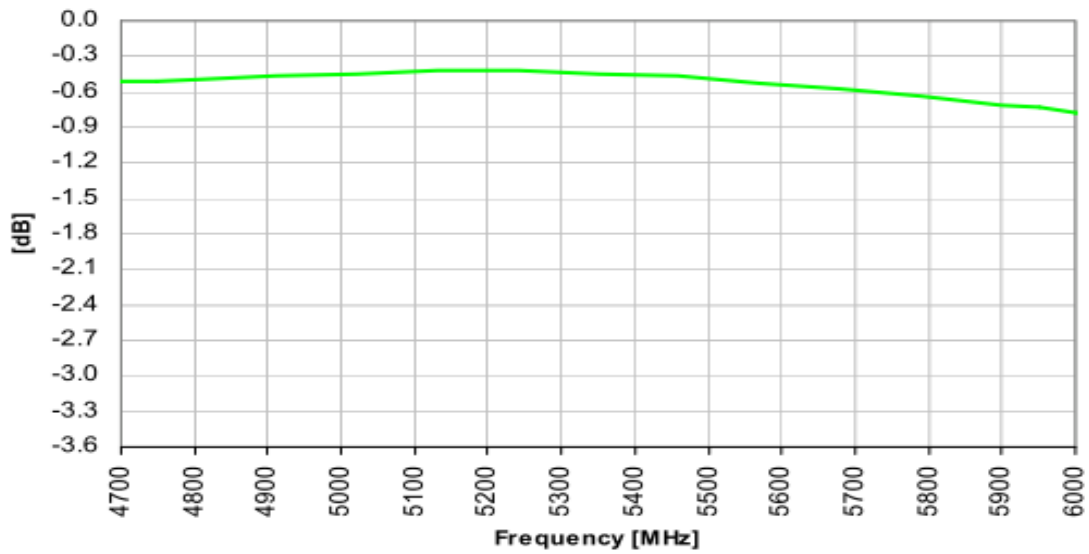
### Power Divider

The power divider is used to split the signal from the input source where one output port is directed to the power amplifier along transmit antenna, and the other output port is to drive the LO port of the mixer. The PD4859J5050S2HF power divider from Anaren is used in this design. The PD4859J5050S2HF is a low profile, sub-miniature Wilkinson power divider, and it comes in an easy to use surface mount package. The PD4859J5050S2HF is matched to  $50\Omega$  and has a height profile of 0.5mm [7]. Figure 4.5 to 4.9, shows the PD4859J5050S2HF's input return loss, insertion loss, amplitude imbalance, phase imbalance, and isolation vs. frequency.



**Figure 4.5: Power divider input return loss (dB) vs. frequency (MHz)**

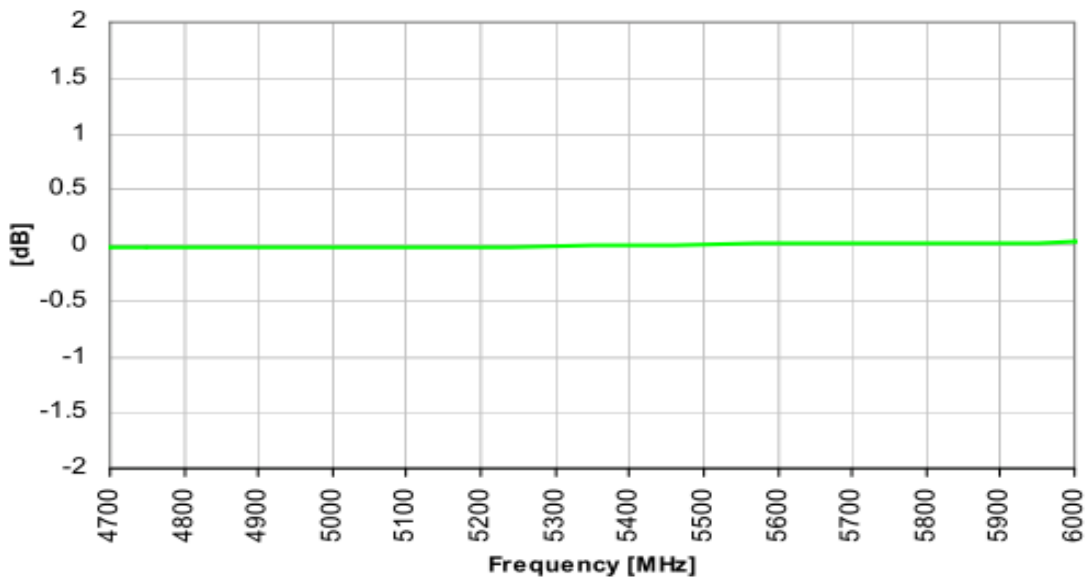
Figure 4.5 shows that the input return loss of the power divider is typically better than -9dB. Return loss is a measure of the effectiveness of power delivery from a transmission line to a load such as an antenna [8]. In other words, the mismatch power loss is lower when the return loss is lower. Return loss of -9dB results in about 0.5dB of mismatch power loss, which is negligible for this design.



**Figure 4.6: Power divider insertion loss (dB) vs. frequency (MHz)**

Figure 4.6 shows the power divider insertion loss which is between 0.4 and 0.7dB.

Insertion loss measures the energy absorbed by the transmission line, or an RF component in the direction of the signal path in dB.



**Figure 4.7: Power divider amplitude imbalance (dB) vs. frequency (MHz)**

Figure 4.7 and 4.8 show the power divider amplitude and phase imbalance which is almost zero. Therefore, the signal amplitude and phase is divided evenly between two ports.

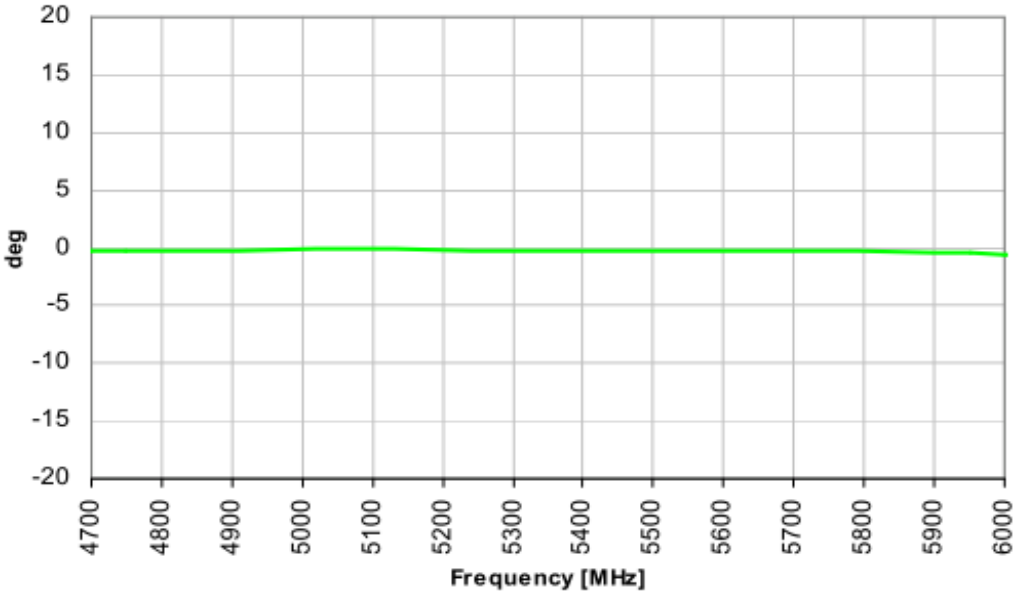


Figure 4.8: Power divider phase imbalance (degree) vs. frequency (MHz)

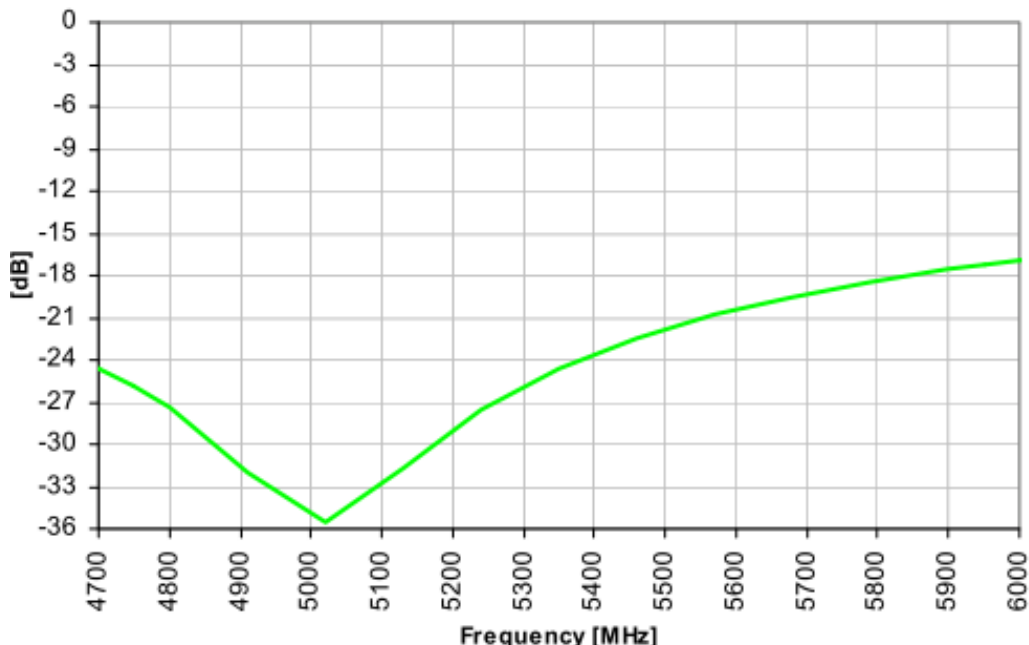


Figure 4.9: Power divider isolation (dB) vs. frequency (MHz)

Finally figure 4.9 shows the isolation between the two output ports of the power divider. Isolation is a unit of measure (in dB) that states the separation of signal levels on adjacent ports of a device. The greater the isolation value, less interference from a signal on one port is present at the other [10]. The isolation of the PD4859J5050S2HF power divider is better than -17dB which provides a good isolation between the two output ports of the power divider.

Therefore, it is very reasonable to use the PD4859J5050S2HF power divider because of its low cost (less than 1 dollar), size, and performance.

## **Power Amplifier**

This system consists of one power amplifier to amplify the input signal transmitting to LO port of the mixer. Based on the mixer datasheet, the LO power level should be between -10 to 10dBm. As discussed in section 4.1, the average input signal power level is -36.3dBm/MHz. The power divider also attenuates the power level by 3dB. Therefore, a minimum gain of 30dB is required to amplify the signal that is being transmitted to LO port of the mixer. For this design, SE5007BT was used which features a 5GHz front end module offering high linear power for wireless applications [11]. This module integrates a power amplifier, an LNA, and transmit/receive switch (known as T/R switch).

However, in this design, only the power amplifier is utilized. SE5007BT comes in a 16 pin 3x3mm QFN package with a typical gain of 30dB. This package operates from 3.0 to 4.5V and integrates a two stage amplifier circuit with its own inter-stage match. RF input and output pins are both matched to 50Ω. The functional block diagram and pin-out diagram are shown in figure 4.10 and 4.11 respectively.

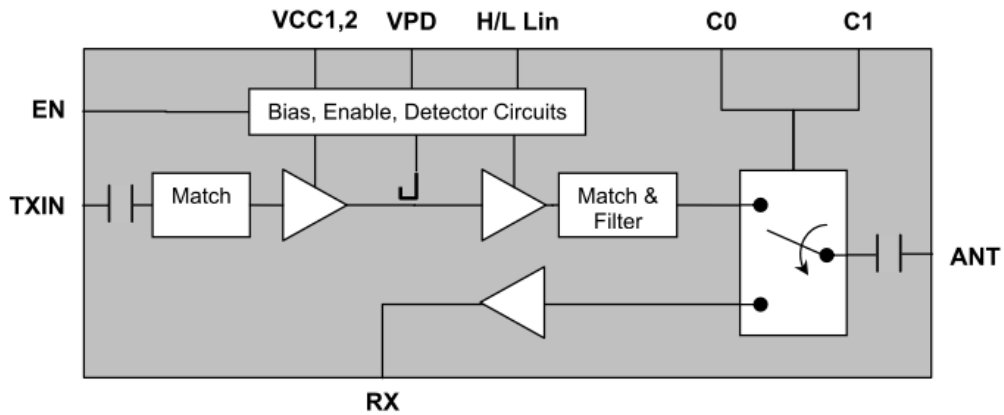


Figure 4.10: SE5007BT functional block diagram

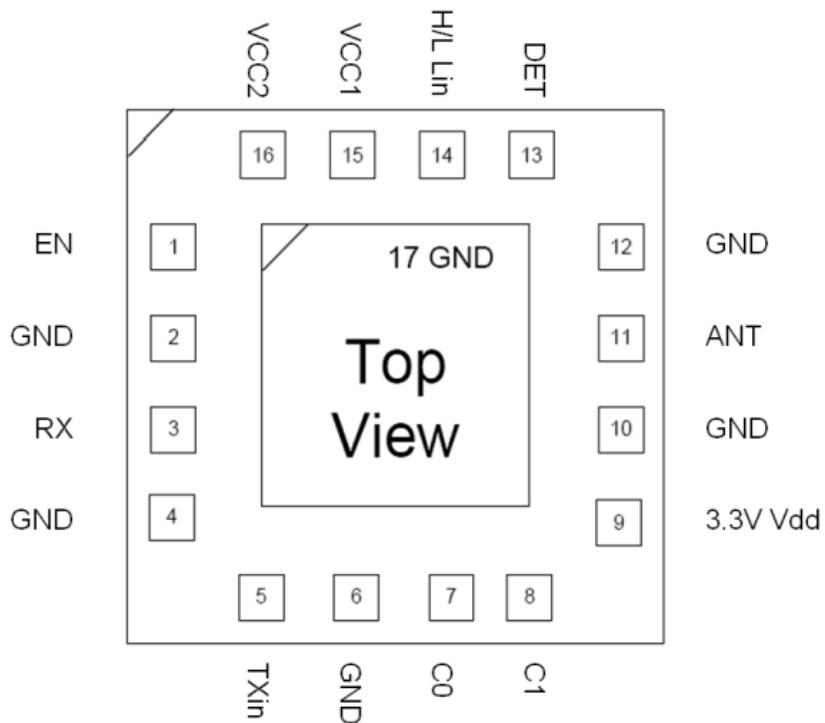


Figure 4.11: SE5007BT package and pin-out diagram

To set this front end module in transmit mode, pin C0 and EN must be set high, and pin C1 must be set to low. Figure 4.12 shows the power amplifier bias and RF connections in this design.



# Power Amplifier

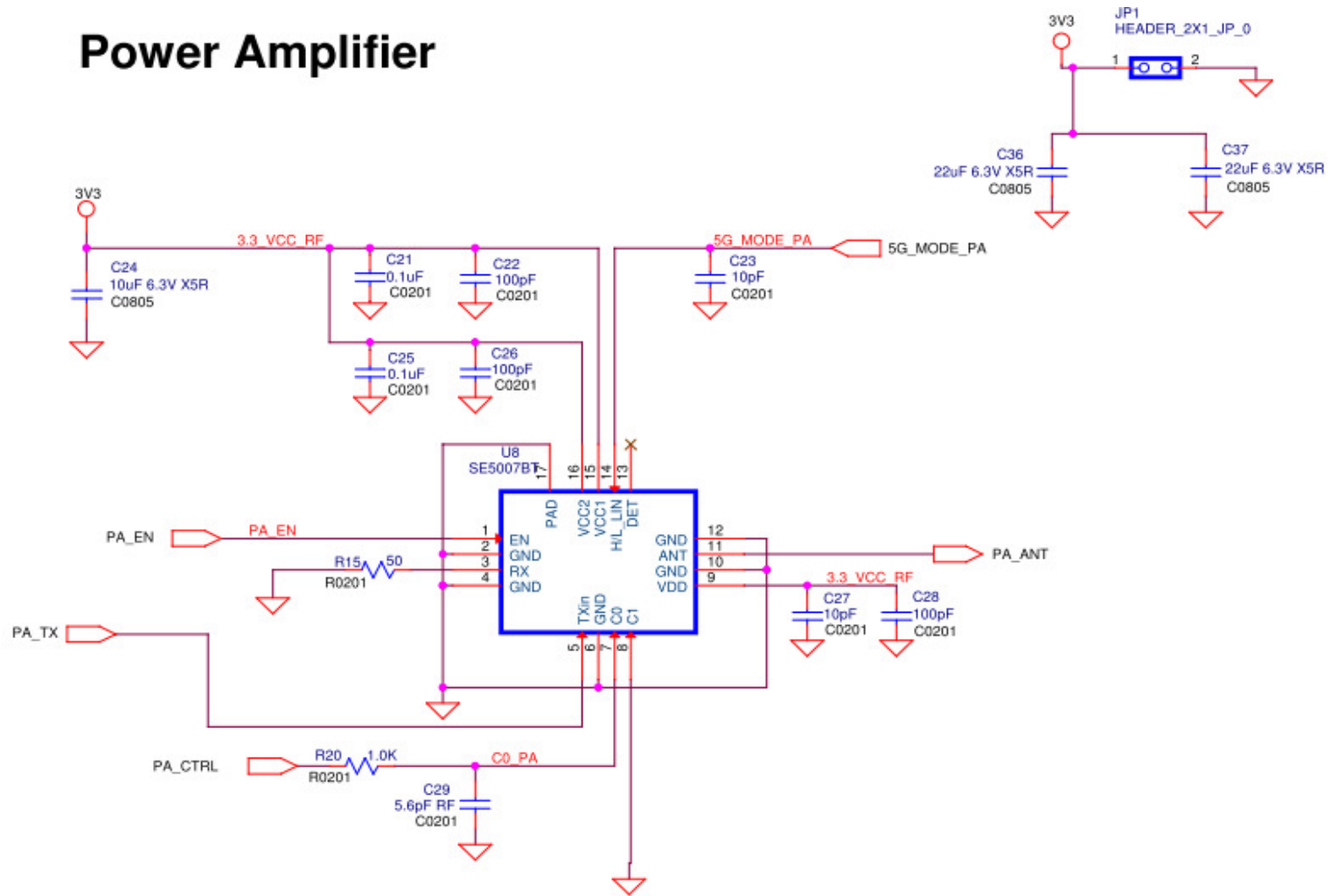
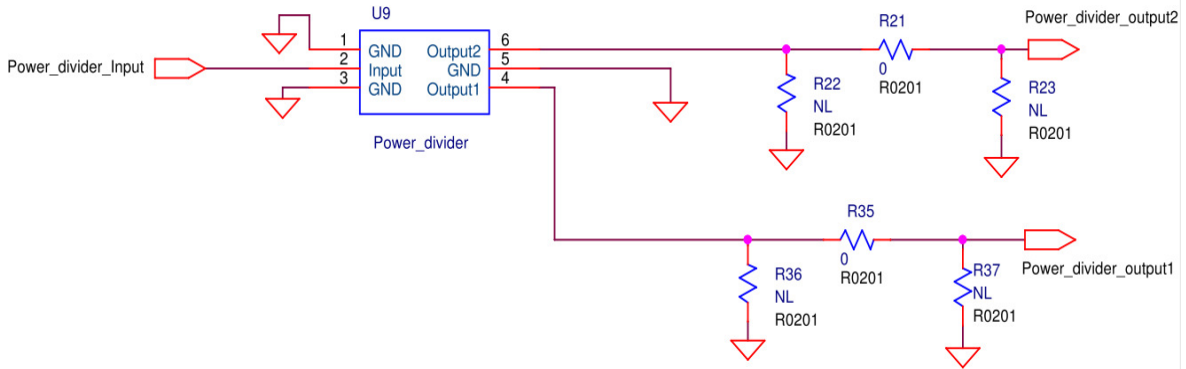


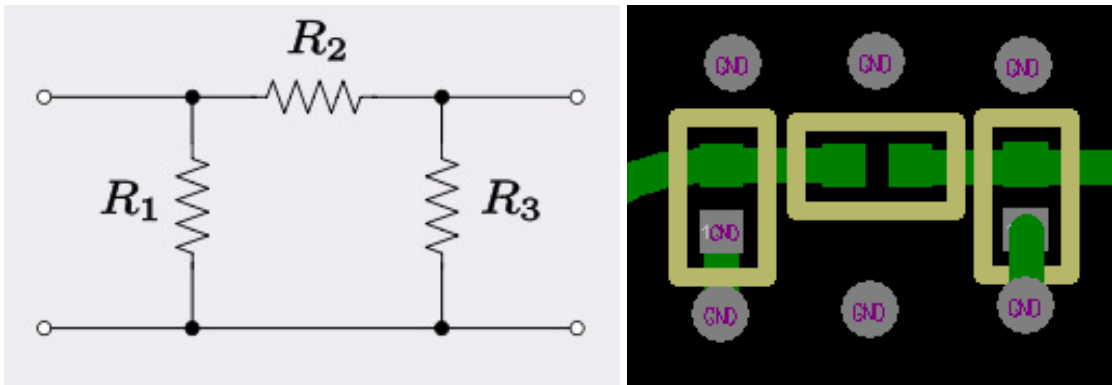
Figure 4.12: Power Amplifier schematic

Since this design is in the development phase, it is a good idea to make the first version of this system easy to tweak and debug. An optional pi-pad attenuator can be used after power divider to attenuate the input power signal if necessary. Figure 4.13 shows the power divider schematic.



**Figure 4.13: Optional pi-pad attenuator**

The pi-pad attenuator is a specific type of attenuator circuit in electronics whereby the topology of the circuit is formed in the shape of the greek letter "Π" made of resistors. The topology of pi-pad attenuator is shown in figure 4.14.



**Figure 4.14: Topology of resistors for pi-pad attenuator**

Table 4.1 can be used to determine the values of Pi-pad resistors for 1, 2, 3, 5, and 10dB attenuation with a 50Ω characteristic impedance.

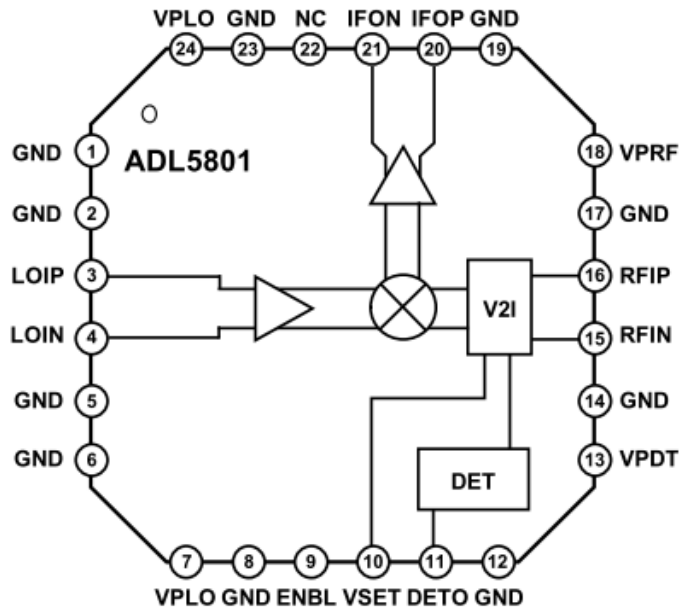
Attenuation (dB)	R1 ( $\Omega$ )	R2 ( $\Omega$ )	R3 ( $\Omega$ )
1	866	5.7	866
2	432	11.5	432
3	294	17.8	294
5	178	30.1	178
10	95	71.5	95

**Table 4.1: Look up table to set attenuation of Pi-pad network**

## **RF Mixer**

For this design, an active broadband mixer (ADL5801) was used to down convert receiving RF signal. ADL5801 uses a high linearity, doubly balanced, active mixer core with integrated LO buffer amplifier to provide high dynamic range frequency conversion from 10MHz to 6GHz [12]. The balanced active mixer arrangement provides superb LO to RF and LO to IF leakage, typically better than -40dBm. The IF outputs are designed to provide a typical voltage conversion gain of 7.8dB when loaded into a 200 $\Omega$ .

ADL5801 comes in a compact 4x4mm, 24-lead LFCSP package. Figure 4.15 shows the functional block diagram.



**Figure 4.15: ADL5801 pinout**

Based on the ADL5801 datasheet, The LO frequency range is 10MHz to 6000MHz, and its input power range is from -10dBm to +10dBm. The RF frequency range is also 10MHz to 6000MHz, and its maximum input power level is 20dBm. The noise figure of the mixer is around 16dB when RF frequency is between 5GHz to 6GHz. However, the total receive path noise figure can be reduced if the low noise amplifier stage has low noise figure. The calculation of total receive path noise figure will be discussed in the Low Noise Amplifier section on page 39.

ADL5801 includes a double-balanced active mixer with a 50  $\Omega$  input impedance and 200  $\Omega$  output impedance. The LO also operates with a 50  $\Omega$  input impedance and can, optionally, be operated differentially or single ended. The ADL5801 can be configured as a down-convert mixer or as an up-convert mixer; however it is being used as a down converter in this design.

The ADL5801 is designed to translate between radio frequencies (RF) and intermediate frequencies (IF). For both up-conversion and down-conversion applications, RFIP (Pin 16) and RFIN (Pin 15) must be configured as the input interfaces. IFOP (Pin 20) and IFON (Pin 21) must be configured as the output interfaces. Individual bypass capacitors are needed in close proximity to each supply pin (Pin 7, Pin 13, Pin 18, and Pin 24), the VSET control pin (Pin 10), and the DETO detector output pin (Pin 11). When the on-chip detector is chosen to form a closed loop, automatically controlling the VSET pin, R7 can be populated with a 0  $\Omega$  resistor, however the on-chip detector is not used in this application. Figure 4.16 illustrates the connections for ADL5801 operation in this design. Many of the components can be left un-loaded because they are only used if the highest performance from the mixer is needed to be achieved at some specific frequencies. Details about the role of each component are out of context in this paper. However, a place holder for the no-load components was positioned in the schematic for possible future work.

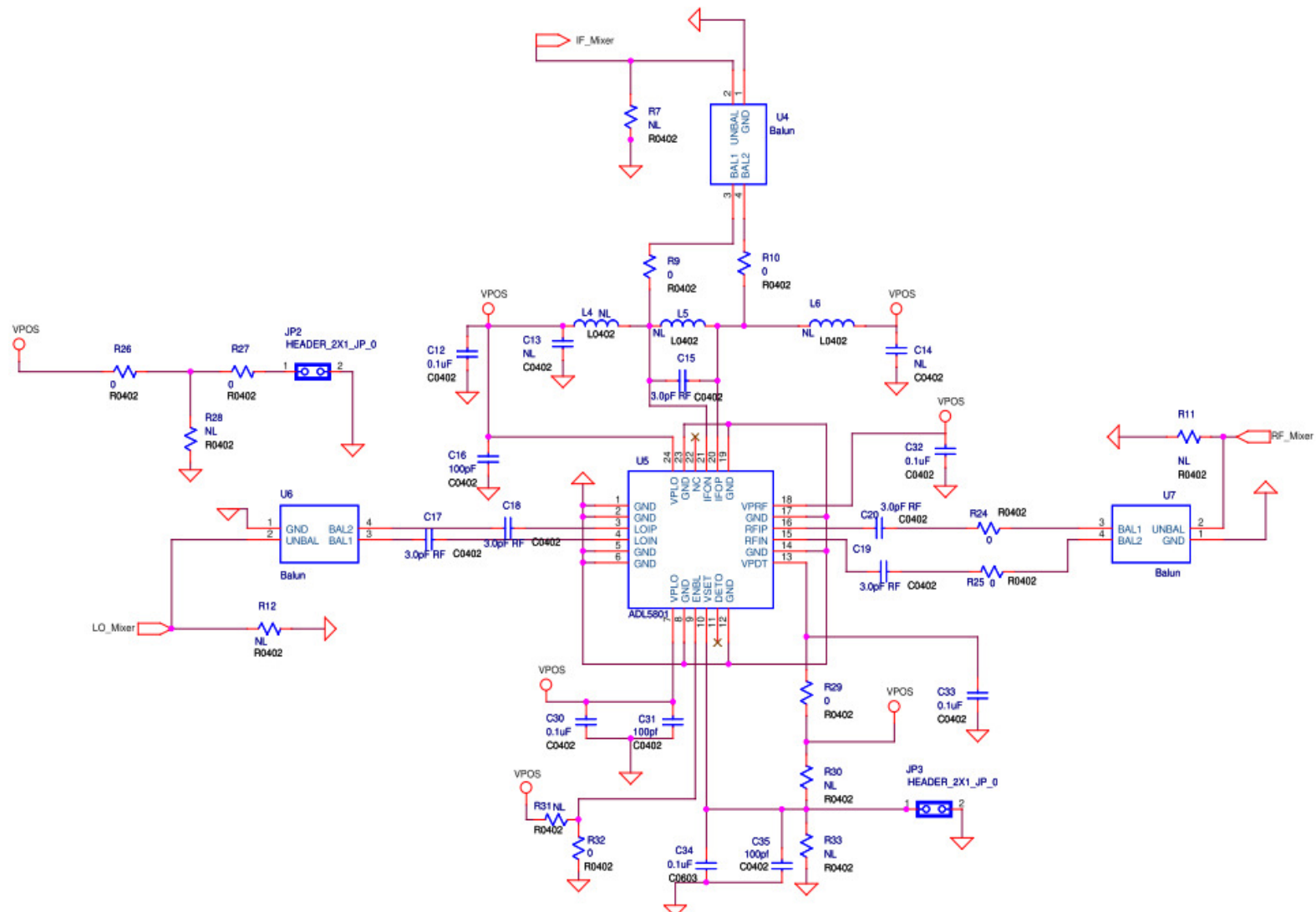


Figure 4.16: RF Mixer schematic

## RF and LO Ports:

The RF and LO input ports are designed for a differential input impedance of approximately  $50\Omega$ . Figure 4.17 and Figure 4.18 illustrate the RF and LO interfaces, respectively. Each of the RF and LO differential ports are driven through a balun for optimum performance. A balun converts between a balanced signal (two signals working against each other where ground is irrelevant) and an unbalanced signal (a single signal referenced with ground [13]). Anaren Inc. offers a high performance balun with  $50\Omega$  impedance on both balance and unbalanced ports with low insertion loss of 0.6dB from 5 to 6GHz [14]. To improve return loss over 5 to 6 GHz, 3.0pF capacitors are used.

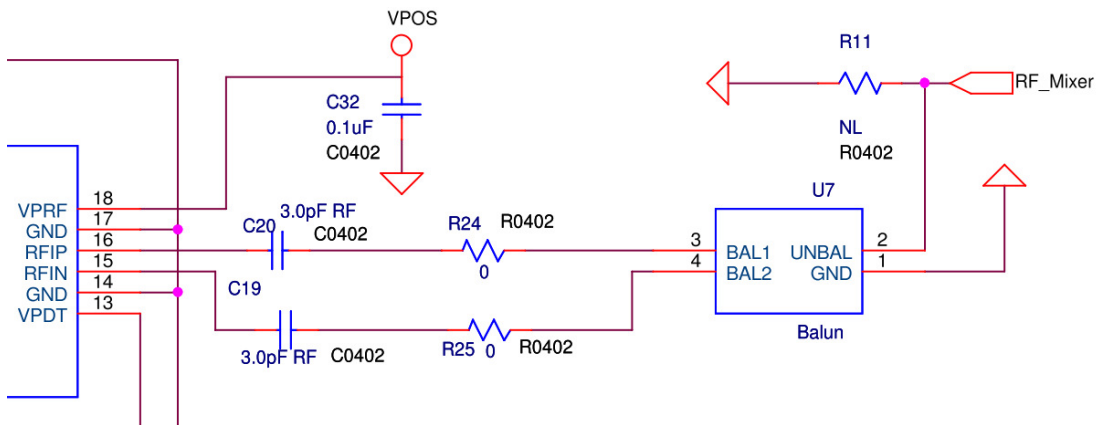


Figure 4.17: RF differential port driven through a balun

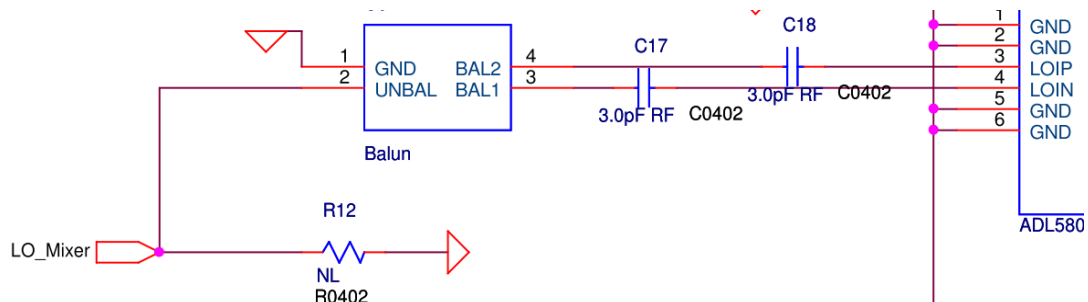
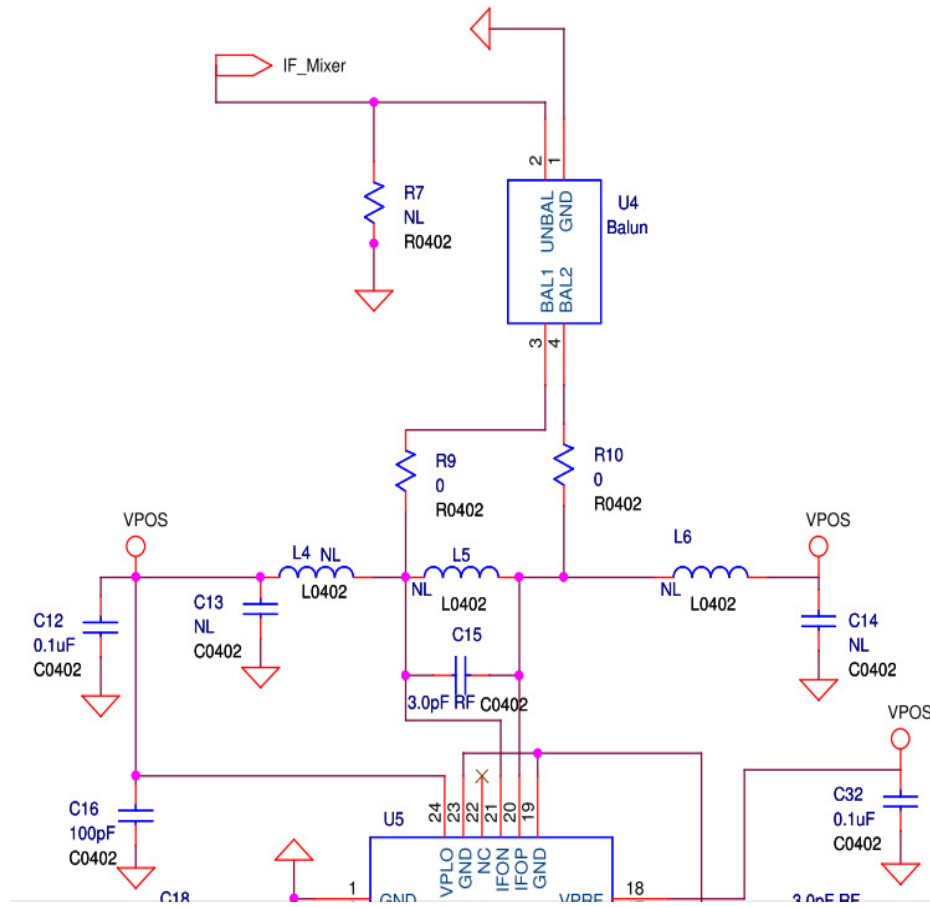


Figure 4.18: LO differential port driven through a balun

**IF Port:**

The IF port features an open-collector, differential output interface. The impedance of the IF port of the mixer is  $200\Omega$ , while impedance of all ports and connections in this FMCW system is  $50\Omega$ . Therefore, in order to avoid power reflection and to deliver maximum power transfer, a 4:1 impedance ratio transformer is being used to transform  $50\Omega$  load into a  $200\Omega$  differential load at the IF output pins. Anaren Inc. offers a high performance balun with  $200\Omega$  impedance on the balanced port, and  $50\Omega$  impedance on the unbalanced port with an insertion loss of 0.5dB from 5 to 6GHz [15]. Figure 4.19 shows a differential IF interface where pull-up choke inductors are used to bias the open-collector outputs. According to the mixer datasheet, the shunting impedance of the choke inductors used to couple DC current into the mixer core should be large enough at the IF frequency of operation not to load down the output current before it reaches the intended load . Also, the DC current rating of the selected choke inductors must be 45 mA or more [12].





**Figure 4.19:** 4:1 impedance ratio transformer is used to transform 50 Ω load into a 200 Ω differential load at the IF output pins

## Low-Noise Amplifier

For the system discussed in this paper, a distance range of 5 meters between the antenna and a reflector is proposed; therefore, the total distances that signal travels is 10 meter. Based on the Friis formula in the equation 4.1, the free space path loss for distance of 10 meter at frequencies between 5GHz to 6GHz is around -67dB as calculated below:

$$\begin{aligned}
 \text{FSPL} &= \left( \frac{4\pi d}{\lambda} \right)^2 \\
 &= \left( \frac{4\pi df}{c} \right)^2
 \end{aligned}
 \tag{4.1}$$

Where  $\lambda$  is the signal wavelength in meters,  $f$  is the signal frequency in hertz,  $d$  is the total distance in meters, and  $c$  is the speed of light.

Also, for this design, we assume that 50% of the transmit signal power (equivalent to 3dB) is lost on the reflector. Therefore, the total path loss is around -70dB (-67dB -3dB = -70dB). As discussed in section 4.1, the antenna transmit power is -41.3dB. Therefore, the received signal power at the antenna can be as low as -111.3dB. (-41.3dB-70dB = -111.3dB). For this design, it is assumed that the IF port of the mixer should have power level of at least -70dBm, so that signal can be received and processed with no further amplification. In order to receive -70dBm at the IF port, a minimum gain of 36.5dB is required from the LNA stage as shown in equation 4.2 (All units are in dB):

$$P_{IF} = P_r - L_{RF\ Circulator} - L_{RF\ Switch} - L_{Microstrip} + G_{LNA} + G_{Mixer} \quad (4.2)$$

$$G_{LNA} = P_{IF} - P_r + L_{RF\ Circulator} + L_{RF\ Switch} + L_{Microstrip} - G_{Mixer}$$

$$G_{LNA} = -70 + 111.3 + 1 + 1 + 1 - 7.8$$

$$G_{LNA} = 36.5$$

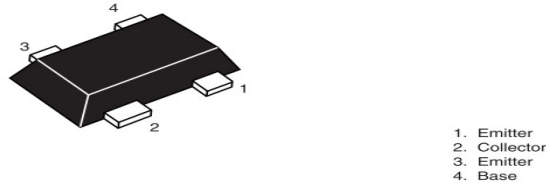
Where  $G_{Mixer}$  and  $G_{LNA}$ , are the Mixer and LNA gain respectively.  $P_r$  is the power received by antenna, and  $L_{RF\ Switch}$ ,  $L_{Microstrip}$ ,  $L_{RF\ Circulator}$  are RF switch, PCB microstrip, and RF circulator insertion loss respectively.

For this design, two different designs for LNA were considered.

### 1. LNA from a discrete transistor

The first LNA design that was studied and designed utilizes an NPN Germanium Carbon RF transistor. NESG7030M04 has ultra low noise figure with typical gain of 14dB from 5 to 6GHz. Figure 4.20 shows the pin-out and package [16]. At frequency

of 6GHz, NESG7030M04 has a typical noise figure of 0.75dB, and gain of 14dB at  $V_{CE}=2V$ . This LNA was biased, and simulated using Advanced Design System tool.



**Figure 4.20: NESG7030M04 pin-out**

According to the NESG7030M04 datasheet, the input matching consists of a shunt capacitor, a DC blocking capacitor, and a section of transmission line [16]. This matching circuit provides a reasonable trade-off between input return loss, and noise figure. The output impedance matching is a series transmission line, a shunt inductor, and a DC blocking capacitor. DC blocking capacitors are used to prevent the DC voltage from one part of circuit affect the other part of circuits [17].

Using the optimization cockpit in ADS, RF components for input and output matching were chosen and tuned to achieve 14 to 16dB of gain. They were also optimized so that input and output return loss was less than -10dB from 5GHz to 6GHz. As mentioned earlier, return loss of less than 10dB results in less than 0.5dB of mismatch power loss. All the parasitic of each lumped component was taken into account too. To optimize the design, the length of transmission line was tuned between 1 and 5mm, and the transmission line width was tuned between 0.25 to 0.5mm. Figure 4.21 shows that the optimized input transmission line length is 1mm, and its width is 0.25mm. Also, the optimized output transmission line length is 2mm, with 0.25mm of width. Figure 4.21 shows the LNA bias, input, and out match. Figure 4.22 shows the return loss and gain plots.

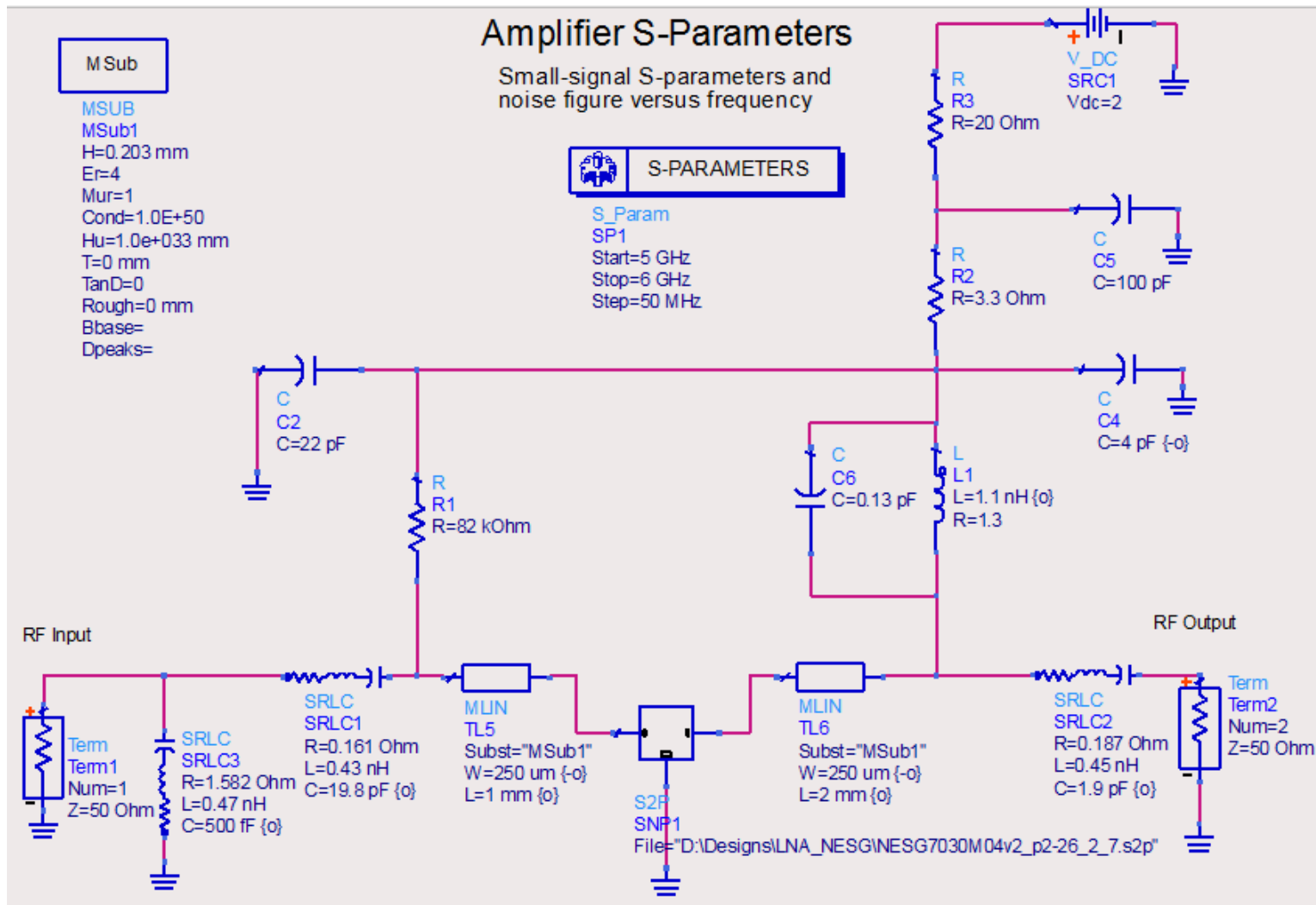
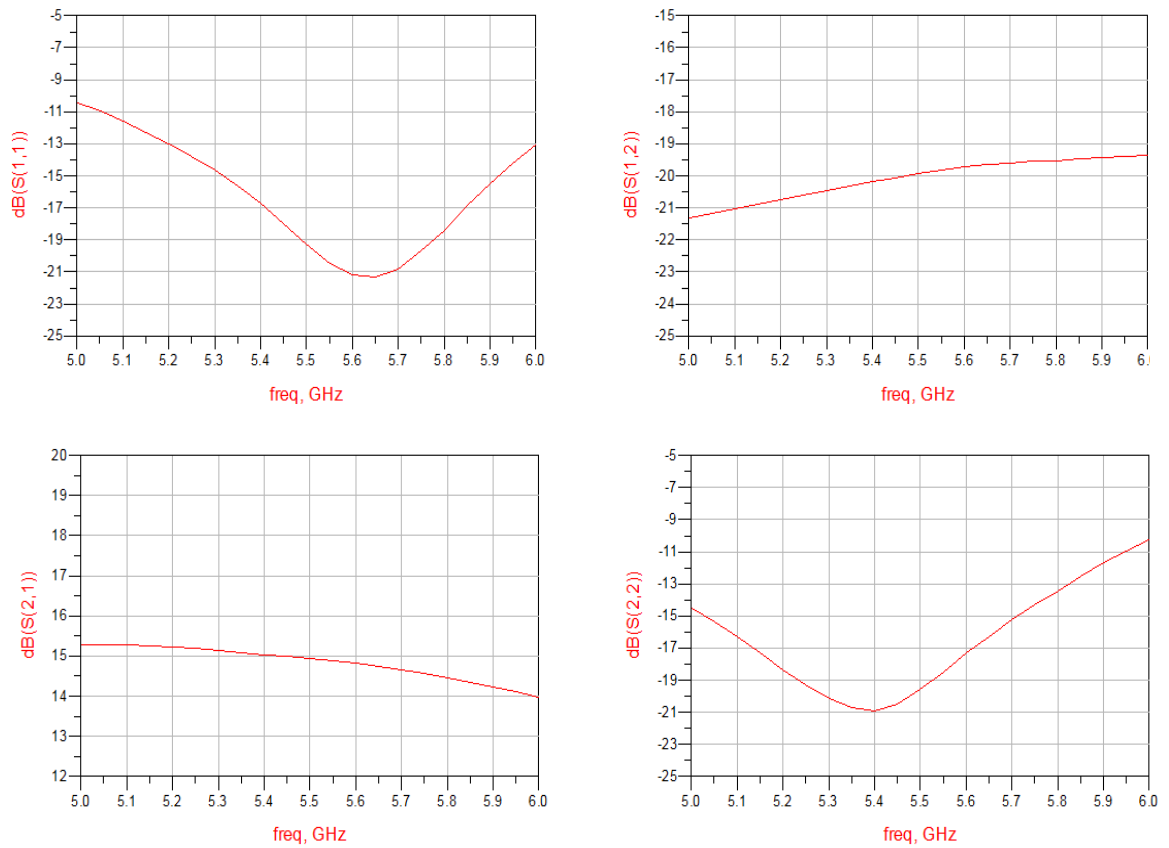


Figure 4.21: NESG7030M04 bias circuit and RF match



**Figure 4.22: NESG7030M04 LNA return loss and gain. The gain is 14 to 16dB, and input and output return loss are both better than -10dB.**

To achieve higher gain on the receive path, two or more LNAs can be cascaded. For example, gain of ~30dB can be achieved if two NESG7030M04 LNAs would be cascaded.

Although, designing an LNA from a discrete transistor seems to be the cheapest option, commercially available amplifier can better fit this application because there are many complete LNAs in the market at a low price that function from 5 to 6GHz.

However, the design of LNA from discrete transistors was discussed here to inform the

reader about the other options rather than a complete LNA packages available in the market, especially because the frequency band of interest is from 3 to 4GHz.

## 2. LNA in 1.5x1.5mm package

SKY65404 features an ultra low noise figure of 1.0dB in a 1.5x1.5mm package with gain of 13dB. A block diagram of SKY65404 is shown in figure 4.23. The device package and pin out for the 6-pin Quad Flat No-Lead are shown in figure 4.21 [18].

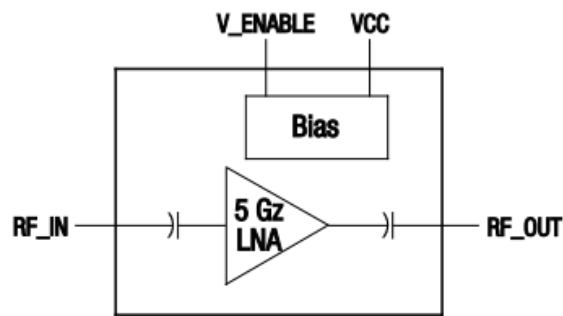


Figure 4.23: SKY65404 block diagram

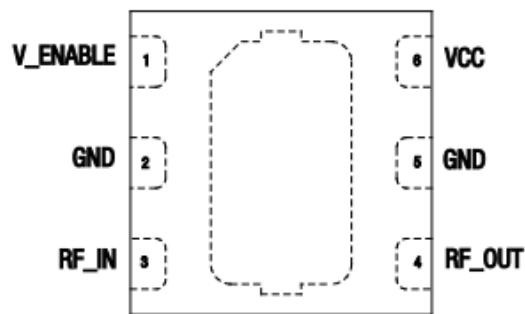


Figure 4.24: SKY65404 package and pin-out

SKY65404 is matched at RF output port (pin 4) and requires only a shunt capacitor match at the RF input port (pin 3). The VCC signal (pin 6) requires a simple bypass

circuit. An external resistor on the V\_ENABLE signal (pin 1) allows a wide range of control voltages to be used. Shutdown mode is achieved by switching the V\_ENABLE signal to 0V. The S-Parameters, noise figure, and IIP3 plots are shown in figure 4.25, 4.26, 4.27 and 4.28 respectively [18].

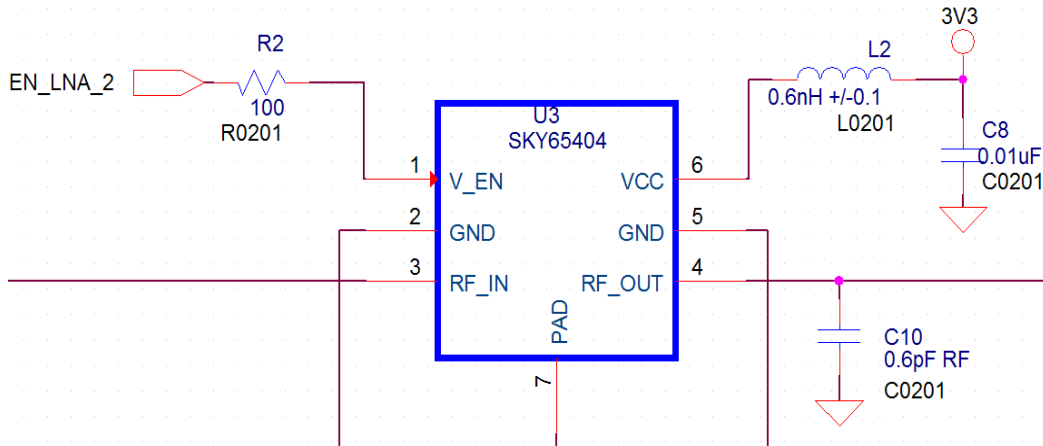


Figure 4.25: SKY65404 Low noise amplifier schematic diagram

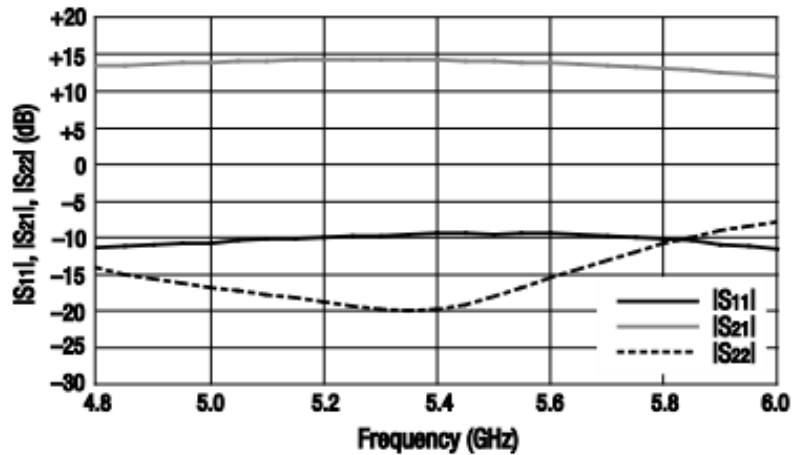


Figure 4.26: SKY65404 S11, S21, S22 (dB) vs. frequency (GHz)

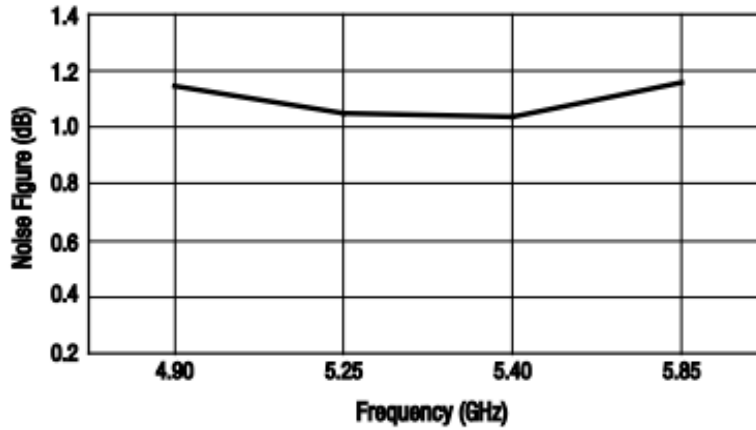


Figure 4.27: SKY65404 Noise figure (dB) vs. frequency (GHz)

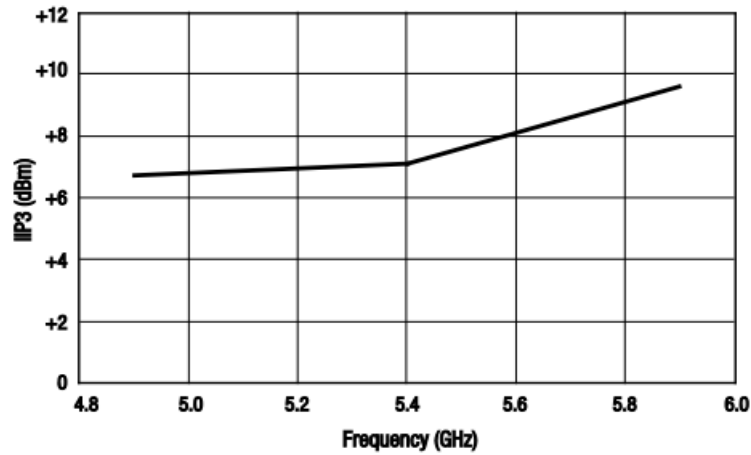


Figure 4.28: IIP3 (dBm) vs. frequency (GHz)

For this FMCW design, three SKY65404 LNAs were cascaded to achieve gain of 39dB.

Figure 4.29 shows the schematic diagram of the cascaded LNAs.

As discussed earlier, the RF mixer noise figure is around 16dB. Also, the attenuation between antenna and LNA input is 3dB (attenuation of RF circulator, RF switch, and microstrip path loss). The noise figure of receiver path between antenna and LNA input is equivalent to its attenuation. Therefore, the noise figure between antenna and LNA input is equivalent to 3dB.



Therefore, in order to minimize the total noise figure on the receive path, the LNA noise figure should be very low. Also, when LNAs are cascaded together, the total noise figure increases. The total noise figure for three stages of LNAs is calculated in equation 4.3:

$$F_{cascaded} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} \quad (4.3)$$

$$F_1 = F_2 = F_3 = 1.2 \text{ dB}$$

$$G_1 = G_2 = G_3 = 13 \text{ dB}$$

Each, LNA has a noise figure of 1.2dB, and gain of 13dB; therefore, the total noise figure will be 1.4dB.

To calculate the total noise figure of the receive path, noise figure of the mixer, the three stages of LNAs, and the attenuation between antenna and LNA should be summed together as shown below:

$$F_{cascaded} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2}$$

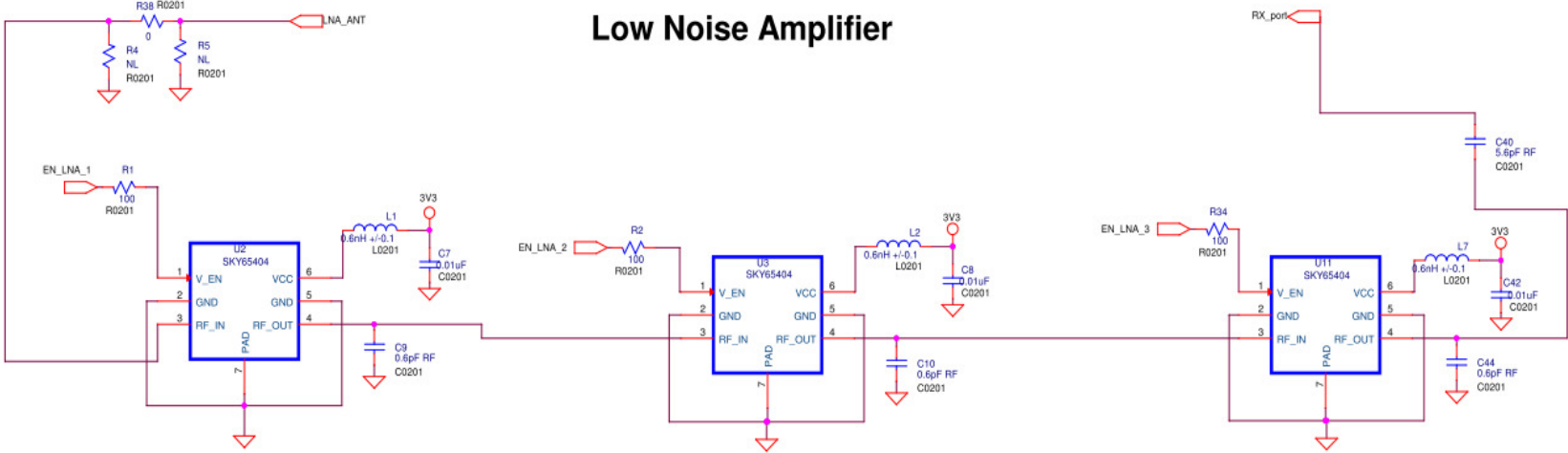
Where  $F_1 = 3\text{dB}$ ,  $G_1 = -2$  (attenuation between antenna and LNA input)

$F_2 = 1.4\text{dB}$  (total noise figure of three stages of LNAs),  $G_2 = 39\text{dB}$  (total gain of LNAs)

$F_3 = 16\text{dB}$  (Mixer noise figure),  $G_3 = 7.8$  (Mixer conversion gain)

Therefore, the total noise figure of the receive path is 4.1dB, and the total gain is 44.8dB.

The schematic diagram of low noise amplifier is shown in figure 4.29. The third amplifier is optional and can be by-passed.



**Figure 4.29: Cascaded Low Noise Amplifier with SKY65404**

## RF Switch

An RF switch is being used in this design to provide an option to use a circulator and one antenna for both transmit and receive, or use two antennas for transmit and receive with no circulator. In this design SKY13370 was used. SKY13370 is a GaAs pHEMT SPDT switch with  $50\Omega$  terminated outputs. This SPDT switch provides isolation of 31dB from 5 to 6GHz [19]. Isolation is a unit of measure (in dB) that states the separation of signal levels on adjacent ports of a device. The greater the isolation value, less interference from a signal on one port is present at the other [10]. Isolation of 30dB provides a very good separation between RF1 and RF2 ports. The SKY13370 comes in a small 1.5x1.5mm, 6 pin package [19]. The functional block diagram is shown in figure 4.30, and the pin configuration and package is shown in figure 4.31.

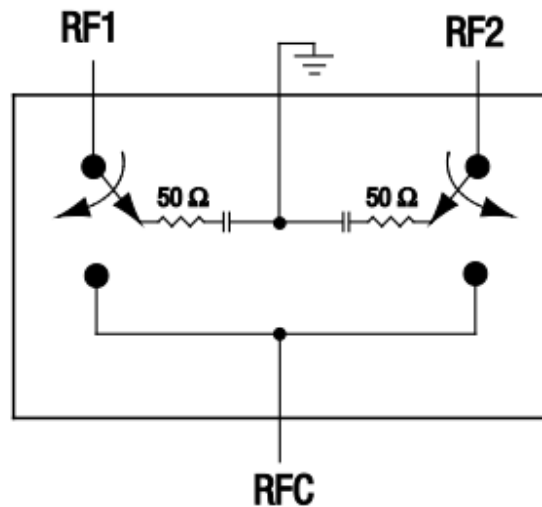


Figure 4.30: SKY13370 block diagram

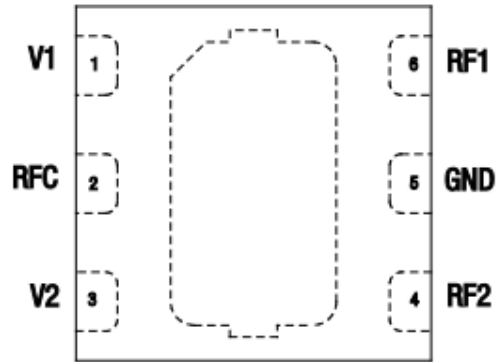


Figure 4.31: SKY13370 package and pin out

Switching is controlled by two control voltage inputs, V1 (pin1) and V2 (pins 3). Depending on the logic voltage level applied to the control pins, the RFC pin is connected to one of the two switched RF outputs, RF1 or RF2, using a low insertion loss path, while the path between the RFC pin and the other RF pin is in a high isolation state. According to the Switch datasheet [19], there is no internal DC blocking, therefore external DC blocking capacitors are required on all RF ports of the switch to filter out any DC signal that can potentially affect the RF performance (Figure 4.32).

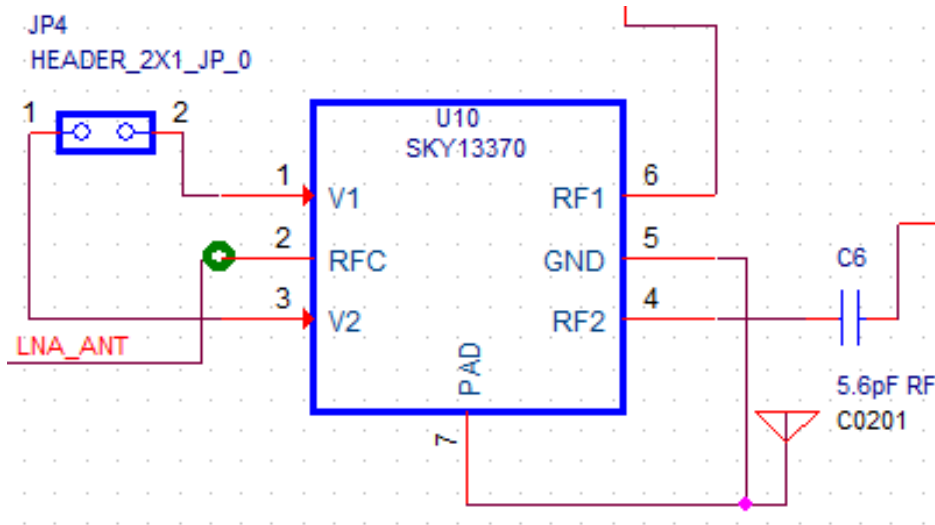


Figure 4.32: SKY13370 schematic diagram

The insertion loss, Isolation, and return loss plots are plotted in figure 4.33 to 4.36.

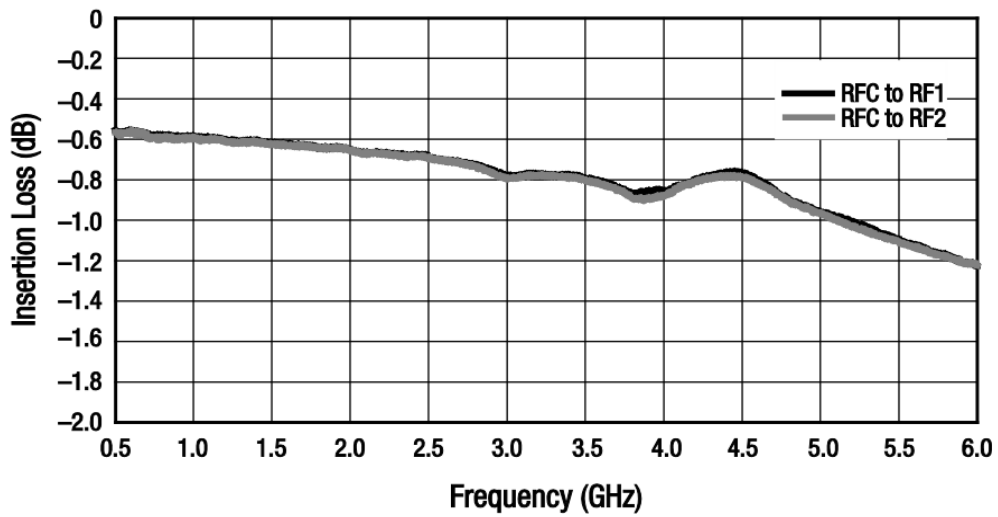


Figure 4.33: SKY13370 insertion loss (dB) vs. frequency (GHz)

Figure 4.33 shows the RF Switch insertion loss which is around 1.2dB from 5 to 6GHz.

Insertion loss measures the energy absorbed by the transmission line, or an RF component in the direction of the signal path in dB.

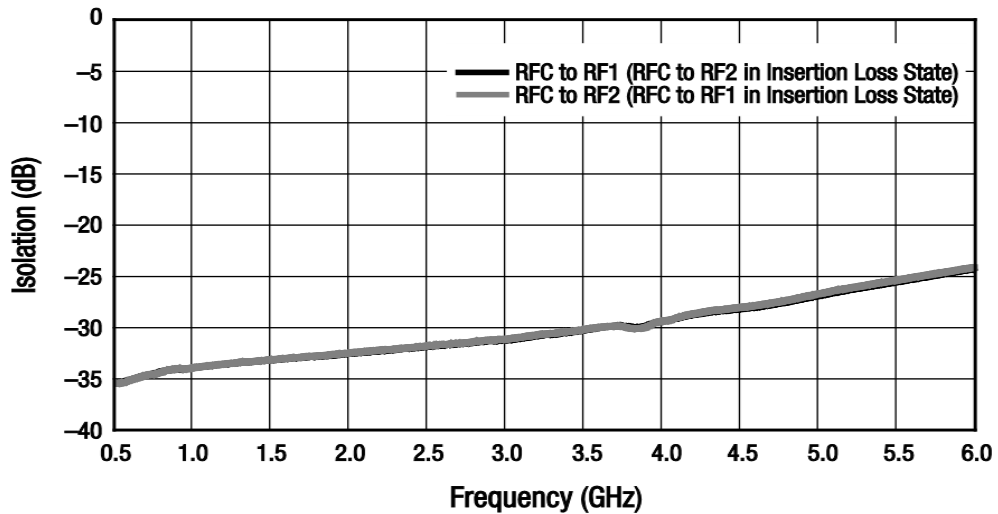


Figure 4.34:SKY13370 isolation (dB) vs. frequency (GHz)

Figure 4.34 shows the isolation of RFC to RF1 port and RFC to RF2 port. Isolation is a unit of measure (in dB) that states the separation of signal levels on adjacent ports of a device. The greater the isolation value, less interference from a signal on one port is present at the other [10]. The isolation of the SKY13370 RF switch is better than -24dB.

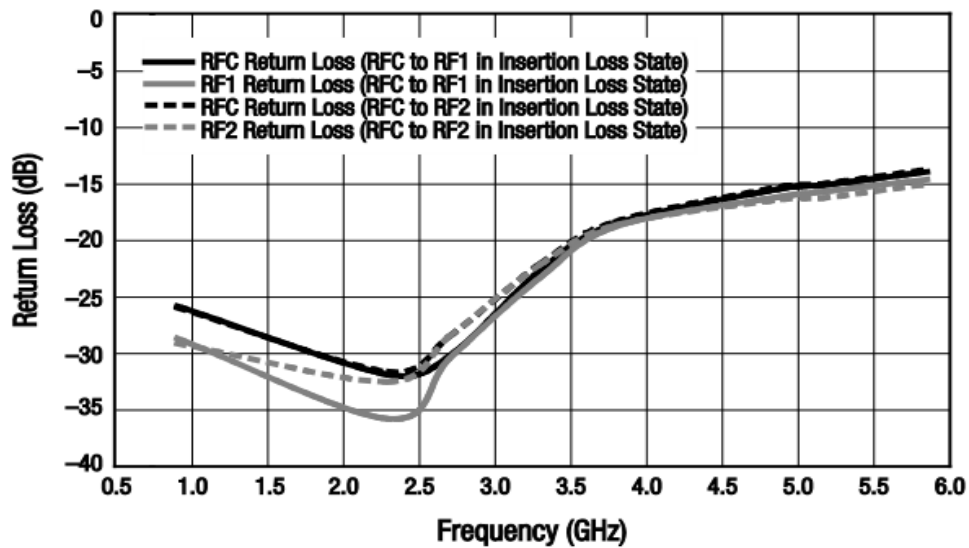


Figure 4.35: SKY13370 return loss (dB) vs. frequency (GHz) in insertion loss state

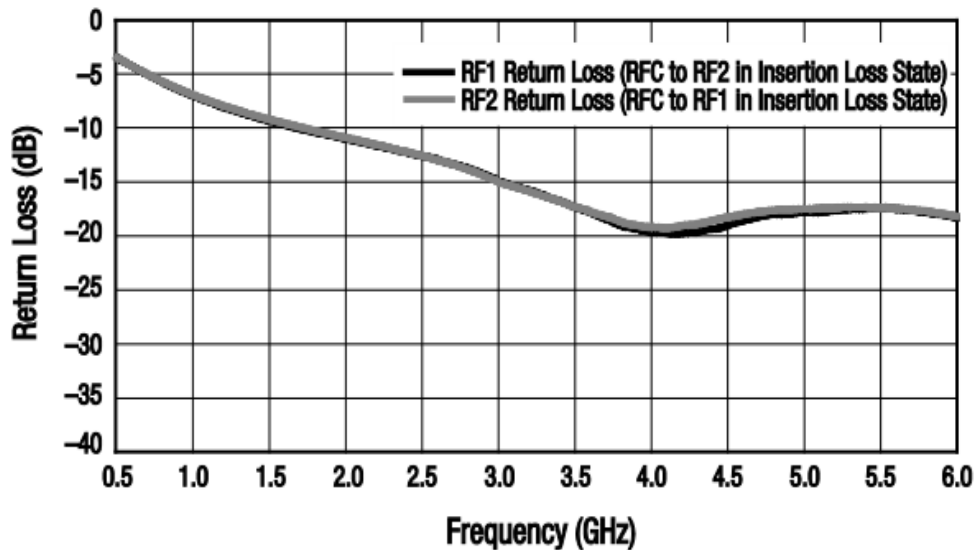


Figure 4.36: SKY13370 return loss (dB) vs. frequency (GHz) in isolation state

Figure 4.35 and 4.36 show the return loss RF switch in insertion loss state and isolation state respectively. Return loss is a measure of the effectiveness of power delivery from a transmission line to a load such as an antenna [8]. In other words, the mismatch power loss is lower when the return loss is lower. From the above plots, the RF Return loss of -15dB results in about 0.2dB of mismatch power loss, which is negligible.

### RF circulator

Instead of using two antennas for transmit and receive, FMCW radar can be built with one antenna using a circulator. A circulator is a passive three port device in which RF signal entering any port is transmitted to the next port in rotation only. In this design, a micro-strip circulator from Trak Microwave Corporation was used [20]. It has maximum insertion loss of 1dB, and isolation of better than 15dB between each port.

Figure 4.37 shows the circulator and its dimensions.

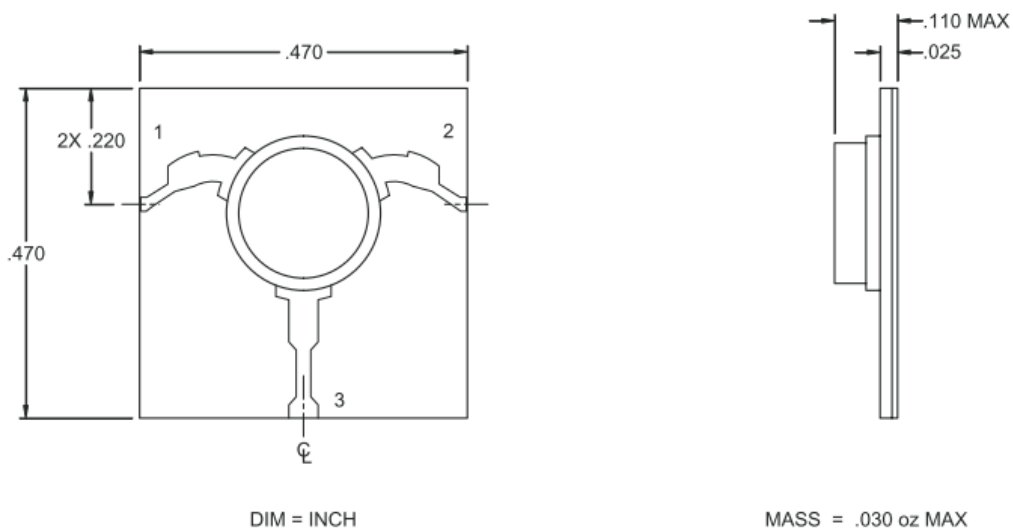


Figure 4.37: C5258/DA circulator

For this design, port 1 is connected to power amplifier output, port 2 is connected to the antenna connector, and port 3 is connected to the RF switch which will be ported to the low noise amplifier on the receive path (Figure 4.38).

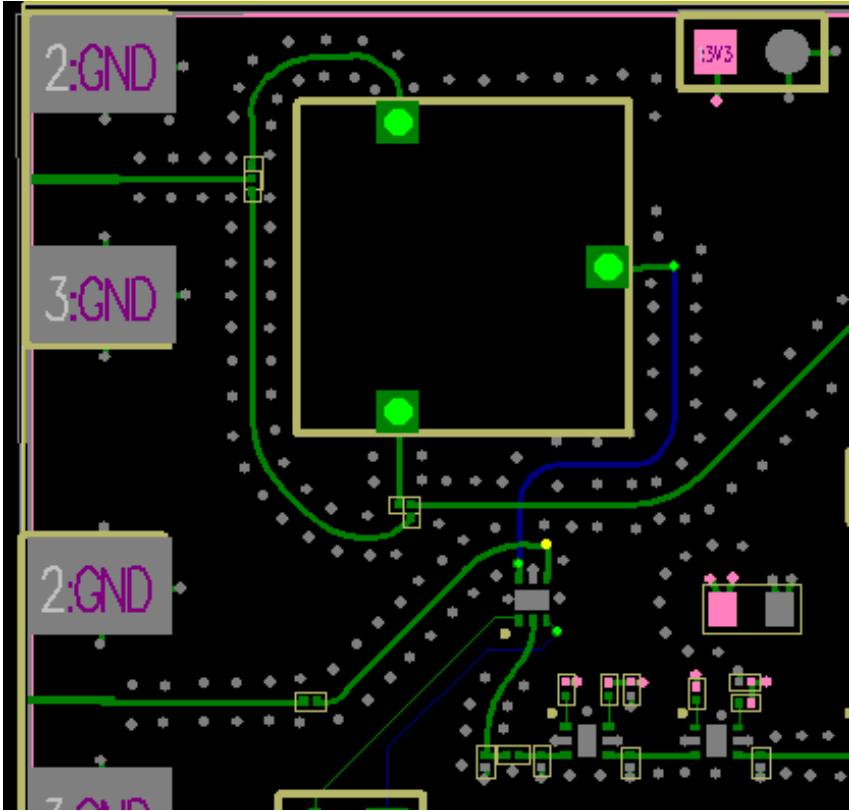


Figure 4.38: Layout topology for RF Circulator

Once the cost and size of antenna is determined (reviewed in the following section), then the decision can be made to use one antenna with a circulator, or to use two antennas. If two antennas are to be used instead of one antenna with a circulator, the capacitor between power amplifier output and circulator port 1 should be removed. Additionally, the capacitor between antenna and port 2 of circulator should also be removed, so that all RF signal from PA output would be routed toward transmit antenna with no effect on



impedance. In this case, control signal on the RF switch enables port 2 of the switch so that RF signals receiving at the second antenna is routed toward the low noise amplifier.

### Antenna

Different antennas were studied for this design. The size, cost and performance was compared to decide which one fits for this application the best.

#### 1. A center fed half-wavelength dipole

The antenna is a center fed half-wavelength dipole fed with RP-SMA connector. This antenna has an average gain of 1dB from 5 to 6GHz, with VSWR less than 2. The length of it is around 10cm, and its diameter is less than 1cm.

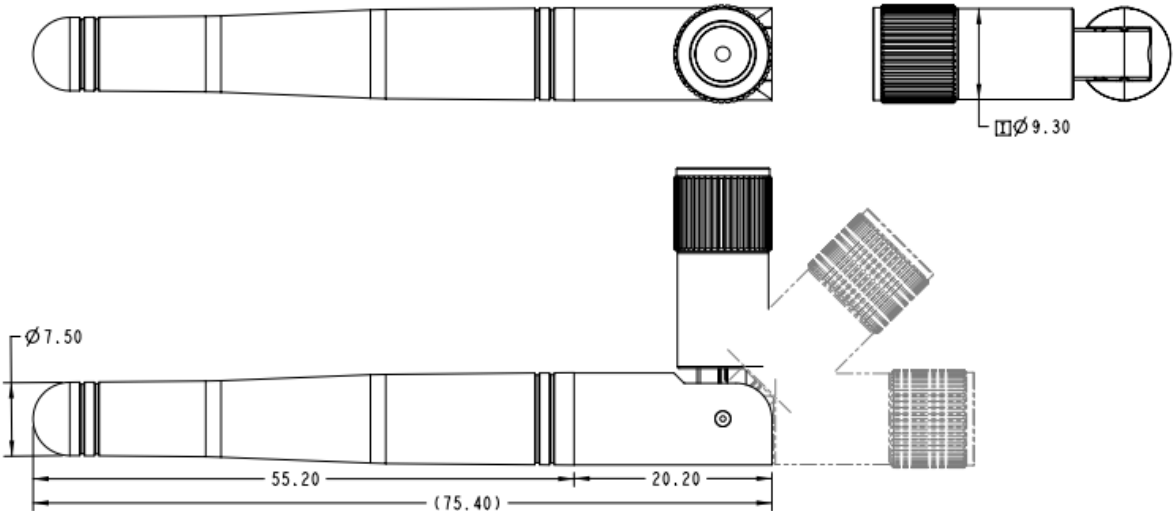


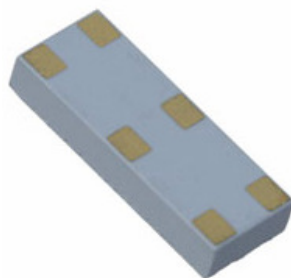
Figure 4.39: Center fed half-wavelength dipole



**Figure 4.40: Photo of a center fed half-wavelength dipole**

## **2. Ceramic Antenna**

A Ceramic Antenna from Ethertronics (M830510) is a candidate that comes in a very small package. It has efficiency of 69%, maximum VSWR of 3:1, and it comes in a small package of 8x3x1.3mm [21].



**Figure 4.41: Ceramic antenna in 8x3x1.3mm package**

Figure 4.42 shows the ceramic antenna efficiency and return loss.

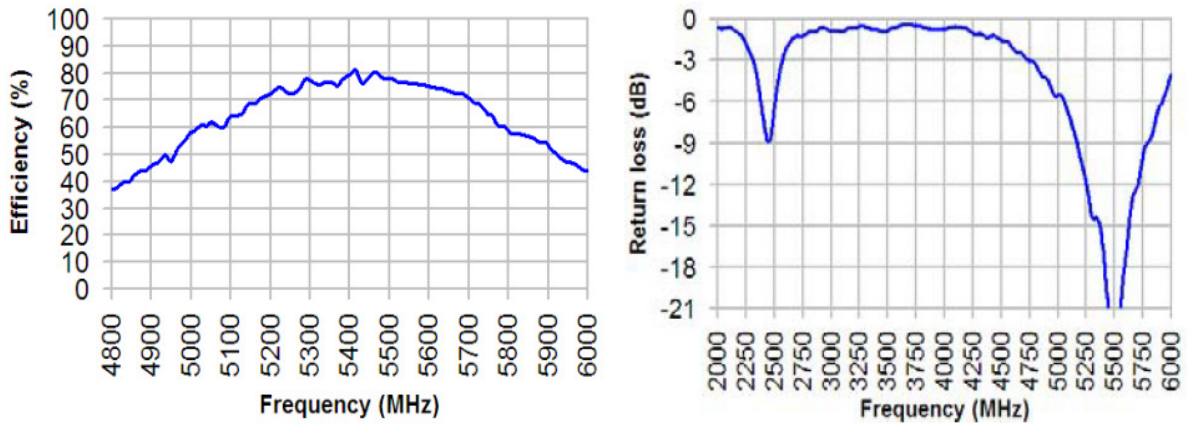


Figure 4.42: Ceramic antenna efficiency and return loss

The return loss of the ceramic antenna from 5 to 6GHz is better than 5dB which results in about 1dB of signal power loss.

The radiation patterns of M830510 antenna is shown in figure 4.44.

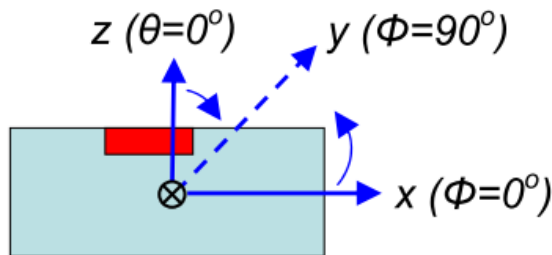


Figure 4.43: Ceramic antenna position

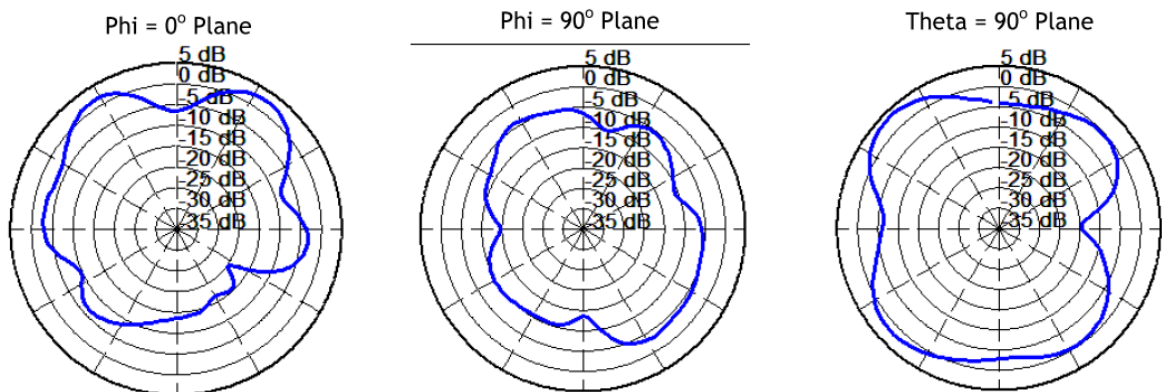


Figure 4.44: Ceramic antenna gain at different orientations

### 3. PCB Antenna

Another omni-directional antenna in a small profile and reasonable performance is a PCB antenna from Laird Technologies.



Figure 4.45: Laird PCB Antenna

This antenna has VSWR of less than two, and the return loss is better than 10dB from 5 to 6GHz. Figure 4.46 shows the return loss vs. frequency. The size of this antenna is 5x1.7cm. The antenna radiation patterns are also shown in figure 4.47 to 4.49 [22].

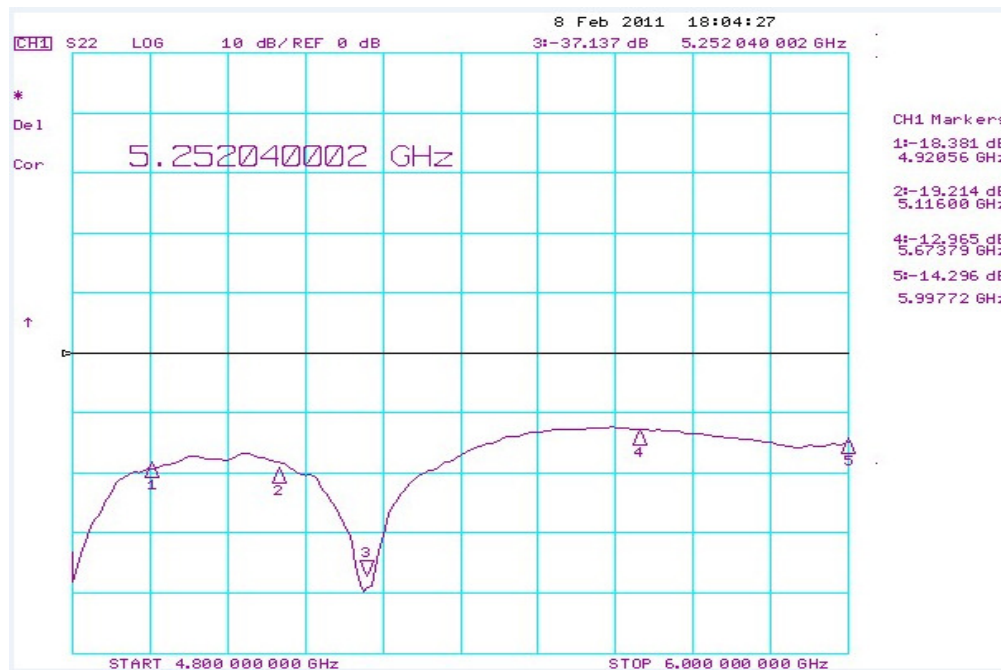


Figure 4.46: PCB antenna return loss

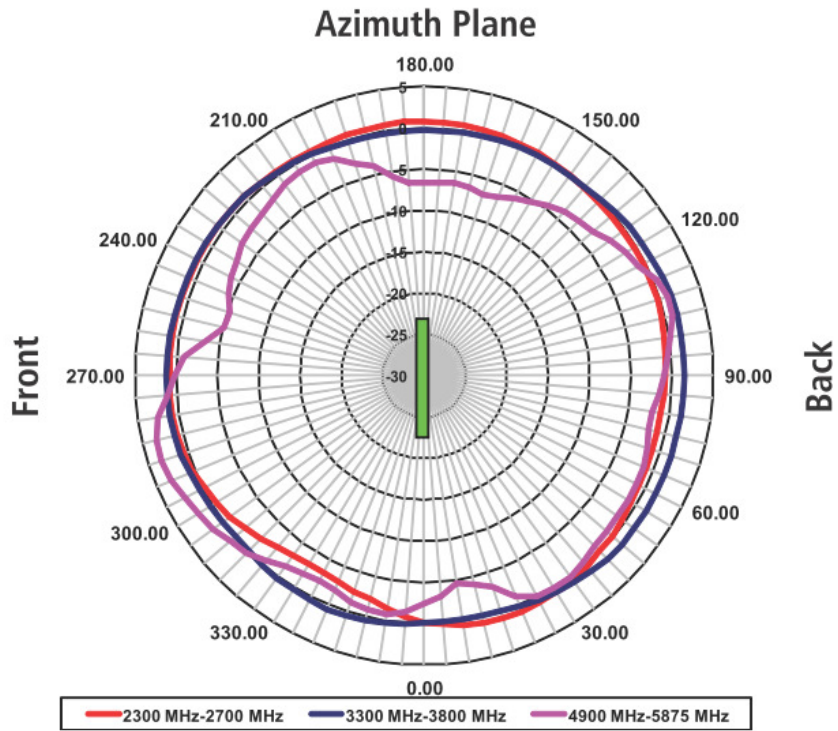


Figure 4.47: PCB antenna gain (Azimuth plane)

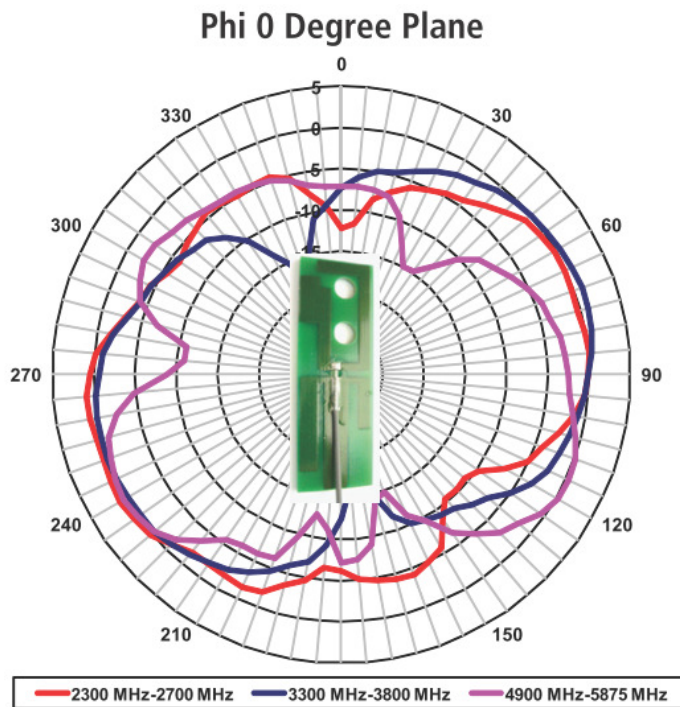
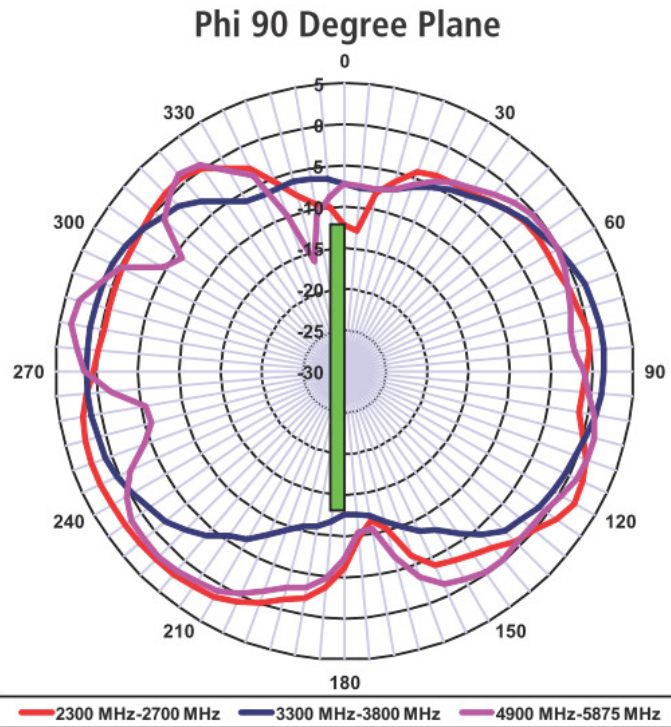


Figure 4.48: PCB antenna gain (Phi 0 degree plane)



**Figure 4.49: PCB antenna gain (Phi 90 degree plane)**

Therefore, based on the PCB antenna radiation patterns, the antenna gain is typically around 0dB. Comparing the dipole, ceramic and PCB antenna, for this application the PCB antenna is the best solution because of its compact size, fairly good performance, and its low cost.

# CHAPTER 5

## FMCW PCB Layout

In this section, the requirements for RF routing in a PCB board is discussed, and the PCB layout for FMCW radar is illustrated. Some of the guidelines for PCB layout are also mentioned.

### 5.1 RF Routing

Voltage of analog signals can be any level at any time, and frequency of the signal can be anything. The signals for this circuit are up to a few hundred MHz. Unlike standard analog signals, frequency of RF signals are very high into GHz. RF transmission lines in a PCB are designed to pass the signal at the desired band. Specifically for this design signals from 5 to 6GHz are the frequency of interest.

RF signals are very sensitive to noise, ringing and reflections. Therefore, it is critical to take into account transmission line affect on wires that carry RF signals. A transmission line is a wire that is on the order of the wavelength of signal. When the wavelength of signal is much longer than the size of wire, the wire can be treated as an ideal wire. Therefore, the voltage on both end of wire will be approximately equal. However, when the wavelength of signal is close to the length of the wire, the wire must be treated as a transmission line. In this application, the wavelength of signal is a few centimeter which is close to circuit size. Thus all lines must be treated as transmission lines that carry the RF signal on the PCB. In order to minimize Return Loss and VSWR, RF signals need impedance ( $Z_0$ ) matching. That means the impedance of a given

transmission line should be the same as impedance of the source and load at each end of transmission line. Transmission line model consists of series inductor and resistor, and shunt capacitor and resistors.

Impedance of RF traces on PCB board is a function of conductor width, and thickness, dielectric constant, and dielectric height. In the next section, dielectric constant or permittivity definition is reviewed.

### **Dielectric Constant (Permittivity)**

Permittivity is the measurement of relative capacitance of insulating material to that of air or a vacuum [23]. In other words, electromagnetic waves are slowed down as they are transmitted through an insulating material. For the circuit designs beyond 1GHz, effect of dielectric constant on propagation delay and signal attenuation should be considered. In general, materials with lower dielectric constant cause smaller propagation delay and signal attenuation. To calculate propagation delay due to the material's dielectric constant for a microstrip circuit, the following circuit can be used:

$$t_{pd} = 1.017\sqrt{\epsilon_{eff}}$$

Where  $t_{pd}$  is propagation delay in nsec/foot, and  $\epsilon_{eff}$  is effective dielectric constant of material [23].

Following the formula, the capacitance along a transmission line is higher when insulators with higher relative permittivity are used. The transmission line impedance, and signal velocity are inversely proportional to relative permittivity. When possible,



materials with smallest relative permittivity should be chosen for high frequency signals to avoid signal attenuation and impedance. [24].

Relative permittivity is a function of frequency in materials. The variation over frequency is small in some materials, but they are expensive. In some inexpensive materials like FR4 that are common to use in printed circuit boards, relative permittivity changes more over frequency. In FR4, the dielectric constant varies from 4 to 4.6 over 3 to 10GHz. As the relative permittivity varies the impedance of transmission changes as well, and it causes signal reflection that can have a major effect in RF signal performance. Therefore, for a given bandwidth, variation in relative permittivity should be taken into account to avoid system malfunction.

In this design, FR4 material is suggested to be used because of its low cost. Although FR4 relative permittivity varies over frequency, but its variation from 5 to 6GHz is negligible (around 4.2). All RF traces must have 50 ohm impedance for system optimal performance. The RF trace thickness, width, dielectric constant, dielectric thickness, copper conductivity, and loss tangent determine the impedance of RF trace. All RF traces are surrounded by ground vias for ground return path resulting in better isolation from the other RF traces. Therefore, a coplanar waveguide with ground plane is the best model that can be used for RF traces (Figure 5.1).

## Coplanar Waveguide

In reality, RF Microstrip transmission lines with ground vias in surrounding are coplanar waveguide with ground. Figure 5.1 shows the topology of coplanar waveguide.

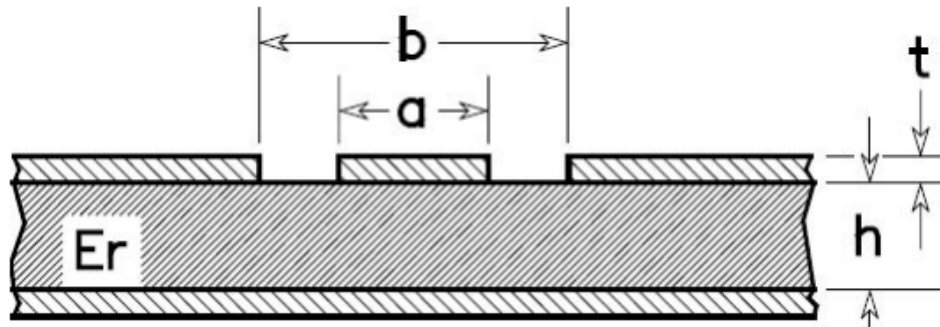


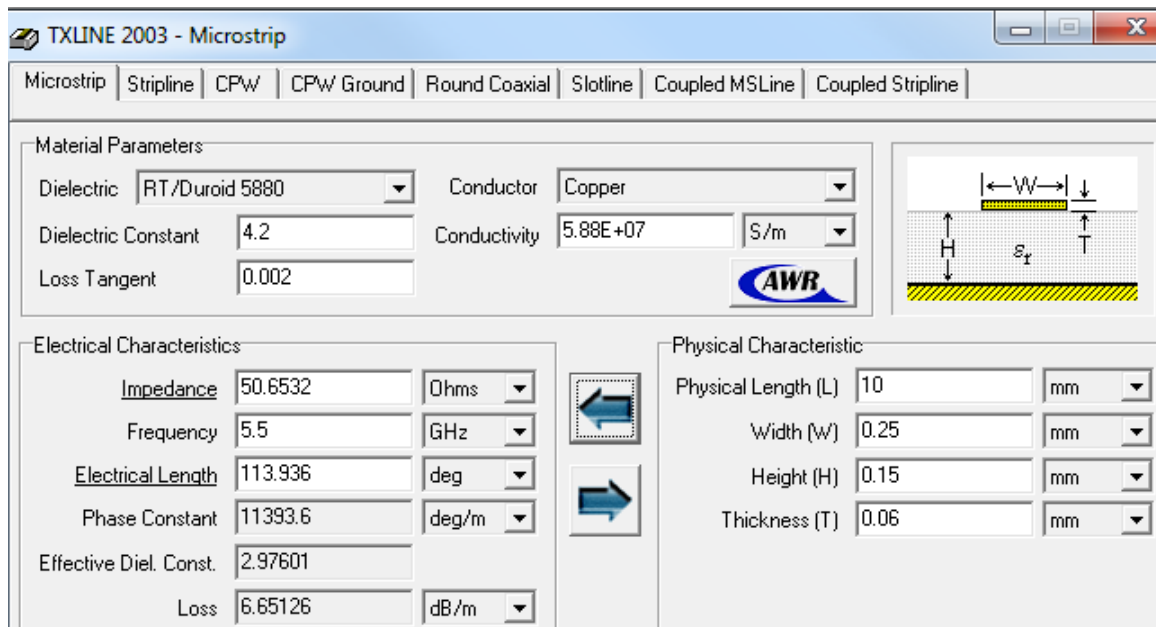
Figure 5.1: Coplanar Waveguide

In order to calculate the required trace width, dielectric height, and microstrip thickness at frequencies between 5 to 6GHz, a free public transmission line calculator named TX-LINE from AWR Corporation was used (Figure 5.1). Given that dielectric constant is around 4.2 at the 5.5GHz, and copper conductivity is around  $5.88E+7$  S/M, impedance of 50 ohms can be achieved when:

Trace width= 0.25mm

Dielectric height= 0.15mm

Trace height = 0.06 mm



**Figure 5.2: Transmission line calculator**

## 5.2 Layout

The PADS Layout application from Mentor Graphics was used to do the PCB layout for this design (This application is public). This module is a 6 layer board in 60x30mm. This board consists of one power plane split to two different parts to supply 3.3V for RF components, and 3.8V for the Mixer. The complete PCB layout is shown in figure 5.3.

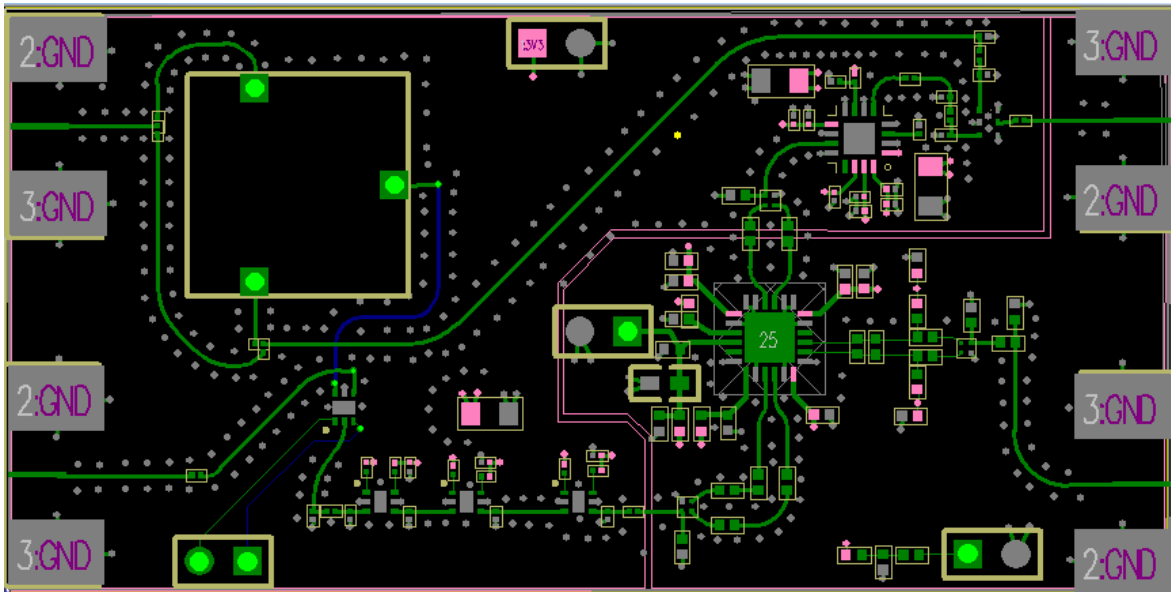


Figure 5.3: PCB layout for the proposed FMCW radar

### 5.3 PCB Stack-up and Layer Definition

The PCB for this design consists of 6 layers. All layers use 1 oz. copper. The PCB is FR-4 material with a 1mm total thickness.

Layer 1	0.035 mm
	0.150 mm
Layer 2	0.035 mm
	0.150 mm
Layer 3	0.035 mm
	0.200 mm
Layer 4	0.035 mm
	0.150 mm
Layer 5	0.035 mm
	0.150 mm
Layer 6	0.035 mm

Figure 5.4: PCB stack-up

## **Layer Definition**

In this section, it is defined the role of each layer.

### **Layer 1:**

Components, RF routing, general routing, and ground pour are placed in the layer 1.

Figure 5.5 shows layer 1.

### **Layer 2:**

A complete ground plane is on layer 2. All components and routing is reference to the ground plane on layer 2.

### **Layer 3:**

This layer is reserved for any additional and optional signal routing

### **Layer 4:**

The two power planes for 3.3V and VPOS supply are split in layer 4. Figure 5.6 shows the topology of power planes.

### **Layer 5:**

A complete ground plane is on layer 5. The routing on bottom layer is reference to the ground plane on layer 5.

### **Layer 6:**

RF routing, signal routing, and ground pour is on the bottom layer (layer 6). Figure 5.7 shows the topology of bottom layer.

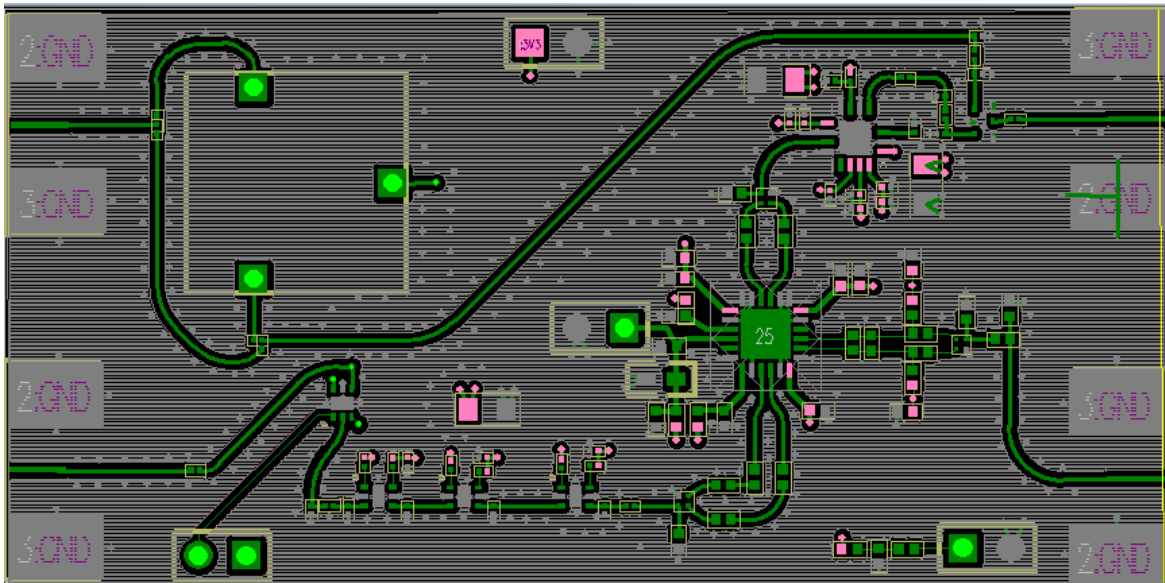


Figure 5.5: Components, RF routing, general routing, and ground pour are placed in the layer 1

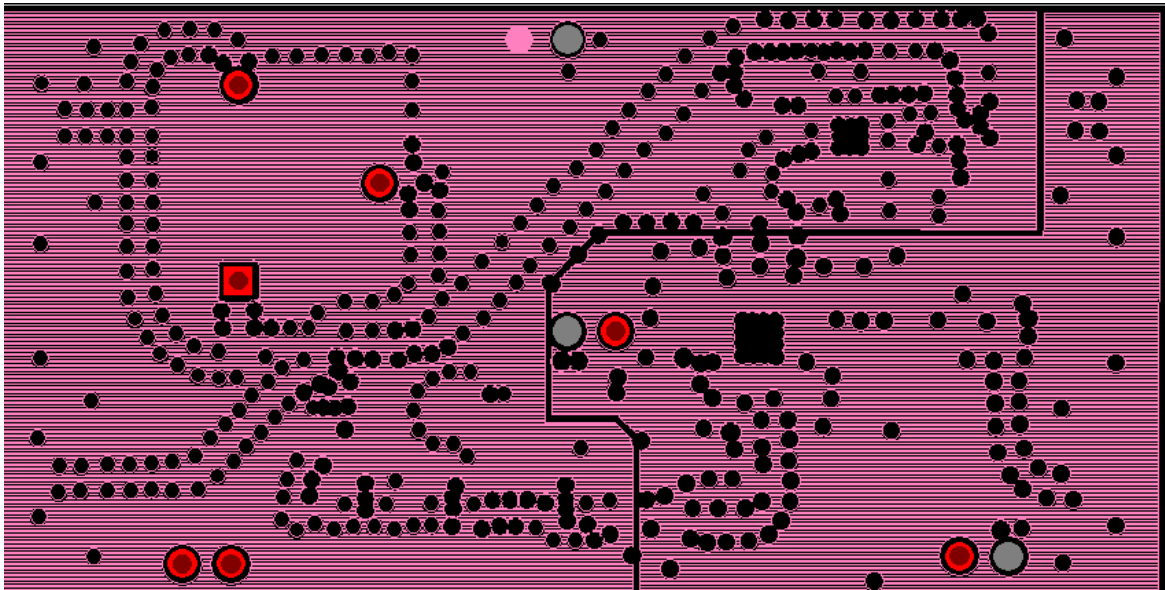


Figure 5.6: Split power plane in layer 4.

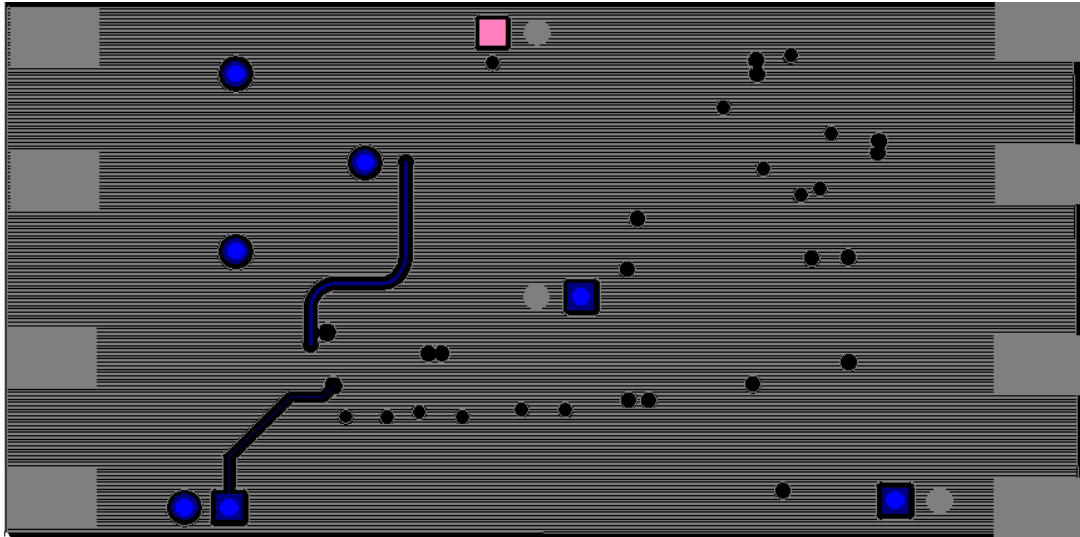


Figure 5.7: Bottom layer

## 5.4 Board Layout Guidelines

All RF signals should be referenced to a solid ground plane on the adjacent layer. In this design, RF traces are on top and bottom layers, and solid ground plane exists on layer 2 and 5.

To avoid cross talk between RF traces, they should be spread apart from each other as much as possible. It is necessary to round the corner of all RF traces to keep the trace impedance close to  $50\Omega$  (Figure 5.8). In addition, each trace should have stitching vias along it to create isolation. Figure 5.9 should how stitching vias are places along the RF trace (each stiching via must be placed manually).

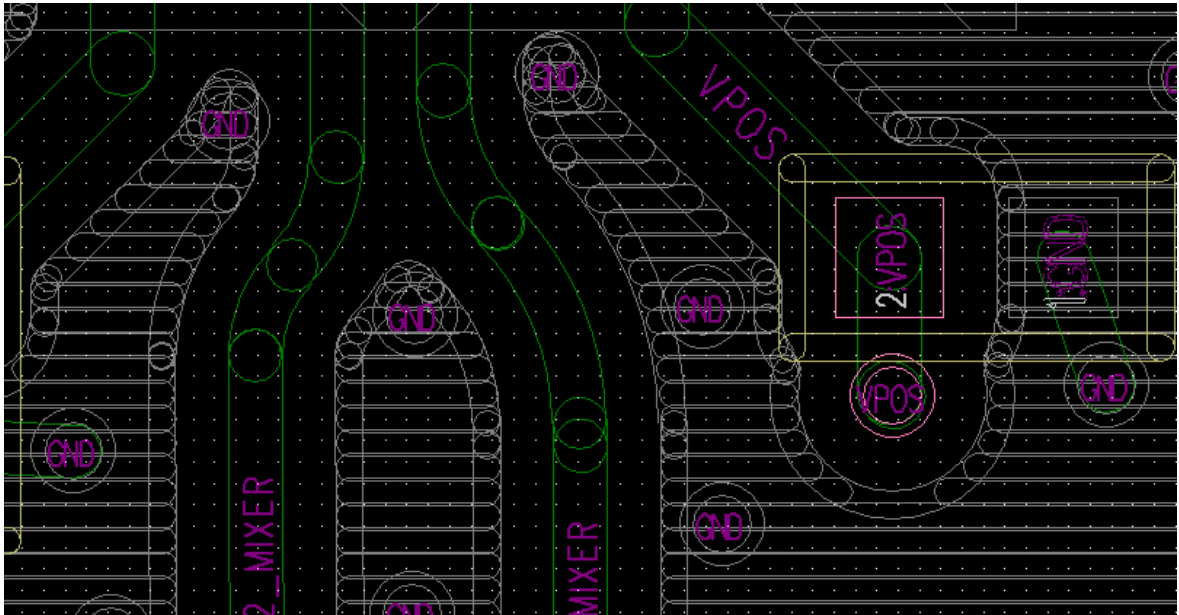


Figure 5.8: RF traces configuration.

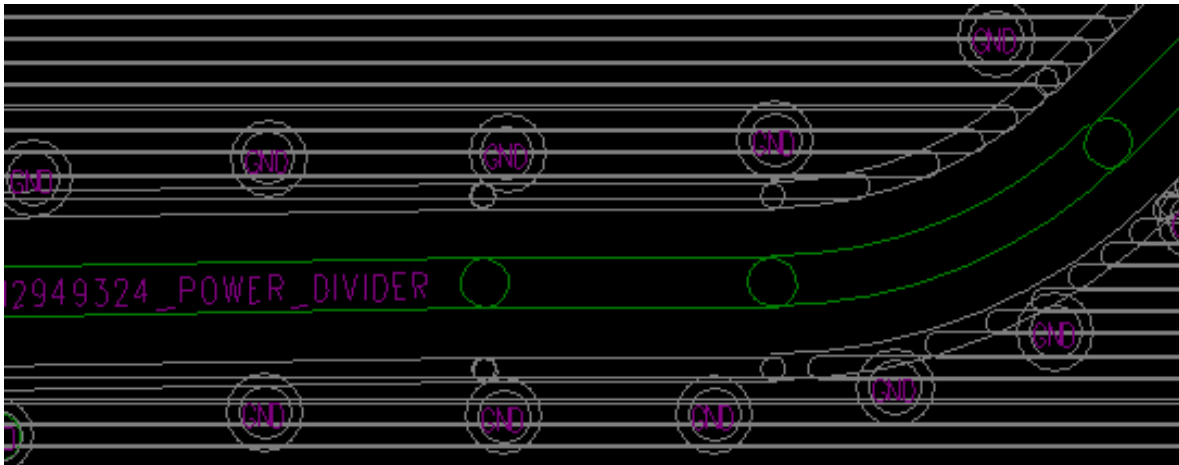


Figure 5.9: Stitching vias along the trace.



# CHAPTER 6

## Conclusion

An UWB-compatible FMCW based approach can be used for boundary detection in an eldercare monitoring system. This thesis presented the design of a low cost approach to small PCB footprint distance detection circuitry for the boundary detection system. The goal of this thesis was to give an overview and discuss the RF components that need to be used in such a system. The pin-out and performance of each component was discussed in detail to inform the reader that why the specific component was selected for this system. In addition, the schematic and PCB layout for the system circuitry was presented. The PCB layout for high frequency systems is very critical, and this paper offered steps and guidelines than should be taken in to account for the board layout. However, the PCB module was not fabricated in this project. To obtain the test data, future work can be done to fabricate this module for future work.

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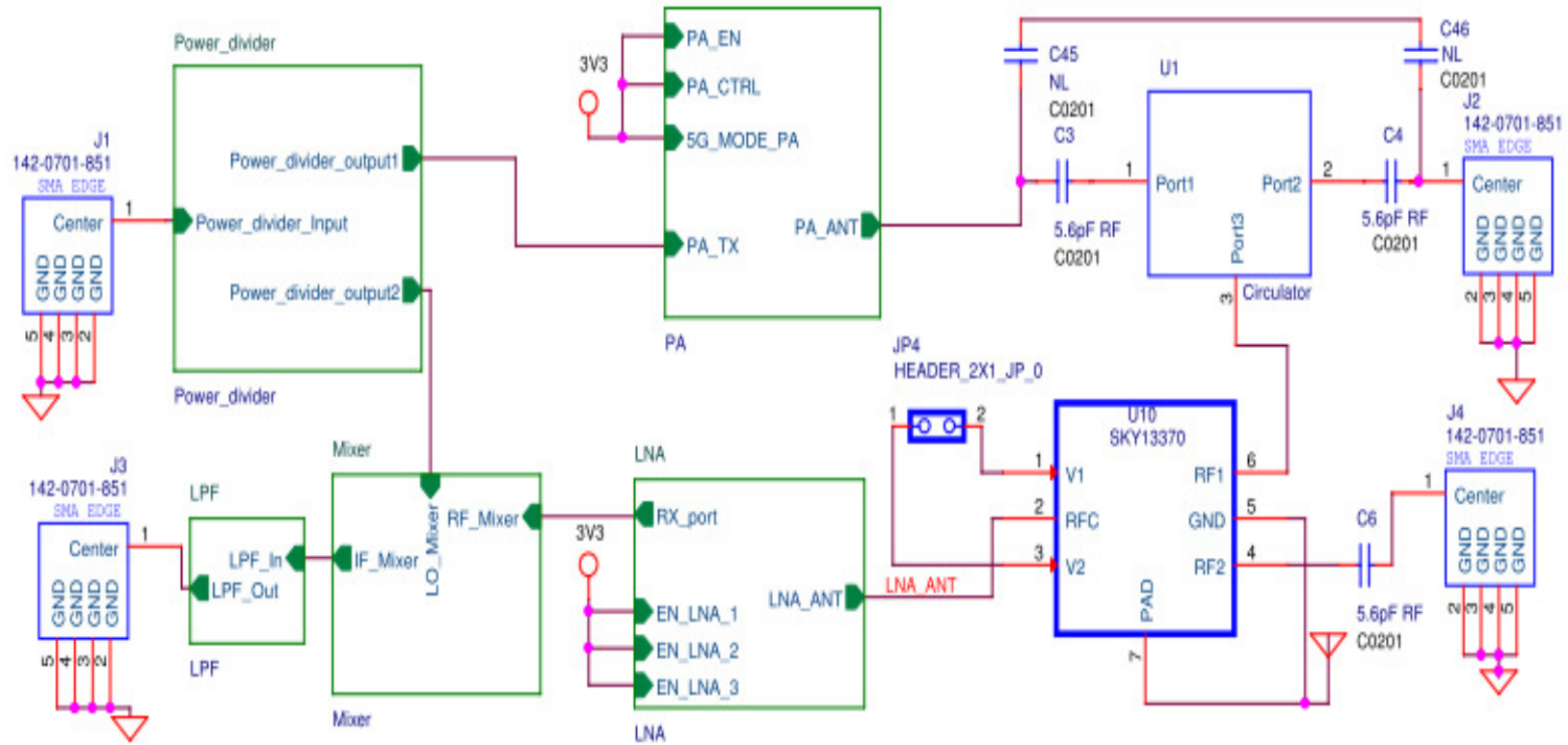
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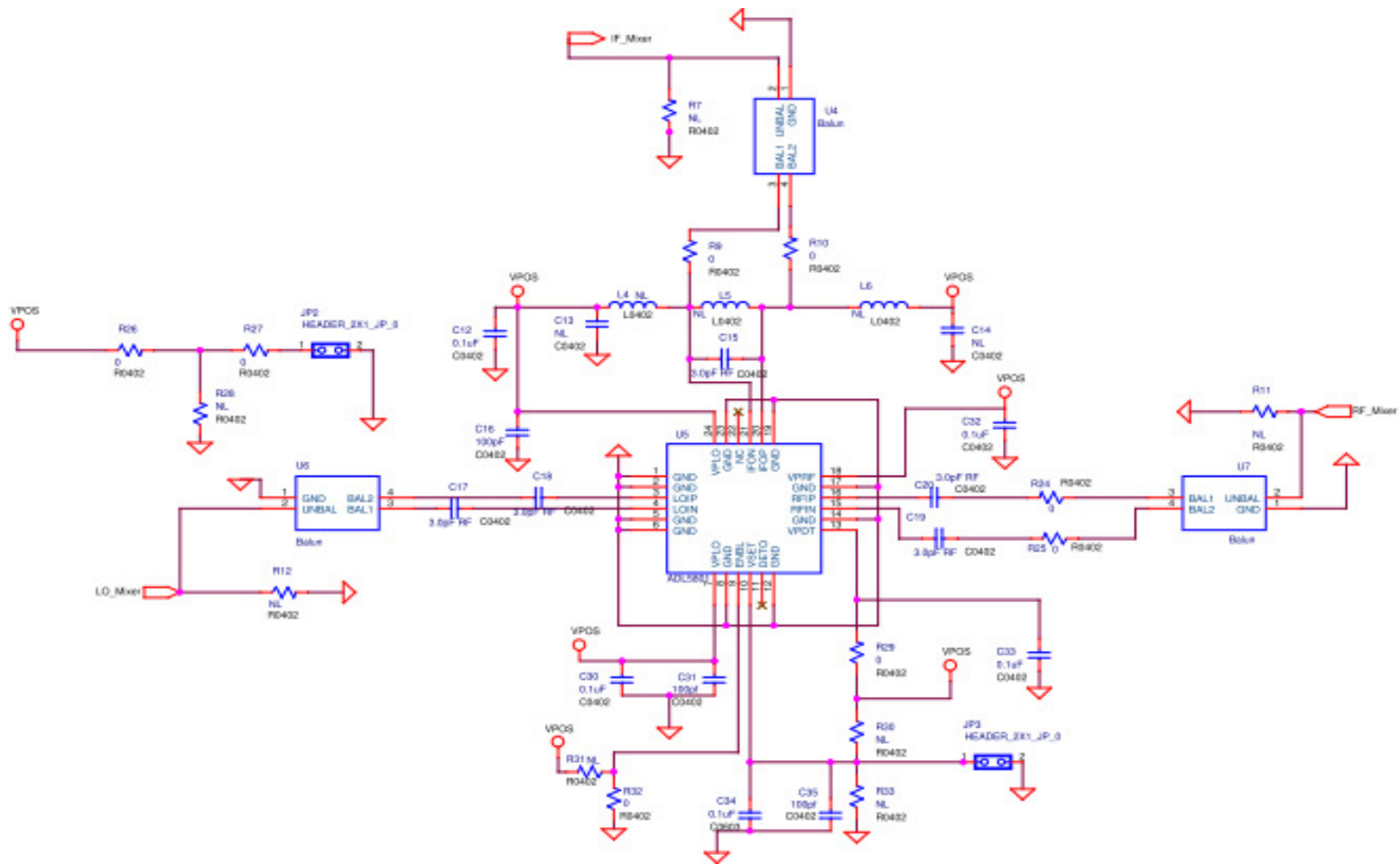
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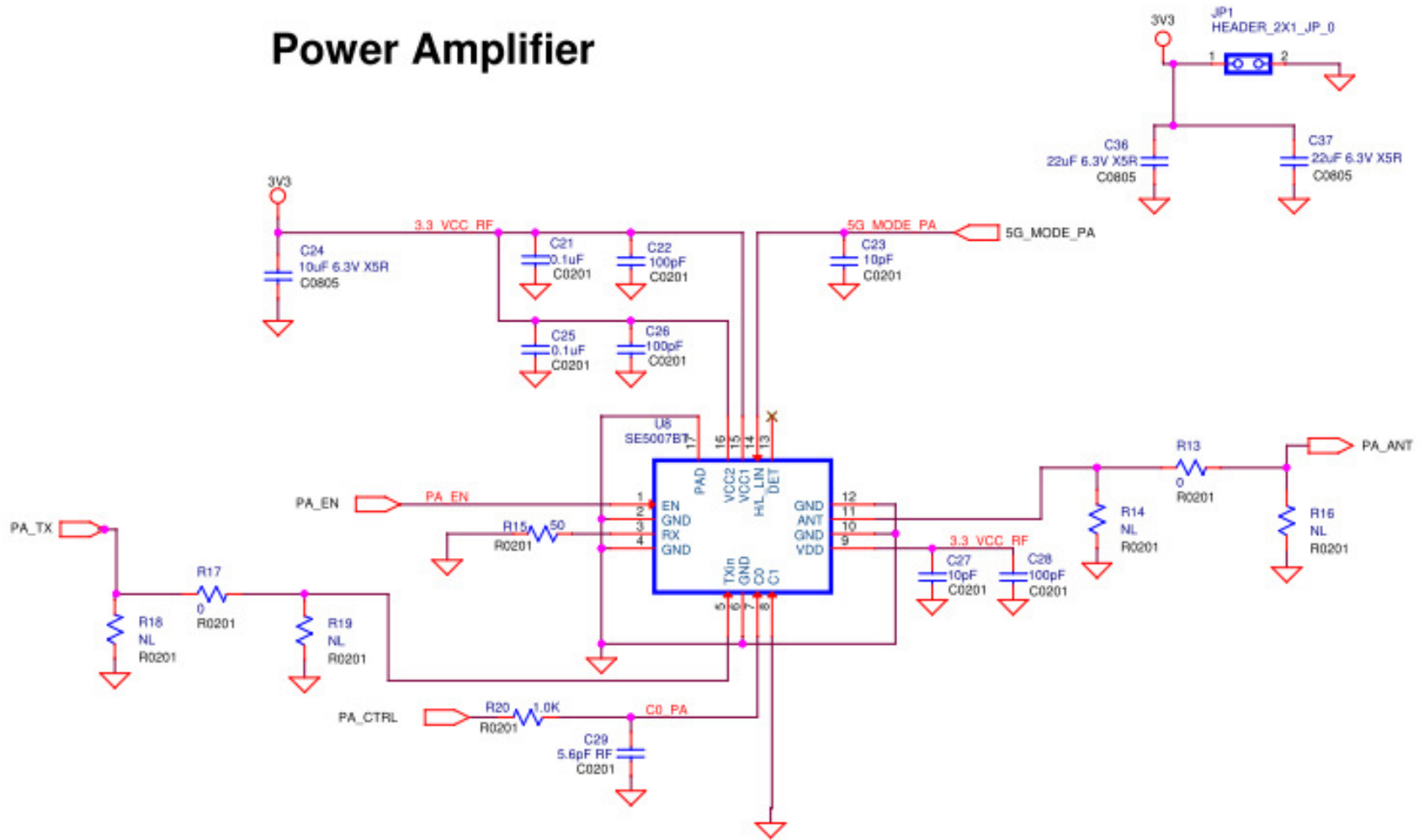
# Hierarchy Connectivity, Matching, and Antenna Connections



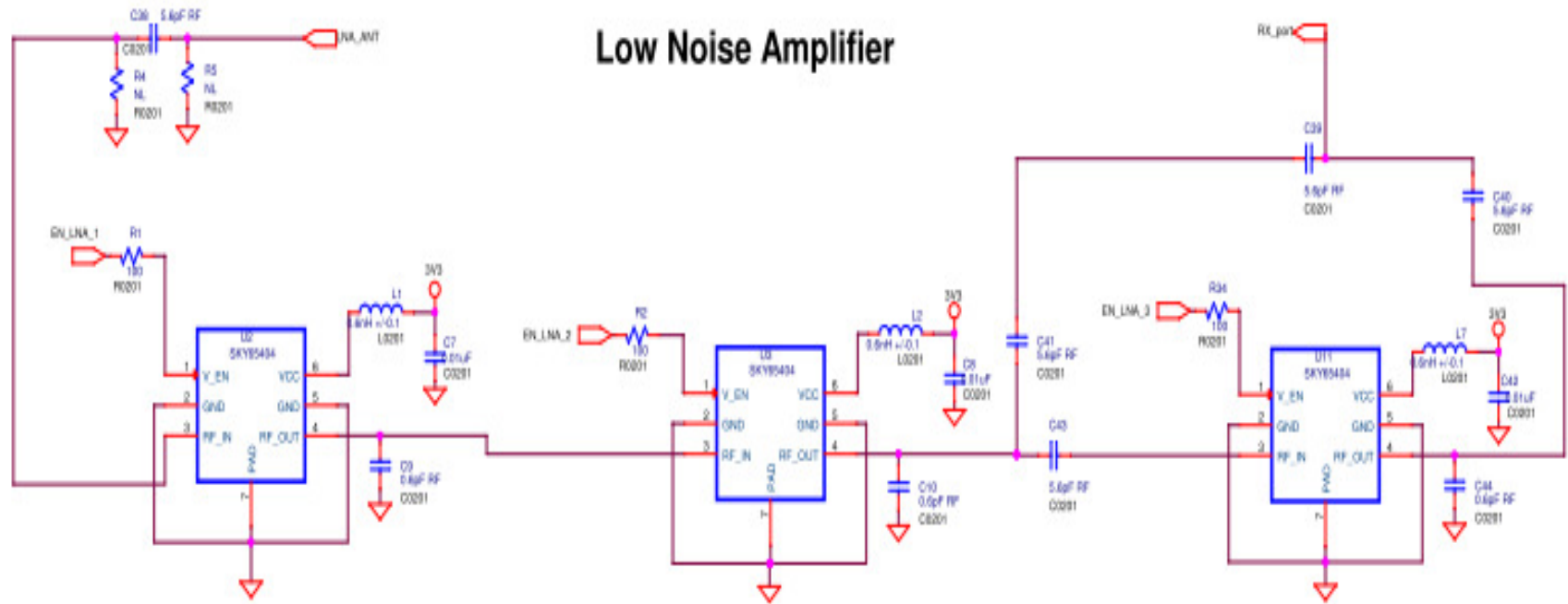
# Mixer



# Power Amplifier

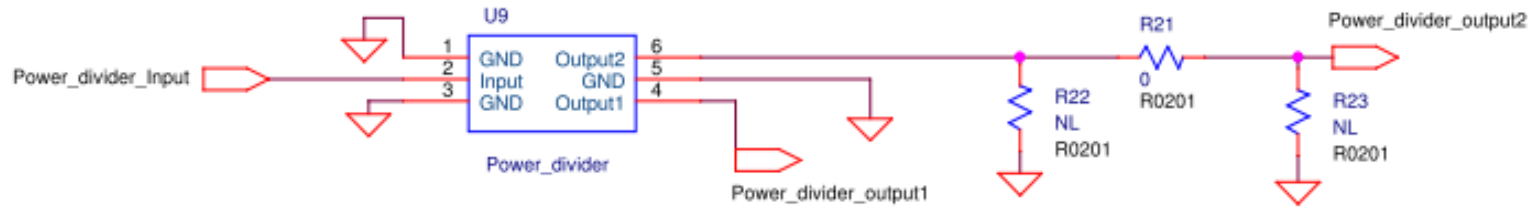


# Low Noise Amplifier





## Power Divider



## Low Pass Filter

