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RF Front End Receiver System Design for 5G Applications

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Abstract - *The demand for new technologies so as to meet peak high speed data rates for enumerated communication perks have surely seen an exponential growth in past few years. In this paper, a system design of receiver RF front end has been designed lying in the frequency range used in 5G applications (sub 6 GHz) of 3.3-3.7 GHz centered at 3.5GHz. The cascaded system comprises of a Low Noise Amplifier having gain of 15dB cascaded with a Band Pass Filter with 1dB insertion loss, that is being fed to one of the input port of power combiner, whereas a Local Oscillator having 3.5GHz as its signal frequency is fed to the other port. The output is then fed to a single diode Mixer that avoids the need of RF and LO baluns with return loss of less than -30dB in RF, LO and IF ports. Overall simulated system gain is 7.916dB. The devices so used in LNA, Oscillator and Mixer are HMC-C022, ATF13786 and HSCH5310 respectively. The proposed circuits realized using microstrip lines in Advanced Design System.*

Keywords — *Low Noise Amplifier, Microstrip line, Mixer, Oscillator, Port-to-port isolation.*

I. INTRODUCTION

Recent trends and innovations in wireless communication surely have intrigued researchers regarding the potential and the power it holds for a utopian technological realm. For any wireless system, there are three basic blocks and that are transmitter, receiver and channel of propagation. In this paper we have designed a cascaded Radio Frequency (RF) front end receiver and have critically tried to analyze some of the peculiar components used in the design for same. Low Noise Amplifier (LNA) is the most essential component in a receiver side as not only being the first active block but it also tends to dominate over the sensitivity of the receiver side [11],[12]. The desired characteristics of a LNA should be minimum noise figure (NF) and maximum gain and that can be achieved by finding point of intersection of constant gain circles and noise figure circles [6]. The trade-off between the characteristics of LNA such as gain, NF and linearity has to be considerably dealt by a RF front end designer so as to increase the sensitivity of the entire receiver side. However, in the case of LNA, it's preferred to design an amplifier with gain less than maximum gain and this is achieved by deliberately introducing mismatches. With the help of S-parameters of transistor and various performance requirements, a systematic procedure is followed for designing of LNA [7].

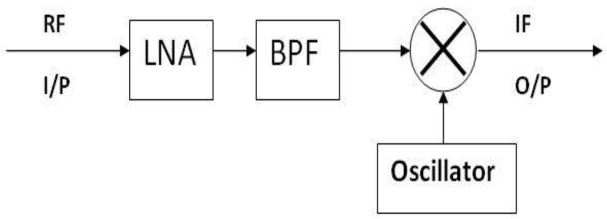

Fig 1(a). Block Diagram of Receiver RF Front End

Oscillators are found in all most every modern wireless communications, radar and remote sensing systems so as to provide signal sources for frequency conversion and carrier generation and are most important part of any RF communication system [4]. In general, Oscillators need to maintain a tradeoff among various performance parameters [17]. At microwave frequencies, diodes or transistors biased to a negative resistance operating point can be used to produce fundamental frequency of oscillations up to 100GHz. In order to improve the operating range and receiver sensitivity of super regenerative repeaters; super regenerative oscillators are used [5].

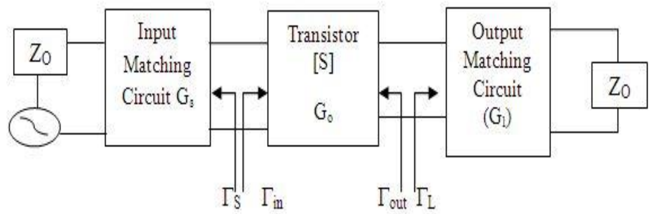

Fig 1(b). Typical Amplifier block diagram, (Source David M. Pozar.)

A low cost and high density integration for millimeter-wave components are to be considered and adopting various attractive techniques [18]. Transistor oscillators generally have lower frequency and power capabilities than diode sources but offer considerably more advantages over diodes [1]. In commercial microwave design, oscillators use high quality factor resonators as frequency discriminators to reduce phase noise [19]. Wilkinson equal power combiner finds its use in achieving good amount of isolation between the output ports but even in turn maintaining matching in all the other ports. Furthermore, it can be used as a power combiner as being made from passive components so is reciprocal.

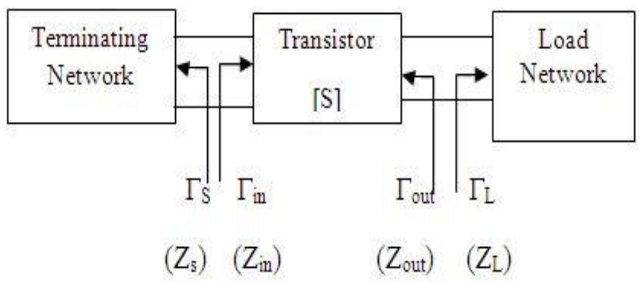

Fig 2. Circuit for a two-port transistor oscillator, (Source David M. Pozar)

In addition to this, it helps in preventing crosstalk when multiple channels are used. A mixer is a three-port device that uses a nonlinear or time-varying element to achieve frequency conversion. RF Mixers provides one of the key building blocks in RF design, enabling frequencies to be translated from one band to another, and plays an important role in translation of RF signlas to IF signal [10],[14]. It is required to have a large isolation between the ports that helps in making the receiver all the more sensitive towards the information coming from transmitter and interconversion between IF and RF is quite essential [15]. In order to reduce the cost of fabrication BiCMOS technology can also be deployed [16]. The mixer is evolved from single diode where RF and LO signal is given to anode and IF is at cathode [8]. Moreover, a single balanced mixer with no crossing of transmission line, 90 degree hybrid coupler is used because it avoids crossing of transmission line [9]. Band Pass Filter (BPF) finds its use to limit the signal's bandwidth in order to just receive or transmit the requisite band of signal. Moreover, Dielectric Resonator (DR) filters have advantages of low insertion loss as of unloaded quality factor [20].As for the receiver side, BPF allows only the selected range of frequencies that can be decoded in order to retrieve the message signal [23],[24].

II. DESIGN PROCEDURE

The design procedure of RF front end receiver comprises of LNA, BPF, Oscillator Wilkinson equal power combiner and lastly mixer. Circuit is realized in **FR4** substrate having specifications as ε_r = 4.4, Hu (height of the air dielectric) = 100mm, T (thickness) =0.15mm, Height (height of the dielectric) = 1.5mm, Conductivity = 5.7e7, tan D (loss tangent) = 0.001, Z_0 (port impedance) = 50 Ω. The design of all components is described as follows:

A. Low Noise Amplifier:

The device so selected for LNA is HMC-C022, GaAs MMIC PHEMT Amplifier that comfortably works within the range of 2-20GHz. Various crucial criteria for selection of a device for LNA device like, enough signal-to-noise ratio, good impedance maching with low and flat gain has to be critically analysed [13]. Hence, keeping all these key points in mind, HMC-C022 was the selected. Furthermore, the S parameter values were taken in the form of SNP, specifically as S2P file with values at 3.5GHz as S_{11}=0.138 / 105.667^{O}, S_{12}= 0.007/-86.902^{O}, S_{21}=5.707/-95.494^{O}, S_{22}= 0.215 / -5.029^{O}.

After **theoretical calculations** at 3.5GHz, stability factor and Mu came out to be **12.350 and 3.924** respectively that matched with software's values and that were **12.348 and 3.922**. Impedance matching was done both at Input and Output side with length of open circuited stub at input side of 21.15400 mm with microstrip line length of 14.290400 mm. Similarly at the output side the length so obtained for open circuited stub was 20.409200 mm with microstrip line length of 6.941210 mm [22]. The width of 50 ohm at 3.5GHz is 2.737580 mm. In addition to this, as when checked from the data sheet of HMC-C022, the expected Noise Figure was around 2-3 and, successfully the achieved NF_{min} was 1.769. LNA is designed with an objective of NF to be less than 3dB and gain of 15dB. The schematic representation is shown in Fig3.

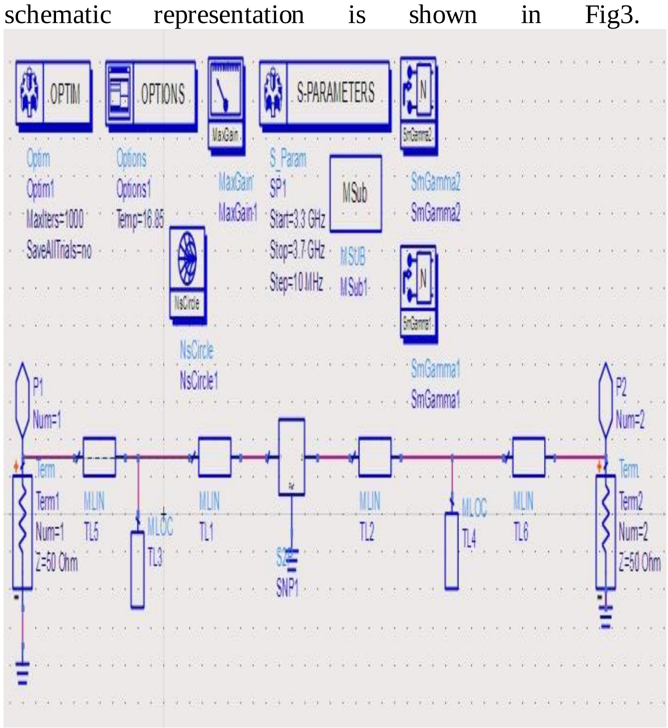

Fig 3. Schematic representation of LNA in ADS

B. Band Pass Filter:

BPF is used to get the desired output frequencies and is designed with a Tschebyshev response with following specifications:

Pass band frequency range = 3.3-3.7GHz
Centre Frequency = 3.5GHz
Out of band Rejection > 25dB
Insertion Loss < 1dB in the passband.

Following the design procedure for coupled section filter design, the layout and response of filter is shown in Fig 4 and Fig 10 respectively [25].

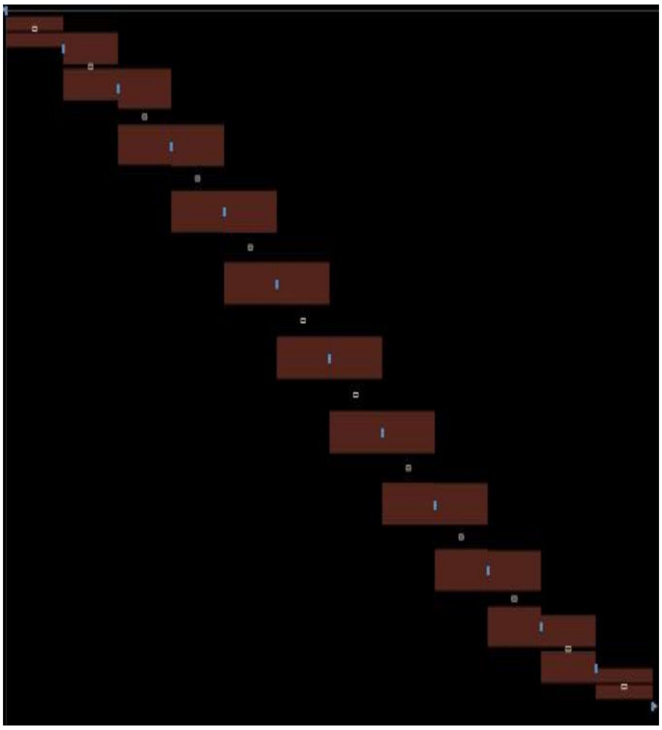

Fig 4. Layout of IF BPF.

C. Oscillator:

In an oscillator, a transistor is the best choice as compared to a diode because it is very easy to integrate a transistor in the circuits than that of diodes [21]. If we use a transistor then we will have more control over frequency of oscillation, output noise, and temperature stability. Hence the selected transistor is **ATF-13786**, as being a low-cost GaAs Schottky barrier-gate field-effect transistor as it works comfortably in the desired range of frequency. Co–simulation was carried out (Fig 10) for the design of negative resistance oscillator so as to incorporate the device so selected [3]. After carrying out the stability test as done in LNA, it was found that the device was unstable as stability factor was **0.688 (less than 1)** so the design was carried out considering the stability circle from which the value of Γ_{out} and Γ_{in} was calculated. **A python code** was also written in order to verify the results from **software as well as theoretical findings** and the final values were $\mathbf{\Gamma_{out}= 10.302 \angle -84.860^o}$ **and** $\mathbf{\Gamma_{in}= 3.096 \angle 91.880^o}$ respectively. Taking these values, impedance matching network was designed both at input and output side with input side length so obtained for microstrip line was 1.108970 mm and for open circuited stub it was 19.049400 mm. Similarly at the output side length of open circuited stub was 22.095800 mm and for microstrip line was 0.693598mm. Schematic representation of Oscillator in ADS is shown in Fig 5.

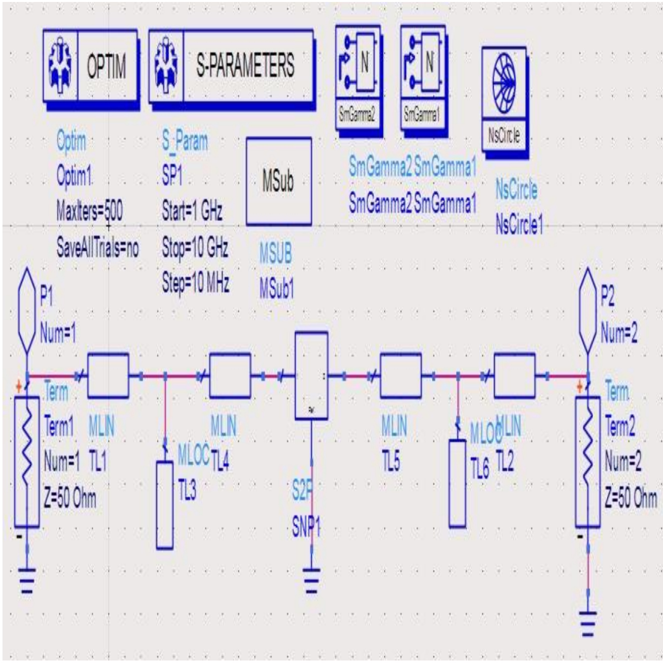

Fig 5: Schematic representation of Oscillator

D. Mixer:

The diode so selected for the design is **HSCH5310.** This diode is best for use in strip line or microstrip circuits. Due to its small size and uniform dimensions, it has low parasitic and repeatable RF characteristics through K-band. In order to obtain practically feasible results with good isolation, impedance matching was done at each port so as to reduce the chances of mismatch. The approach followed was for a single diode mixer [2]. It was observed that power coming from coupled port of branch line coupler was getting wasted or wasn't being utilized, so in the final cascaded circuit instead of a branch line coupler, Wilkinson power combiner was used.

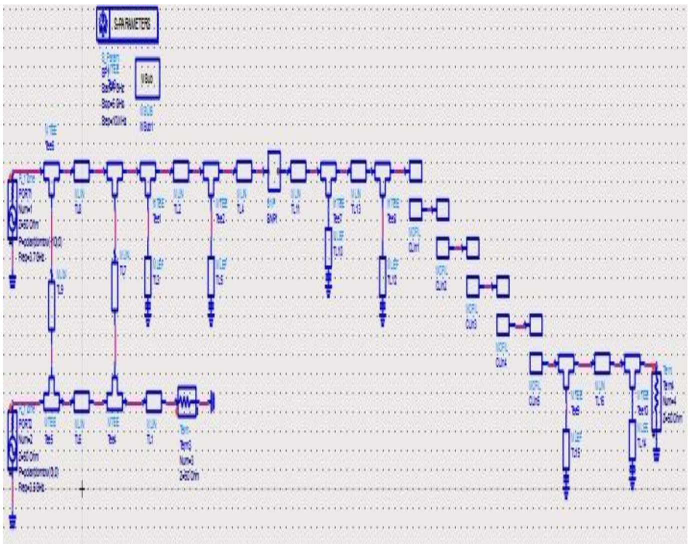

Fig 6. Schematic representation of Mixer

Furthermore, due to quite a lot of impedance mismatch, impedance matching network were designed at each level so as to have feasible practical results. In mixer two signals are to be mixed, band limited RF signal that is to be combined with oscillator signal of 3.5GHz. Combined output is passed through a diode. Here matching is done at input side of diode matched with output of Branch Line Coupler and at output side of diode matched with input of BPF. Schematic representation is shown in Fig 6.

E. Cascaded RF Front-End Receiver :

A receiver side for a RF Front end is nothing but a cascaded circuit of LNA and BPF being fed to one of the port of Wilkinson Power Combiner and the other port of same being fed by the output of an Oscillator. The combined output is fed to a single diode mixer that eliminates the need of RF-LO baluns. The output coming from LNA is fed to a BPF of 3.3-3.7GHz as its band. Impedance matching is done at the output of Wilkinson Power Combiner which is matched with input of mixer's diode and then output of mixer is then matched with characteristic impedance. The entire cascaded co-simulation circuit design is shown in Fig 7.

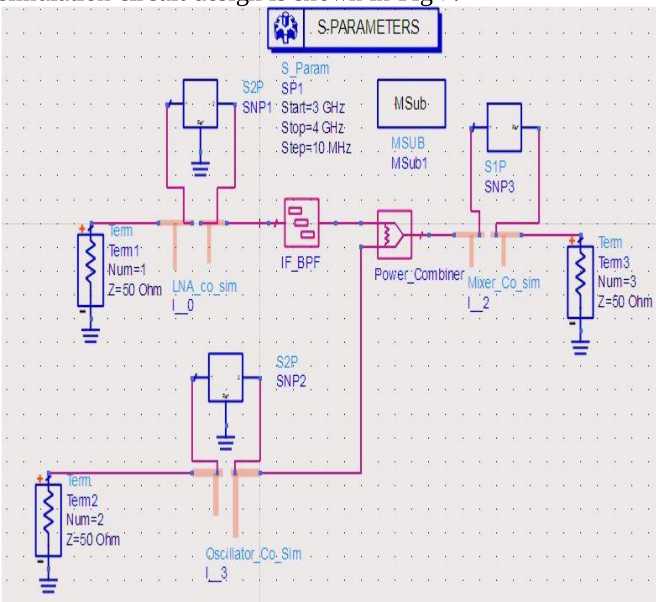

Fig 7. Schematic representation of Receiver

III. RESULT AND DISCUSSION

Following the design procedure for each component, this section deals with the results so obtained along with the requisite design in order to check the practicality of the design. For LNA the gain provided by HMC-C022 amplifier is 15.23dB with 1.769 as the minimum noise figure as shown in Fig 9. It gives +18dBm of output power at 1 dB gain compression. In Fig 8 it should be noted that co-circuit simulation of the entire design has been done in ADS so as to visualize the results in real time scenario, with matching done at input and output yielding (50.85-j*16.75) ohms and (50.15+j*0.024645) ohms respectively. The transducer power gain is given by,

$$G_{TU} = G_S + G_O + G_L \quad \text{----------(1)}$$

where G_S is found to be 2.698dB, $G_O = |S_{21}|^2$ theoretically it is 15.128dB and simulated G_O is 15.233dB. G_L is given by $1/(1-|S_{22}|^2)$ and is found out to be 0.205dB. Using eq(1) overall transducer gain of LNA is calculated and found out to be 17.833dB and 18.136dB respectively having the variation of 0.303dB from theoretical value.

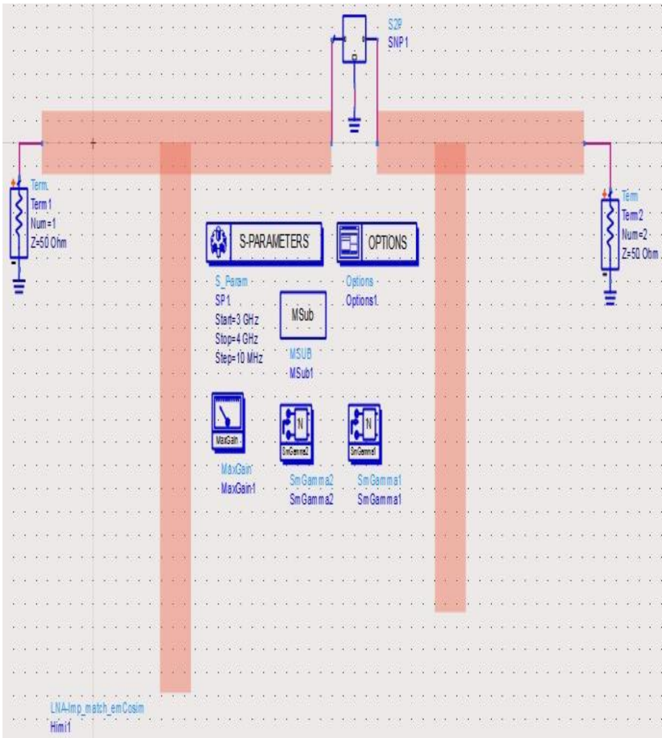

Fig 8. Co-Simulation of LNA

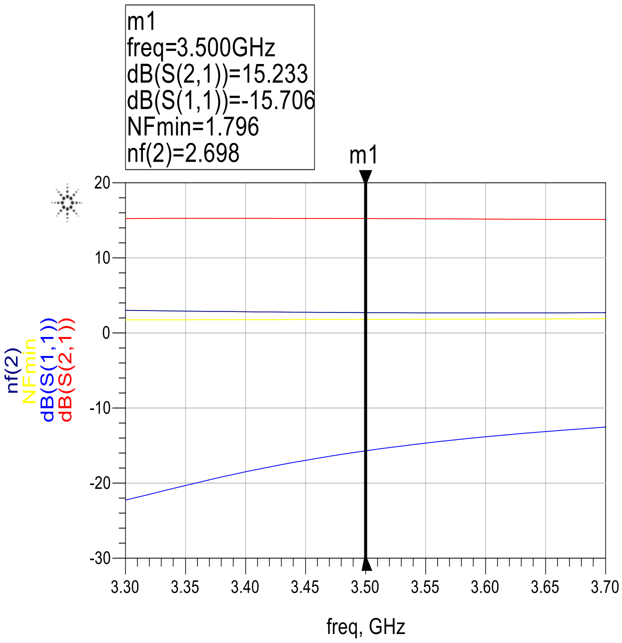

Fig 9. Results of LNA

Taking into the viewpoint of IF Band Pass Filter, Fig 4 shows the layout design of same with results depicted in Fig10.

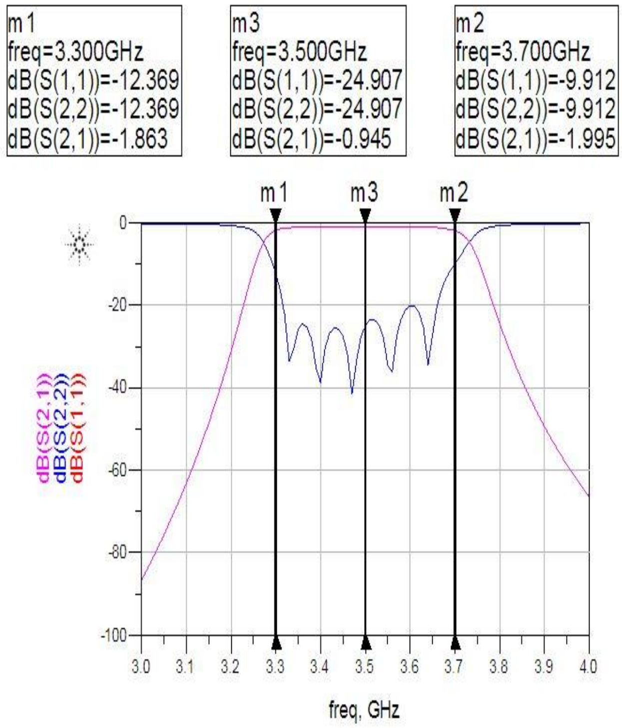

Fig 10. Results of IF BPF

Similarly in the design of Oscillator, co-simulation was done in ADS Fig 11 along with results as depicted in Fig 12. The overall gain achieved at 3.5GHz in case of oscillator is 15.852dB with a good amount of return loss of -32.128dB and RF Power output of 25.852dBm.

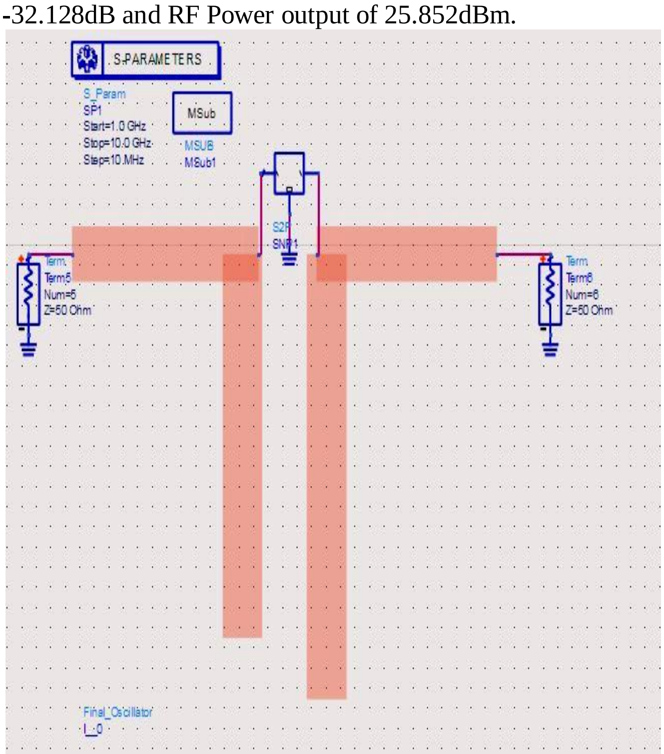

Fig 11. Co-Simulation of Oscillator

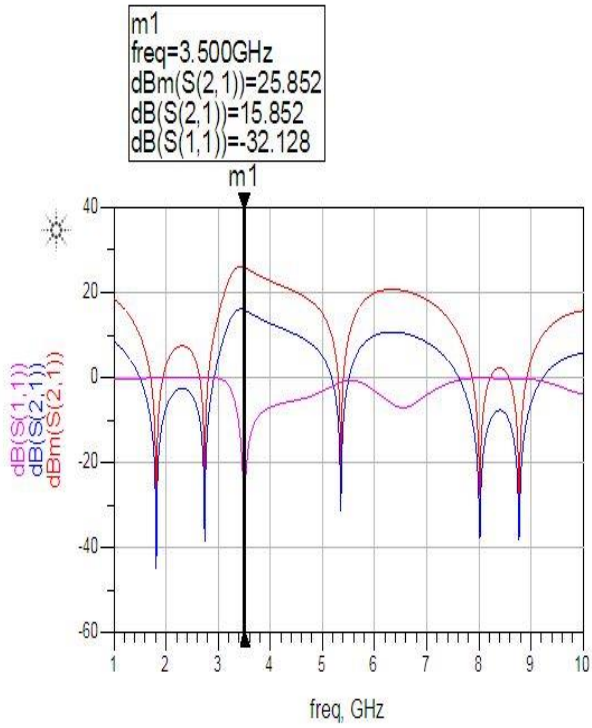

Fig 12. Gain (S(2,1)) and Return Loss (S(1,1)) of Oscillator

In addition to this, the Wilkinson Power Combiner was also simulated and designed at 3.5GHz yielding more than -30dB of return loss. Following the design procedure for mixer, the results so obtained Fig 13 are practical feasible and follow the requisite requirements with RF-IF port isolation of 19.032dB, LO-IF port isolation of -19.886dB.

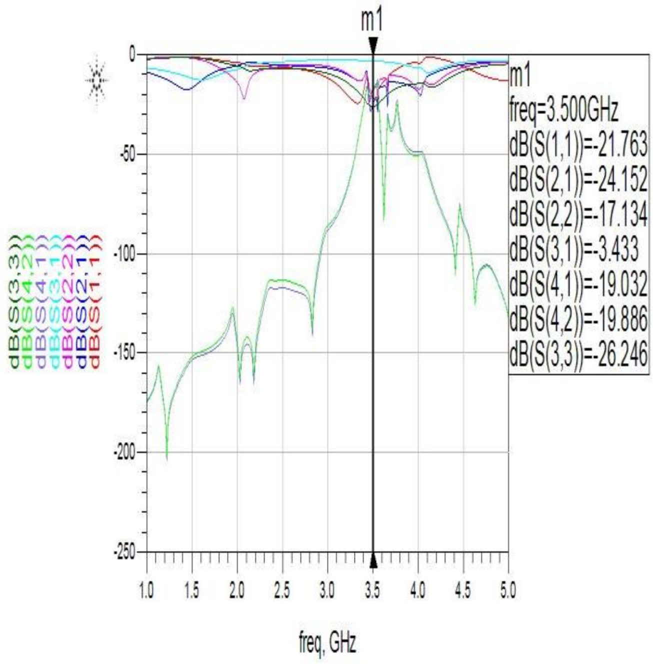

Fig 13. Various S parameter values of mixer checked at 3.5GHz.

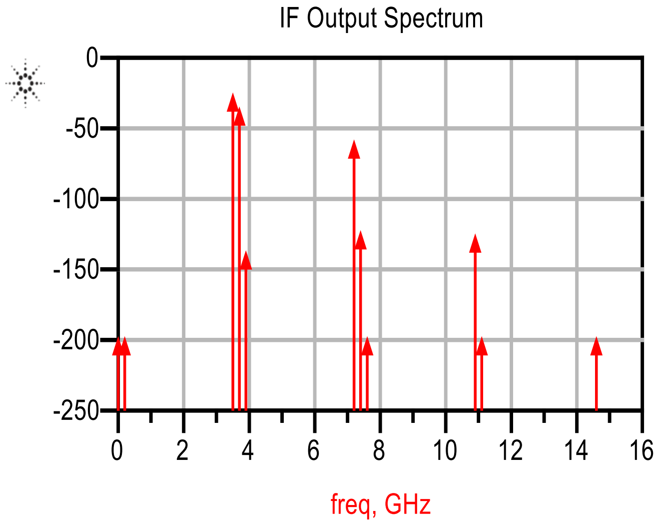

Fig 14. IF Output Spectrum at various frequencies.

The RF port was fed with an input power of 10dBm at 3.7GHz while LO port was fed with an input power of 0dBm at 3.5GHz yielding us the results as depicted in Fig 13. The conversion loss of mixer is obtained using the formula,

L_C = 10log$_{10}$ (RF Input Power / IF Output Power) ---- (2),

i.e. 15dB – 9.886dB = 5.114dB, which lies in the permissible range and meet the design specifications of the mixer.

Finally, the entire cascaded circuit results of RF Front End Receiver are shown in Fig 15, Fig 16 and Fig 17, while keeping Fig 1(a) as our reference. A good amount of port to port isolation was achieved, with RF port return loss of -30.035dB, IF port return loss of -33.724dB and lastly LO port return loss of -33.724dB. The RF to IF gain was 7.196dB at 3.5GHz, 2.476dB at 3.3GHz and 6.732dB at 3.7GHz while LO to IF gain was 9.476dB at 3.5GHz, 5.675dB at 3.3GHz and 7.859dB at 3.7GHz.

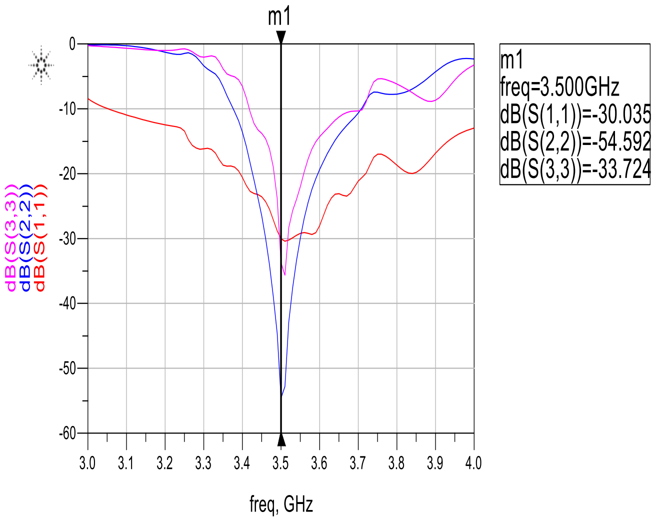

Fig 15. Return Loss of Receiver

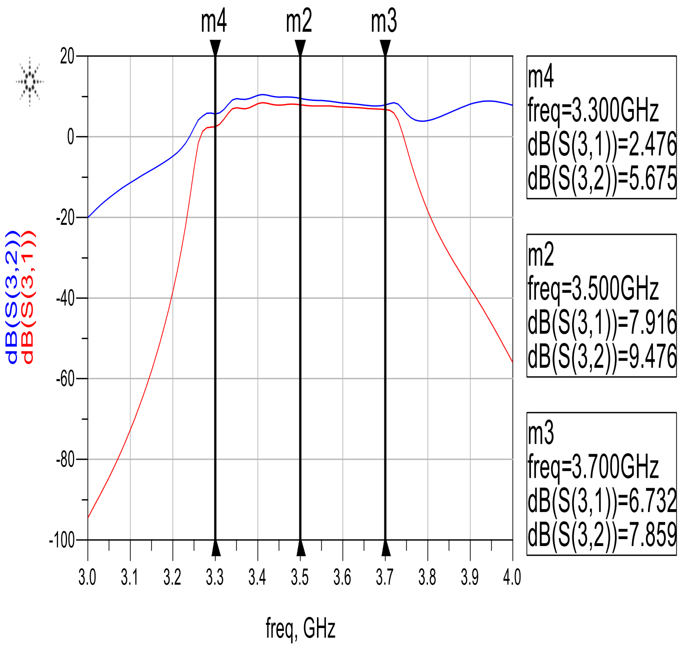

Fig 16. Gain of Receiver at various frequencies

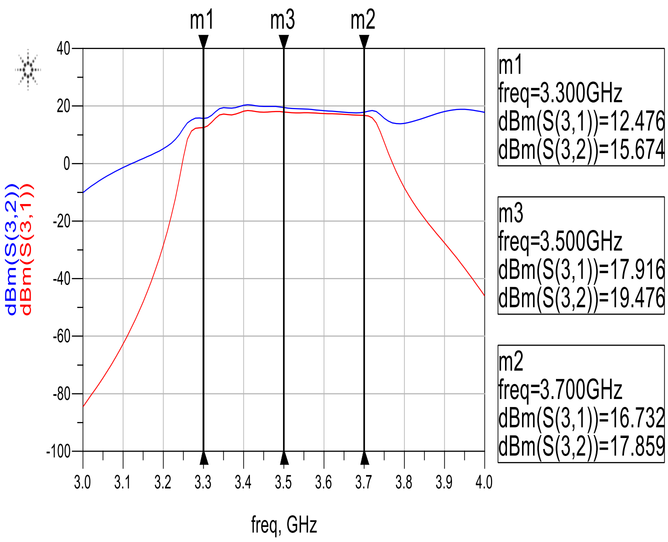

Fig 17. Gain of Receiver in dBm when LNA port fed with +10dBm input power at 3.7GHz and LO port fed with 0dBm input power at 3.5GHz

System Gain is calculated using the following relation
Overall system gain =Gain of LNA-Insertion loss of BPF-Mixer conversion loss ------ --(3)

Using the eqn (3), system gain was calculated to be **8.128 dB** and from Fig 16, S (3, 1) simulated system gain obtained is 7.916dB which has variation of 0.212dB from the theoretical value. Henceforth, the **overall system gain theoretically is 6.5** whereas the **simulated gain is 6.188** showing the **variation of 0.312** .

IV. CONCLUSIONS

RF Front End Receiver was designed centered at 3.5GHz, lying in the frequency range of 3.3-3.7GHz, the frequency band used in 5G communication (sub 6GHz) achieving the gain of 7.916 dB having the variation of 0.212dB from theoretically expected gain, with good amount of port to port isolation being achieved, with RF port return loss of 32.067dB, IF of 33.671dB and lastly LO of 31.615dB. LNA was designed to achieve the gain of 15 dB and oscillator to generate synchronized signal at 3.5 GHz producing RF power output of 25 dBm was designed and simulated using ***HMC-C022, ATF13786.*** Such high gain LNA with NF of 2.6 dB is highly used in narrow bandwidth. Phase synchronized Oscillator producing RF power output of 25dBm finds an application in low power applications. The mixer was designed and realized using ***HSCH5310*** producing RF to IF gain was 9.172dB at 3.5GHz, 8.661dB at 3.3GHz and 8.968dB at 3.7GHz while LO to IF gain was 12.182dB at 3.5GHz, 12.391dB at 3.3GHz and 9.925dB at 3.7GHz. The entire design was simulated in ADS realized with FR4 for microstrip circuit realization.

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