RRI-EEG Internal

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50 – 500 MHz Low Noise Amplifier with FM band rejection

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ABSTRACT

Observing the radio sky at low frequencies, particularly in sites where FM signal and other RFI dominates, is highly challenging, since the radio receiver is prone to be driven to saturation by these strong signals. So it is required that the receiver should have high dynamic range and / or very low sensitivity to FM signal for proper observation. We have developed a low- noise amplifier with about 40 dB rejection to the FM signal, in the frequency range of 50 – 500 MHz for use in the Sky Watch Array Network (SWAN). It has a noise temperature ranging from 40-80 K, a gain of 20 dB with a variation of ± 1.5 dB around the band center and around 60 dB dynamic range over the specified band. The design details and test results are presented in this report.

1. Introduction

With the advancement in the technology, the RF spectrum is completely occupied by communication channels like FM radio, television, Radar and various other man made signals. In the presence of these highly dominant undesied signals, carrying out the sky observation is highly challenging since the receivers are driven to saturation. This makes it very difficult to detect sky signal of very weak in nature. Therefore successful detection requires a receiver system with either a large dynamic range or poor sensitivity to undesired radio frequency signal particularly FM. We have adopted the latter methodology for observing the sky in the presence of FM signals. This has been accomplished by designing band-stop filters in front of Low noise Amplifier, with a rejection of about 40 dB over the FM band. It is also designed to have less insertion loss for minimizing the degradation of noise performance of the Low-Noise Amplifier. LNA output has gain eqalization circuit to ensure identical gain of the receiver at all frequencies. The operating frequency range of the entire receiver is limited to 50-500 MHz, with the help of high- pass and low-pass filters. Also the low- noise amplifier should have good input and ouput VSWR for interfacing to successive stages, and gain slope equivalization circuit to minimize the slope in the band of interest. A band- pass filter is also an essential in the chain to shape the band to avoid the aliasing effects in further processing stages. One such amplifier has been designed in the frequency range 50-500MHz which has the neccesary specified sub sections integrated into a single module.

Section II describes briefly the integrated Low-noise Amplifier. Design and implementation of sub units of the integrated LNA are presented in Section III. Section IV discusses the measurements and results of the work carried out is given in Section V.

2 Description :

A low-Noise Amplifier module in the frequency range 50-500MHz has been designed and developed in the EEG - RF laboratory and it’s block diagram is shown in figure 1. The low-noise amplifer is implemented using Mini-circuit based PGA-103+ high dynamic range monolithic amplifier. It is an advanced wideband high gain amplifier offering low noise figure ranging from 0.5dB to 1.4dB from 50MHz to 4GHz frequency range. In our application, the frequency band is limited to 500MHz having reasonable gain of 20dB with gain flatness of ±1.5dB. The noise figure is optimized to 0.5dB at lower frequencies and 1.2dB maximum at 500MHz. To achieve the requirement of an integrated low-noise amplifier in this application, the band- pass filter is implemented as a combination of high- pass filter and a low- pass filter. The low loss high-pass filter with sharp high cutoff at 40MHz is incorporated as the first element and a sharp roll-off low- pass filter with cut-off at 500MHz as the final element has been incorporated. The FM band-stop filter is preceeding the low noise amplifier section. Since the high- pass filter and the FM band-stop filters are the initial elements, it’s a challenge to design these filters having lowest insertion loss in the pass band to minimise the effect of worsening the noise figure nosie. The low-noise amplifer with gain equivalization section has been optimized to have over all reasonably high dynamic range throughout the frequency range of operation.

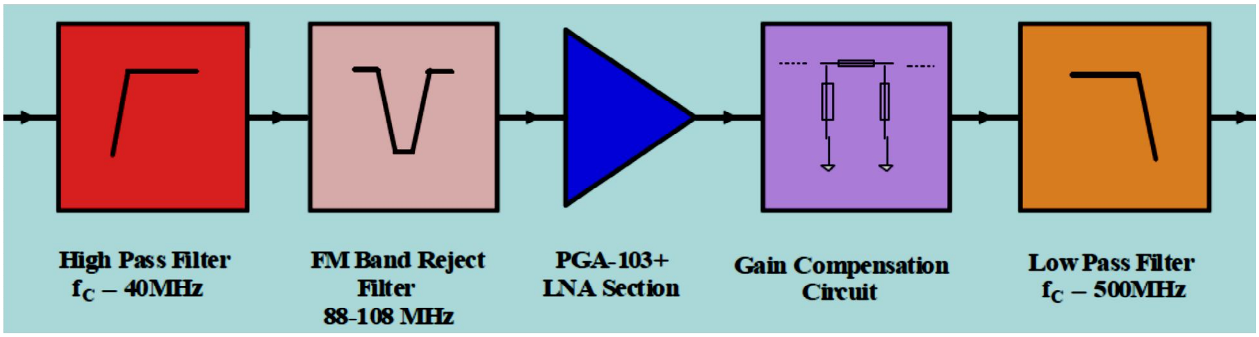

Figure 1. Block diagram of the Low Noise Amplifier integrated with FM rejection filter and gain equalization circuit

All the filters in the integrated LNA module incorporates of ellptic type. The elliptic filter is characterized by the ripple in both pass-band and stop-band as well as the fastest transition between pass-band and ultimate roll-off of any RF filter type. The levels of ripple in the pass-band and stop-band are independently adjustable. This results in a cut-off which is sharper than most other filters. The insertion loss only affects the forward (S21) and backward (S12) transmission, but not the reflection coefficients (S11 ,S22). The input impedance in the stop band only affects the phase of the reflection coefficients.

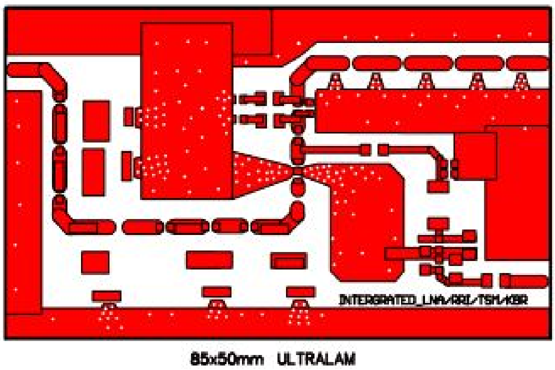

Figure 2 PCB Layout of Integrated Low-Noise Amplifier

The low- noise amplifier PCB layout is shown in the figure 2. The circuit is fabricated on ULTRALAM 2000 printed circuit board which has di-electric constant Er of 2.5 and dissipation factor tan δ of 0.0022, which are the significant factors at high frequencies. The transmission line trace width on the pcb has been optimized to match the system impedance to 50 Ω.

3 Design and Implementation

3.1 High- Pass Filter

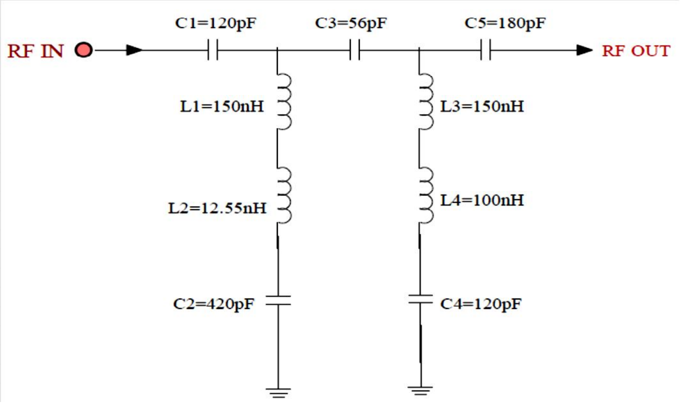

Figure 3. Schematic diagram of the High -Pass Filter

40MHz high- pass filter is the first section of the integrated amplifier. It is a 5th order filter with minimum inductor topology. Since inductors are usually larger, more expensive and have lower quality factor minimum inductance topology are normally the first choice. The filter is designed with cauer chebyshev characteristics with 40db stop band attenuation and 0.1 db ripple in the pass band. The filter is tuned and optimized for minimum insertion loss over the frequency range 40-500MHz, so that the noise figure of the entire system is least affected. The 3dB cut-off frequency of the filter is tuned at 40MHz with reasonably good VSWR of 1.4:1 over the band. The detailed circuit diagram with component specifications is shown in the annexure.

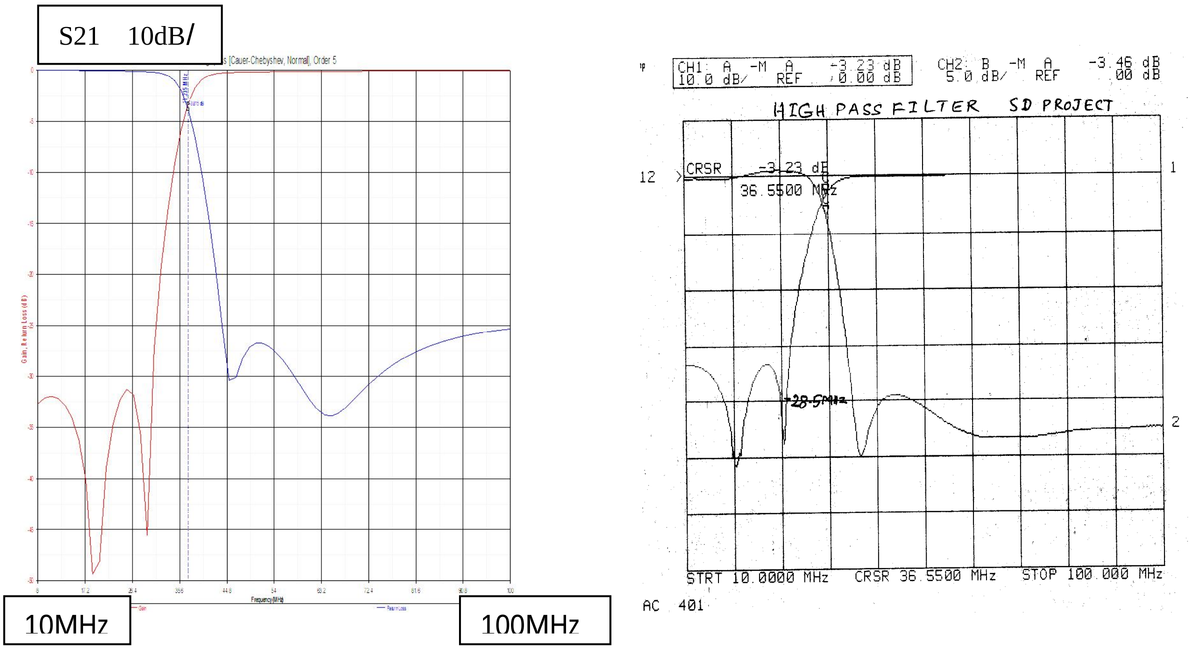

Figure 4 a) Simulated Response b) Measured Response

3.2 Band- stop (Notch) Filter

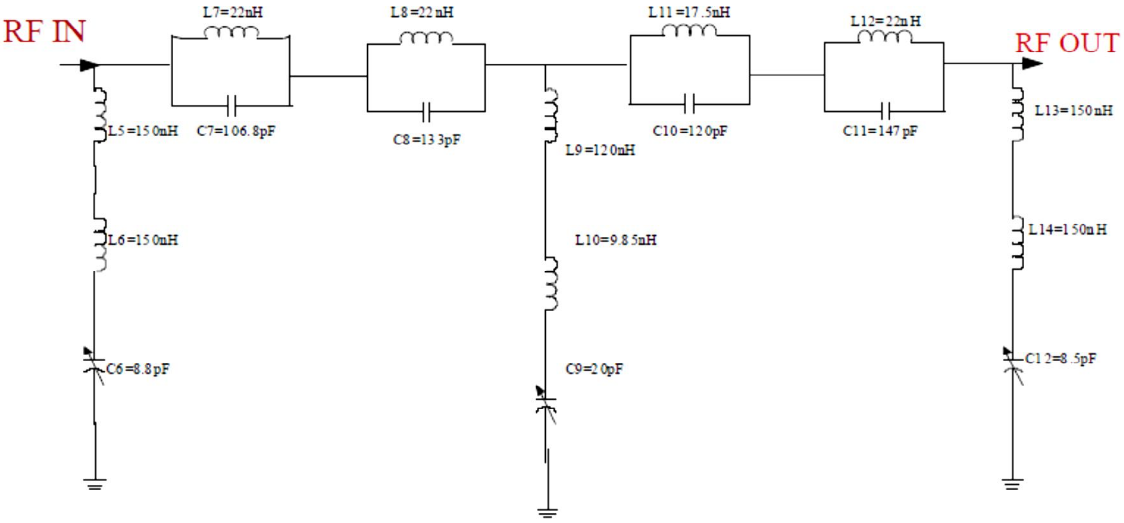

Figure 5 Schematic diagram of the FM Band Stop Flter

A notch -filter followed by the high pass filter is implemented to reject the strong FM radio signals in the frequency range 88-108MHz. The filter is of 5^{TH} order elliptic, cauer type. The attenuation in the rejection band is around 40 dB and the insertion loss in the pass band is optimized to be very low. The capacitors C1, C4 and C7 are chosen as variable elements for the comfort of tunability of the filter. All the inductors are of high Q type to obtain the sharp roll off in the rejection band.

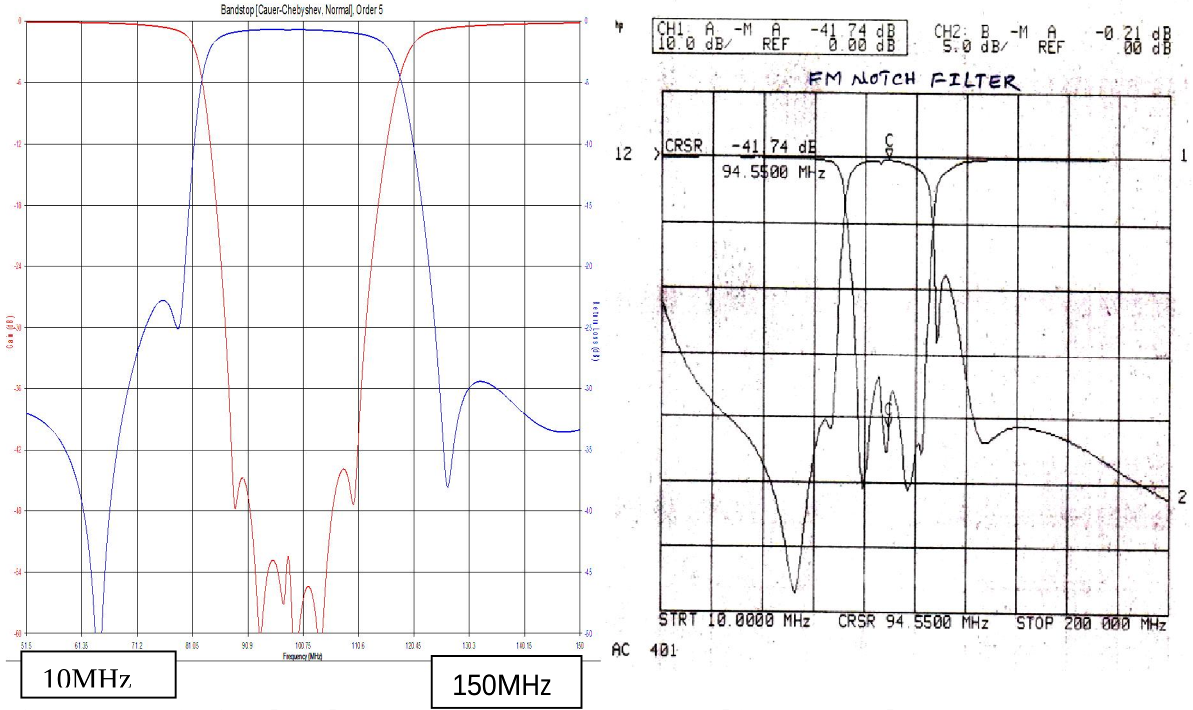

Figure 6 a) Simulated Response b) Measured Response

3.3 Low- Pass Filter

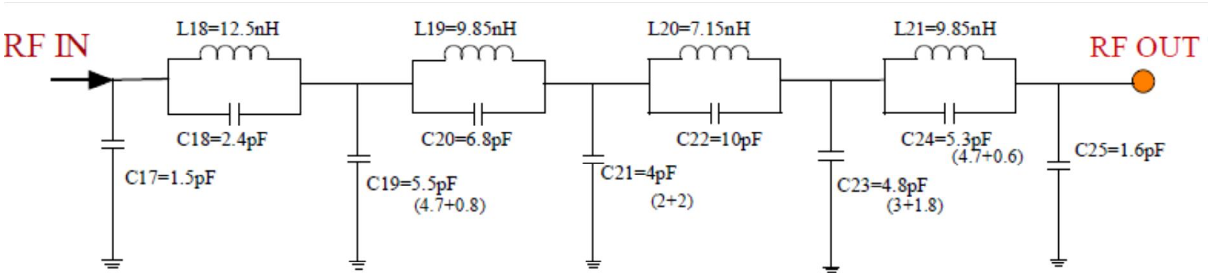

Figure 7 Schematic diagram of the Low- pass Filter

Low- pass filter is designed for 550MHz cut off frequency. This is 9th order cauer chebyshev elliptic filter. Minimum inductor and minimum capacitor subtypes are the low- pass options. Because inductors are usually larger, more expensive and have lower quality factor minimum inductance topology are normally the first choice.

The minimum inductor subtype has a shunt capacitor for the input branch. The next branch is a series parallel resonator L-C.

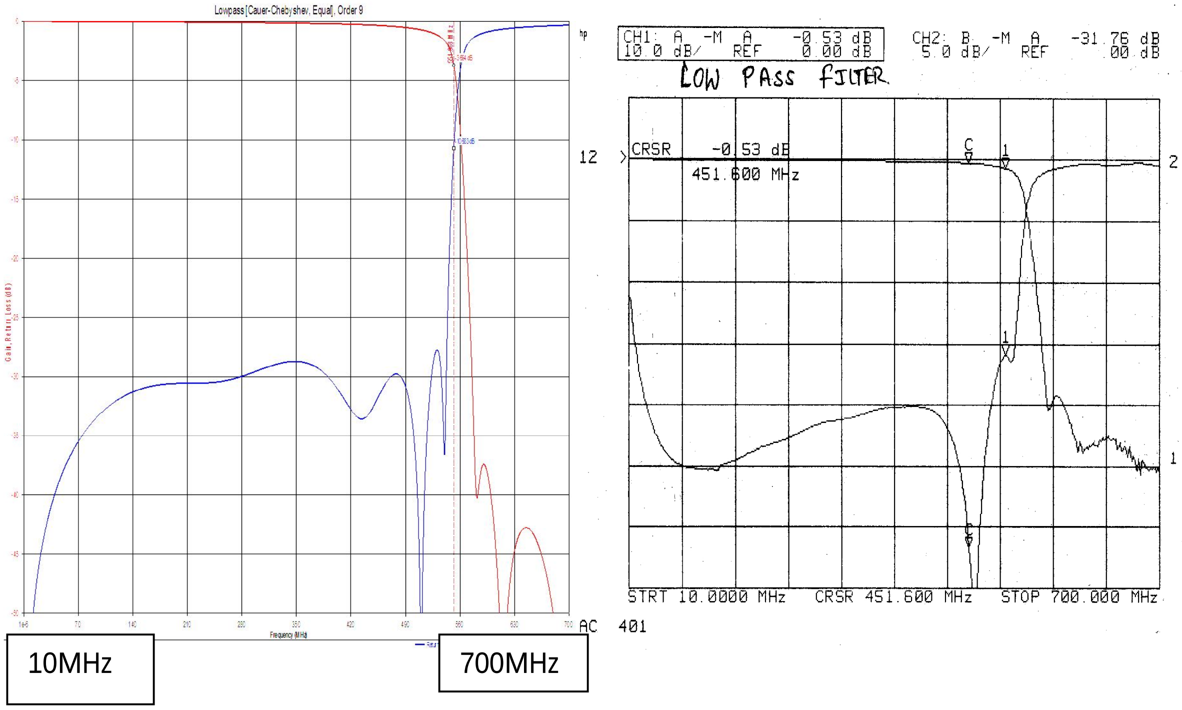

Figure 8 a) Simulated Response b) Measured Response

3.4 Low- noise Amplifier section

PGA-103+ is an advanced wideband amplifier fabricated using E-PHEMT technology and offers extremely high dynamic range over a broad frequency range and with low noise figure. In addition, the PGA103+ has good input and output return loss over a broad frequency without the need for external matching components and has excellent reliability. This device can operate for both 5V/3V.

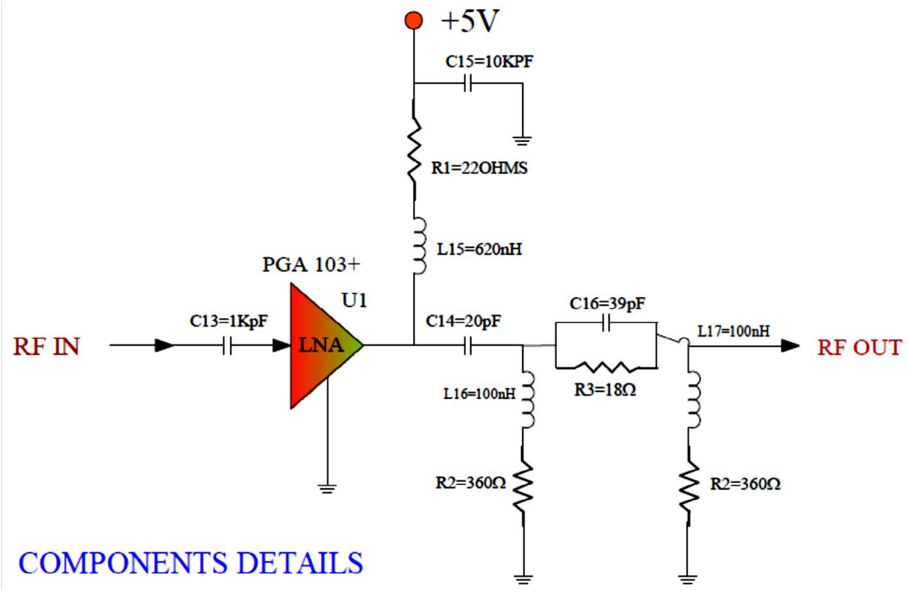

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Figure 9 Schematic of Low Noise Amplifier with Gain equalization network

The measured response of the gain vs frequency curve indicates that the gain has 5dB to 6dB slope from 50 MHz to 500MHz frequency range. The equivalise the gain, a compensation circuits is implemened followed by the amplifier cuircut. The gain equivalization circuit is basically an ideal attenuator network such as a tee, and add capacitors to "short out" the series resistive elements with frequency, and inductors to "open" the shunt resistive elements with frequency. Separately low- noise amplifier with gain compensation network alone is simulated in Genesys software as shown in the figure.

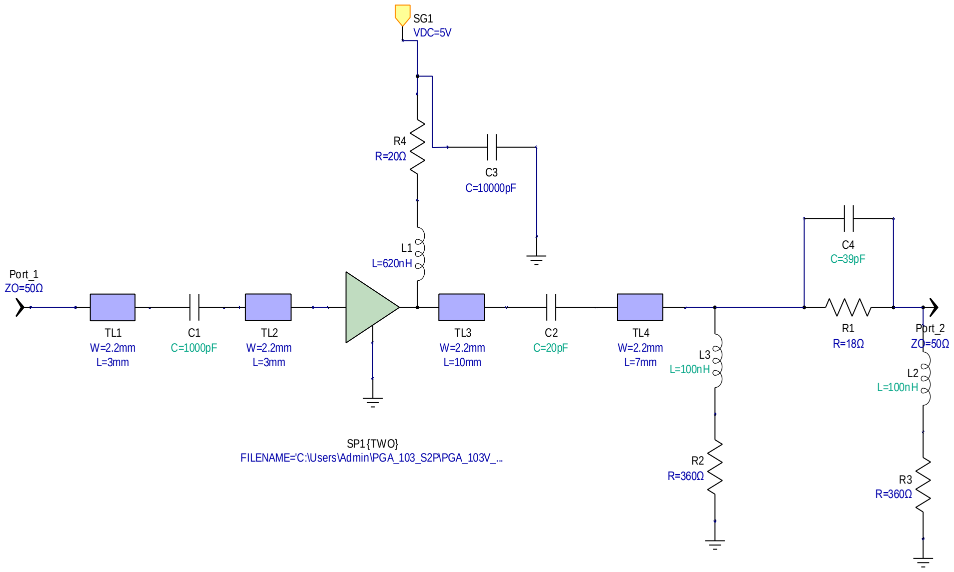


Figure 10 Simulation model of Low-Noise Amplifier with Gain compensation network

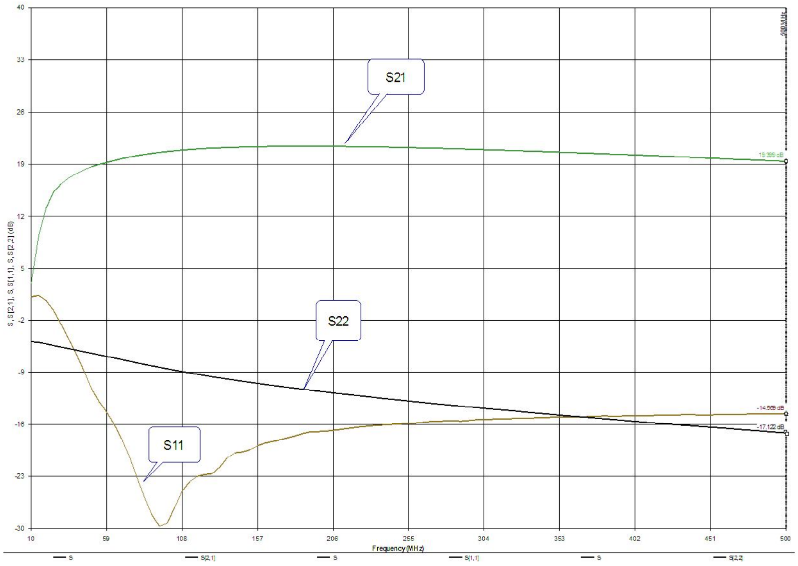
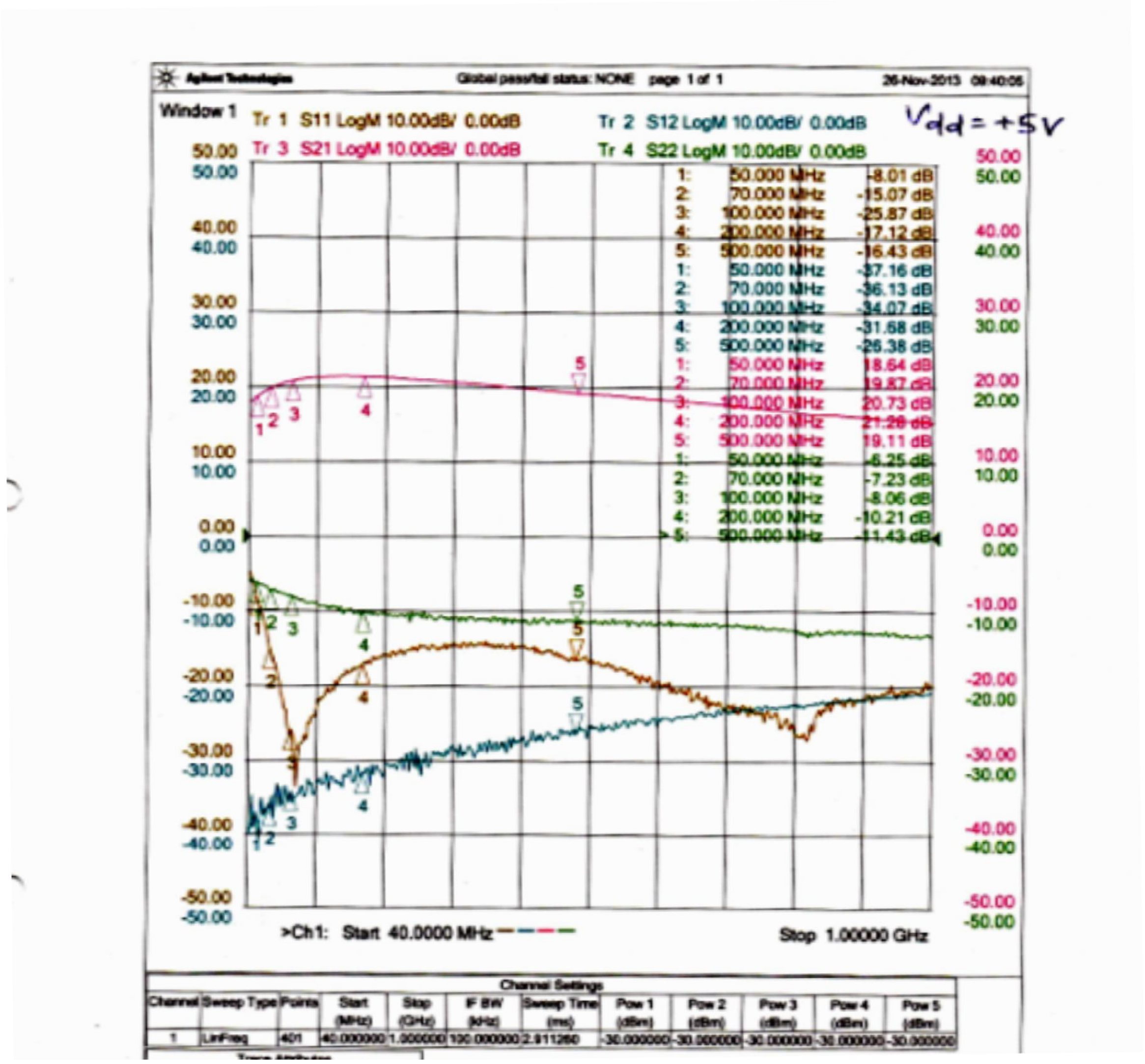


Figure 11 Simulation result of S parameters of LNA with Gain compensation



1: 50.000 MHz -8.01 dB
2: 70.000 MHz -15.07 dB
3: 100.000 MHz -25.87 dB
4: 200.000 MHz -17.12 dB
5: 500.000 MHz -16.43 dB
1: 50.000 MHz -37.16 dB
2: 70.000 MHz -36.13 dB
3: 100.000 MHz -34.07 dB
4: 200.000 MHz -31.68 dB
5: 500.000 MHz -26.38 dB
1: 50.000 MHz 18.64 dB
2: 70.000 MHz 19.87 dB
3: 100.000 MHz 20.73 dB
4: 200.000 MHz 21.28 dB
5: 500.000 MHz 19.11 dB
1: 50.000 MHz -6.25 dB
2: 70.000 MHz -7.23 dB
3: 100.000 MHz -8.06 dB
4: 200.000 MHz -10.21 dB
5: 500.000 MHz -11.43 dB

Channel Settings

Channel	Sweep Type	Points	Start (MHz)	Stop (GHz)	IF BW (kHz)	Sweep Time (ms)	Pow 1 (dBm)	Pow 2 (dBm)	Pow 3 (dBm)	Pow 4 (dBm)	Pow 5 (dBm)
1	LinFreq	401	40.000000	1.000000	100.000000	2.911260	-30.000000	-30.000000	-30.000000	-30.000000	-30.000000

Figure 12 **Measured Gain S12, Input Return Loss S11, Output Return Loss S22, Reverse Isolation S12 Response of the LNA with Gain compensation**

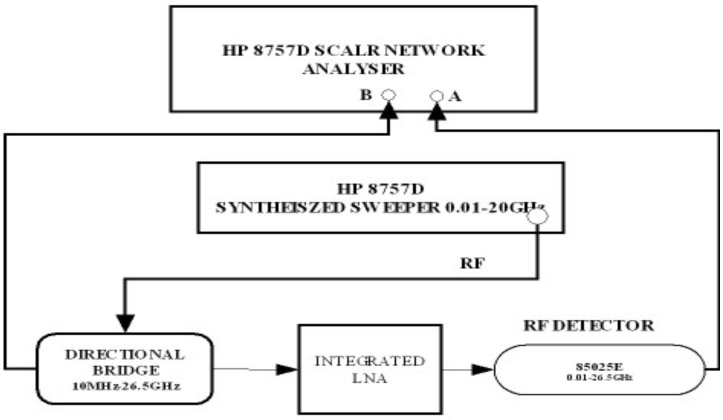
The simulation and measurement results in figures 11 and 12 shows that the gain at 50MHz is reduced from 22dB to 20dB from 50MHz onwards upto 200MHz and the same is compensated to 19dB at higher frequencies upto 500MHz. So the total gain S21 of the low-noise amplifier is 20dB with 1.5dB variations over the entire frequency band. The input return loss S11 is tuned to -10dB at 40MHz and average -13dB onwards at higher frequencies upto 500MHz.

3.5 Low- Noise Amplifier Measurements

3.5.1 S –Parameter Measurement

The complete integrated low- noise amplifier has been simulated in GENESYS 12 software by cascading the S-parameters of individual designed stages. The simulated response is shown in the figure 13.

SET UP FOR MEASUREMENT OF S PARAMETERS



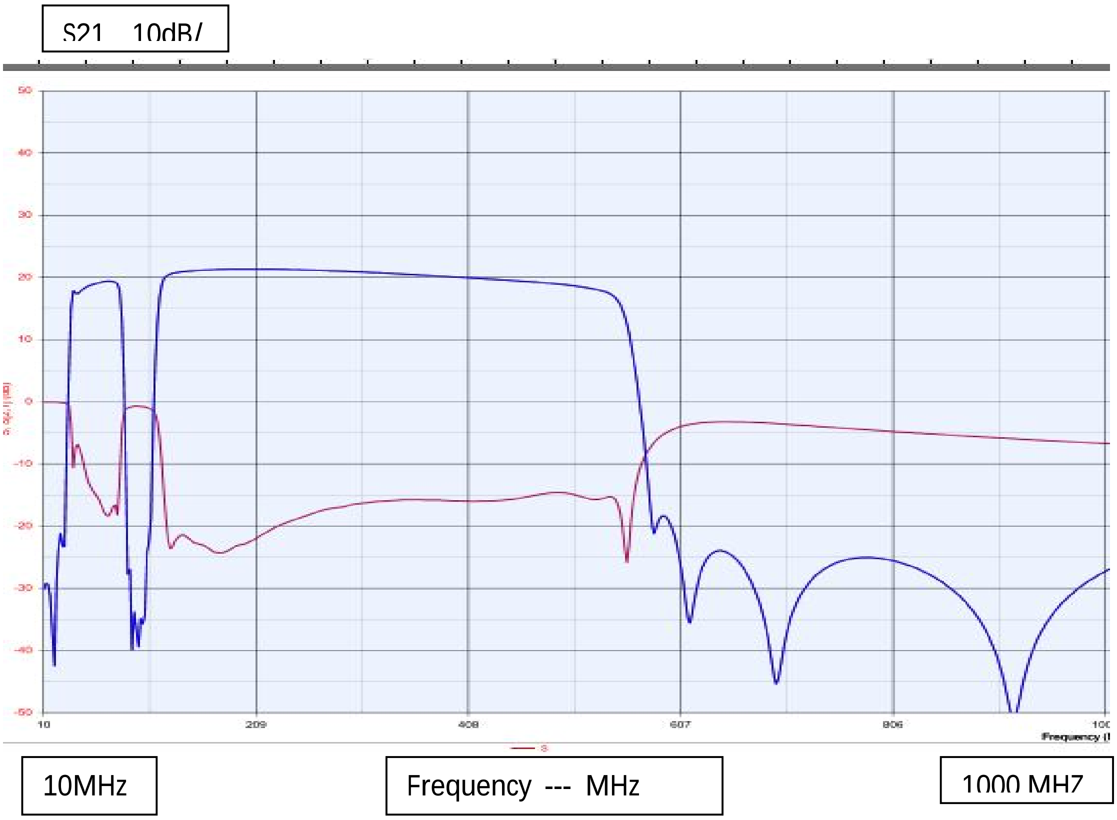
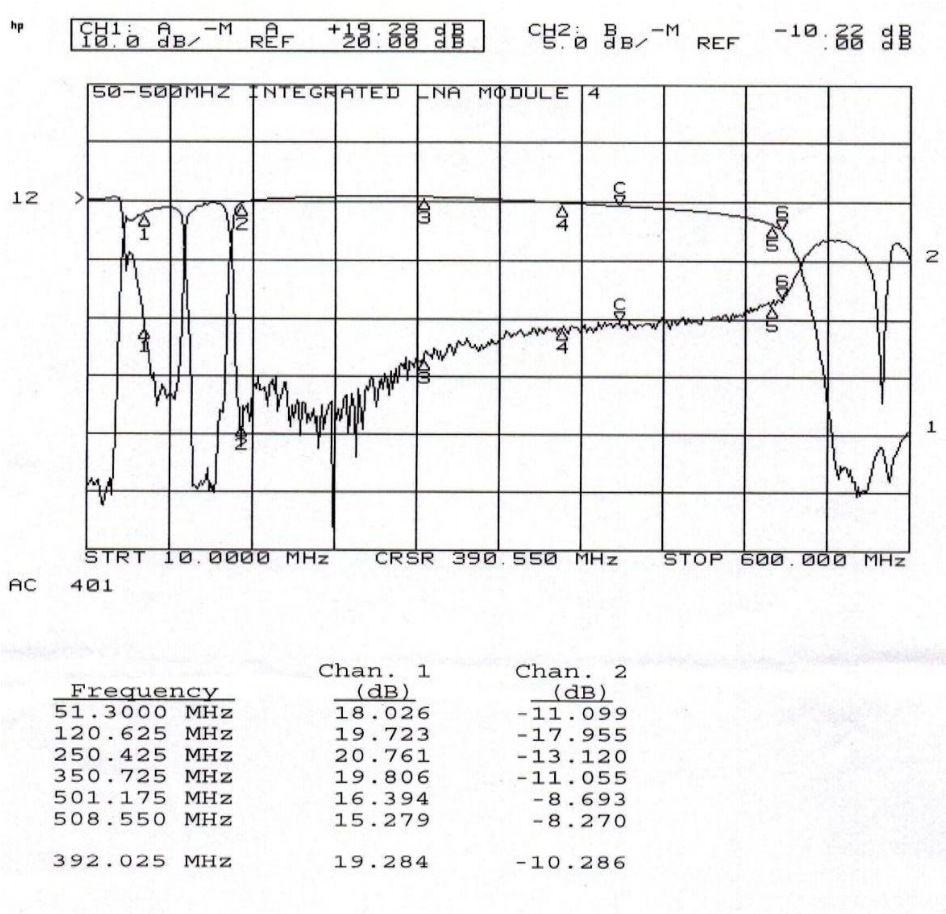


Figure 13 Simulated Response of Low -Noise Amplifier with FM suppression



Frequency	Chan. 1 (dB)	Chan. 2 (dB)
51.3000 MHz	18.026	-11.099
120.625 MHz	19.723	-17.955
250.425 MHz	20.761	-13.120
350.725 MHz	19.806	-11.055
501.175 MHz	16.394	-8.693
508.550 MHz	15.279	-8.270
392.025 MHz	19.284	-10.286

Figure 14 Measured S11 and S21 Response of Low Noise Amplifier

3.5.2 Noise figure measurement

Noise figure of a network is the decrease or degradation in the signal-to-noise ratio as the signal goes through the amplifier. A perfect amplifier would amplify the noise at its input along with the signal, maintaining the same signal-to-noise ratio at its input and output (the source of input noise is often thermal noise associated with the temperature or with losses in the system). A realistic low-noise amplifier however, also adds some extra noise from its own components and degrades the signal-to-noise ratio. A low noise figure means that very little noise is added by the amplifier.

For integrated low-noise amplifier, the total noise figure is the equivalent noise at it’s input which is the cascade effect of the high-pass filter, band stop filter, low- noise amplifier and then the low- pass filter. Even though the lossy filters are preceding the low-noise amplifier PGA-103, the insertion losses in the pass band are optimized to be very low so that the overall noise figure of the integrated low noise amplifier is least affected by them. The noise figure measurement set up is shown in the figure 15.

The Noise Temperature is calculated from the Noise figure is as shown

Noise Temperature = [Noise Factor -1]*290 K

The total cascaded noise temperature T_N of the integrated LNA is calculated using the following relation

$$T_N = T_1 + \frac{T_2 - 1}{g_1} + \frac{T_3 - 1}{g_1 \cdot g_2} + \cdots + \frac{T_N - 1}{g_1 \cdot g_2 \cdot \cdots \cdot g_{N-1}} \quad [K]$$

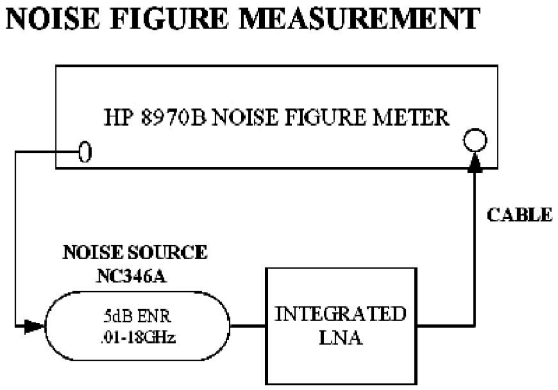


Figure 15 Integrated LNA Noise figure measurement(Noise Temperature) setup

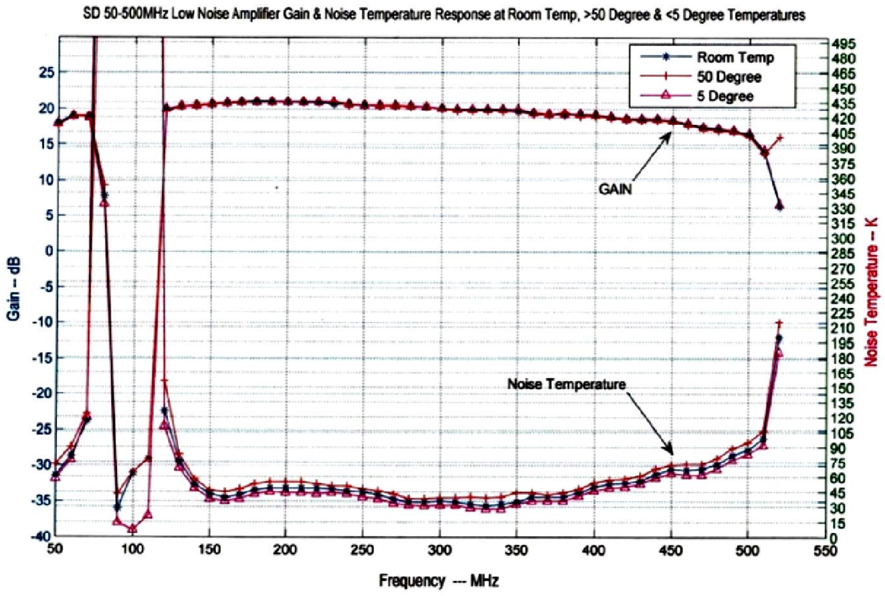


Figure 16 Measured Noise Figure (Noise Temperature) Response of LNA

The figure 16 shows the Noise temperature in K over the frequency band 50-500MHz. It can be seen that the noise temperature is 60K-70K at lower frequencies. In the frequency region 90MHz- 108MHz since the FM filter rejection loss is very high the corresponding noise temperature is very high. Then from frequencies 120MHz onwards upto 400MHz the noise temperature of the integrated LNA is areound 35K-40K, and then degrades to 75K at 500MHz. The integrated module was subjected to low temperatures as low as 5°C and to higher temperatures as high as 50°C. Measurements were noted at these conditions and it is seen that the noise temperature curves are varied by ±5K from room temperature condition.

3.5.3 IP3 measurements

When an amplifier or other circuit becomes non-linear, it will begin to produce harmonics of the amplified inputs. The second, third, and higher harmonics are usually outside of the amplifier bandwidth, so they are usually easy to filter out if they are a problem. However, non-linearity will also produce a mixing effect of two or more signals.

If the signals are close together in frequency, some of the sum and difference frequencies called inter-modulation products produced can occur within the bandwidth of the amplifier. These cannot be filtered out, so they will ultimately become interfering signals to the main signals to be amplified. These products increase at a rate three times that of the first-order product. Third-order products are the most troublesome of the inter-modulation effects caused by non-linear operation. The IP3 value is an imaginary point that indicates when the amplitude of the third-order products equals the input signals. This point is never reached, as the amplifier will saturate before this condition can occur. It is a good indicator of amplifier linearity. To ensure maximum possible linearity the inter-modulation distortion (IMD) products should be greatly reduced.

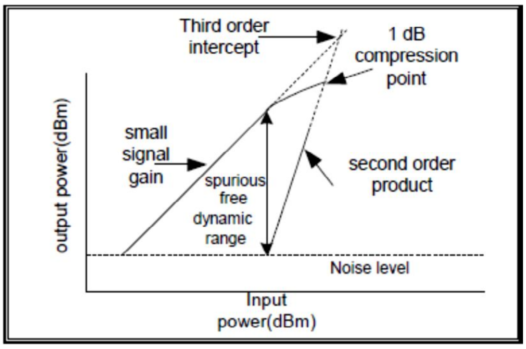
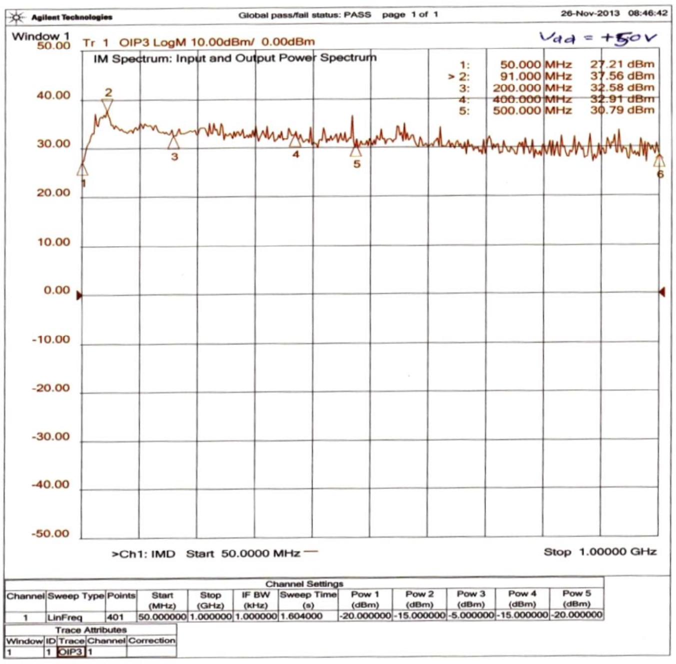


Figure 17 **3rd Order Intercept point**

The output IP3 measurement over the frequency band 50MHz – 500MHz were done using Agilent PNA instrument as shown in the figure 17. It's observed from the plot that for the gain compensated integrated low noise amplifier it varies from +27dBm to +31dBm.



Agilent Technologies Global pass/fail status: PASS page 1 of 1 26-Nov-2013 08:46:42

Window 1

Tr 1 OIP3 LogM 10.00dBm/ 0.00dBm

Vdd = +5.0V

IM Spectrum: Input and Output Power Spectrum

1:	50.000 MHz	27.21 dBm
> 2:	91.000 MHz	37.56 dBm
3:	200.000 MHz	32.58 dBm
4:	400.000 MHz	32.91 dBm
5:	500.000 MHz	30.79 dBm

>Ch1: IMD Start 50.0000 MHz — Stop 1.00000 GHz

Channel Settings

Channel	Sweep Type	Points	Start (MHz)	Stop (GHz)	IF BW (kHz)	Sweep Time (s)	Pow 1 (dBm)	Pow 2 (dBm)	Pow 3 (dBm)	Pow 4 (dBm)	Pow 5 (dBm)
1	LinFreq	401	50.000000	1.000000	1.000000	1.604000	-20.000000	-15.000000	-5.000000	-15.000000	-20.000000

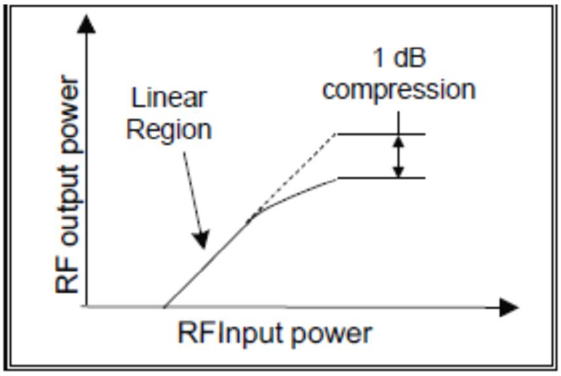
Trace Attributes

Window	ID	Trace	Channel	Correction
1	1	OIP3	1	

Figure 18 Third order Intercept point measurement response of Integrated LNA

3.5.4 1dB compression measurement of Integrated LNA

Most linear amplifiers have a fixed gain for a specific frequency range. The output power versus input power, a linear relationship line can be observed over a range. The slope of the line is the gain. This is the range over which the output power varies linearly with respect to the input power. As the input power continues to increase, at some point the gain begins to decrease. The amplifier goes into compression where no further output increases occur for an input increase as shown in the figure 18. It is important to know at what point compression begins to occur so input levels can be restricted to prevent distortion. That point is usually the input power that causes the gain to decrease 1 dB from the normal linear gain specification. This point is called the output 1dB compression point. The 1-dB compression point is important since it shows you the input power point where compression begins and distortion will occur. Amplifiers should be operated below the compression point. A general rule of thumb the output power of the amplifier is operated 10 dB below the 1dB compression point value.



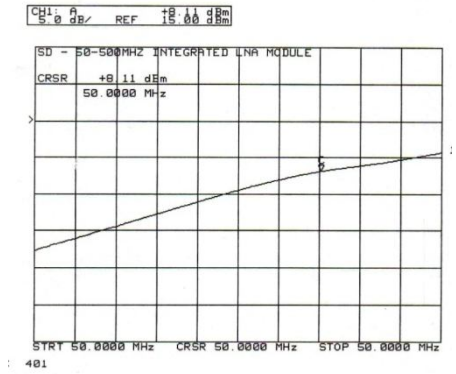
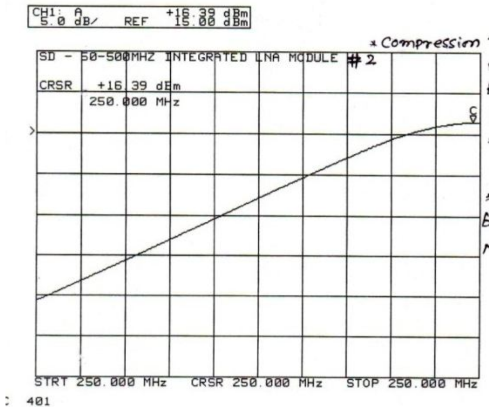
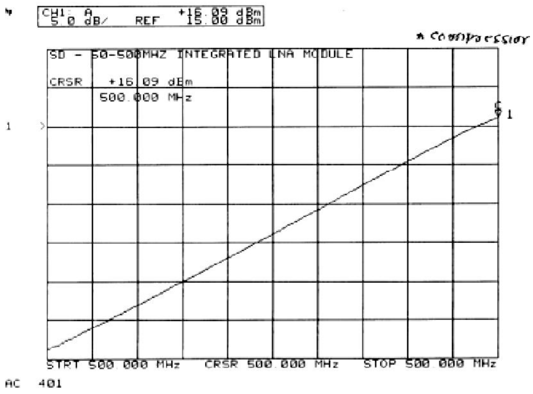


Figure 19 Concept of 1dB Compression Point **1dB compression point @50MHz**

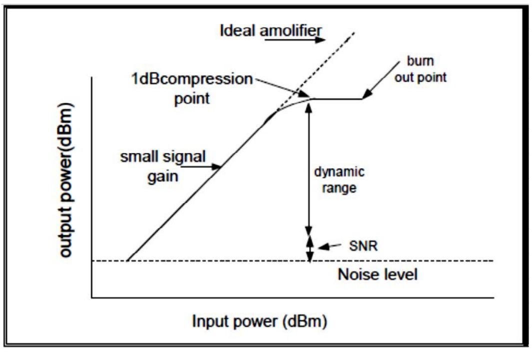




1dB compression point @250MHz **1dB compression point @500MHz**

It is observed from the measured plots in figure 19 that the output 1dB compression point of the integrated amplifier is +8 dBm at 50MHz, +16dBm at 250MHz onwards. The low value at lower frequency is due to the gain equivalization implementation .

3.5.5 Dynamic Range of Integrated LNA



Dynamic range may be defined as the difference in power level between the OIP3 point and the system noise floor. The dynamic range that an amplifier can utilize before being degraded by spurious signals is a more useful definition in reality. When more than one signal is applied to an amplifier the ideal dynamic range is degraded by the third order products. The dynamic range that is free of spurs when two equal amplitude signals are applied to the input can be determined if the third order output intercept point, gain and minimum detectable signal levels are known. The minimum power level is the amplifier noise floor which is the minimum detectable signal by the amplifier.

From the noise figure plot the noise floor power per MHz can be calculated as follows.

MDS = -111dBm + Bandwidth dB + Noise figure dB

The spurious free dynamic range of the integrated amplifier can be found out by the following equation

Spurious Free Dynamic Range = $\frac{2}{3}$ [[OIP (dBm) – Gain (dB)– MDS (dBm)]

Using the above equations, the IP3 and the noise figure plots, the spurious free dynamic range for the integrated low noise amplifier can be calculated as follows :

MDS = -111dBm + 27dB+1dB = -83dBm (For 500MHz bandwidth)

SFDR = $\frac{2}{3}$ [33dBm – 20dB +83dBm] = 64dB (For 500MHz Bandwidth)

3.5.6 D.C. Bias Details:

The Integrated low- noise amplifier circuitry is operated with +5V D.C bias. Since a +5V low dropout regulator LM2937-5V is incorporated in the layout, the applied voltage to the module is +6V minimum externally through a feed through capacitor as shown in the picture.

The current drawn by the amplifier module is 70mA.

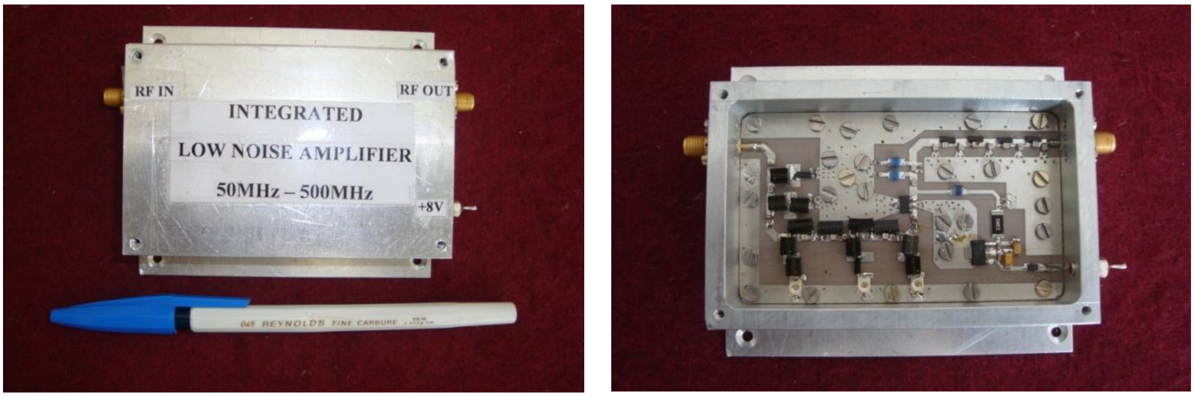
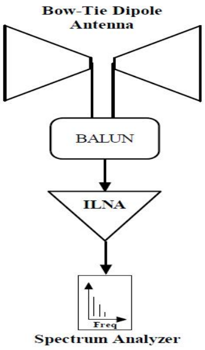


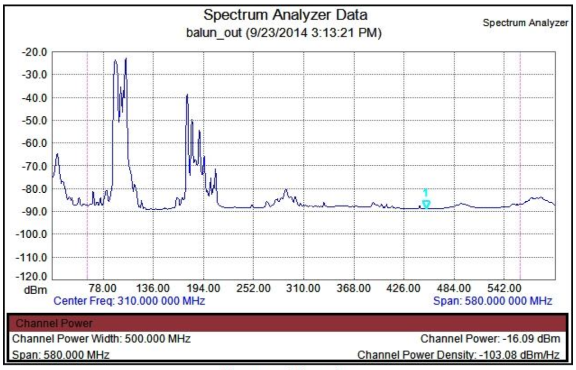
Figure 20. Integrated Low- Noise Amplifier Photograph

4 Measurement Test Set up



5 RESULTS

Measurements carried out at RRI Bangalore


Spectrum Analyzer Data

balun_out (9/23/2014 3:13:21 PM)

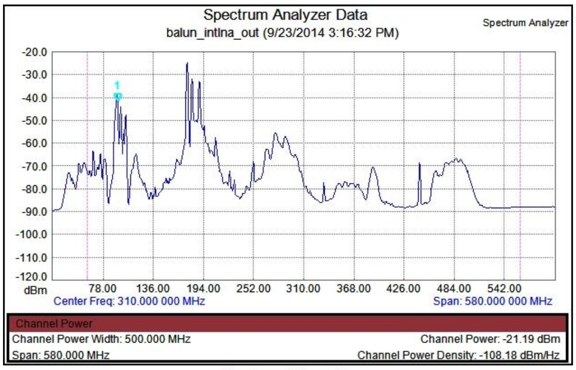
Channel Power

Channel Power Width: 500.000 MHz   Channel Power: -16.09 dBm

Span: 580.000 MHz   Channel Power Density: -103.08 dBm/Hz

Measurement Parameters

		Start Frequency	20.000 000 MHz
Trace Mode	Normal	Stop Frequency	600.000 000 MHz
Preamp	OFF	Frequency Span	580.000 000 MHz
Min Sweep Time	0.001 S	Reference Level	-20.000 dBm
Reference Level Offset	0 dB	Scale	10.0 dB/div
Input Attenuation	0.0 dB	Serial Number	726040
RBW	1.0 MHz	Base Ver.	V2.01
VBW	1.0 kHz	App Ver.	V3.17
Detection	RMS	Date	9/23/2014 3:13:21 PM
Center Frequency	310.000 000 MHz	Device Name	RRI


Spectrum Analyzer Data

balun_intlna_out (9/23/2014 3:16:32 PM)

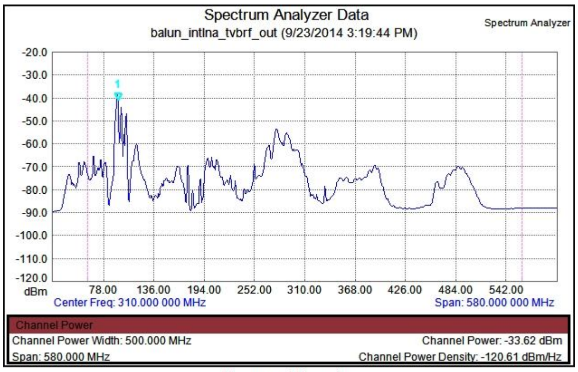
Channel Power

Channel Power Width: 500.000 MHz   Channel Power: -21.19 dBm

Span: 580.000 MHz   Channel Power Density: -108.18 dBm/Hz

Measurement Parameters

		Start Frequency	20.000 000 MHz
Trace Mode	Normal	Stop Frequency	600.000 000 MHz
Preamp	OFF	Frequency Span	580.000 000 MHz
Min Sweep Time	0.001 S	Reference Level	-20.000 dBm
Reference Level Offset	0 dB	Scale	10.0 dB/div
Input Attenuation	0.0 dB	Serial Number	726040
RBW	1.0 MHz	Base Ver.	V2.01
VBW	1.0 kHz	App Ver.	V3.17
Detection	RMS	Date	9/23/2014 3:16:32 PM
Center Frequency	310.000 000 MHz	Device Name	RRI


Spectrum Analyzer Data

balun_intlna_tvbrf_out (9/23/2014 3:19:44 PM)

Channel Power

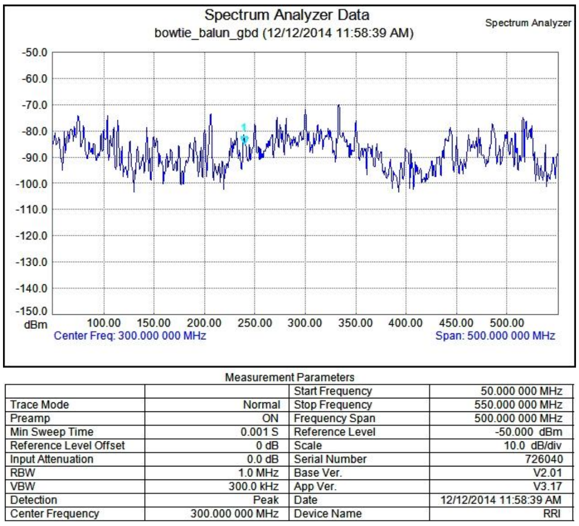
Channel Power Width: 500.000 MHz   Channel Power: -33.62 dBm

Span: 580.000 MHz   Channel Power Density: -120.61 dBm/Hz

Measurement Parameters

		Start Frequency	20.000 000 MHz
Trace Mode	Normal	Stop Frequency	600.000 000 MHz
Preamp	OFF	Frequency Span	580.000 000 MHz
Min Sweep Time	0.001 S	Reference Level	-20.000 dBm
Reference Level Offset	0 dB	Scale	10.0 dB/div
Input Attenuation	0.0 dB	Serial Number	726040
RBW	1.0 MHz	Base Ver.	V2.01
VBW	1.0 kHz	App Ver.	V3.17
Detection	RMS	Date	9/23/2014 3:19:44 PM
Center Frequency	310.000 000 MHz	Device Name	RRI

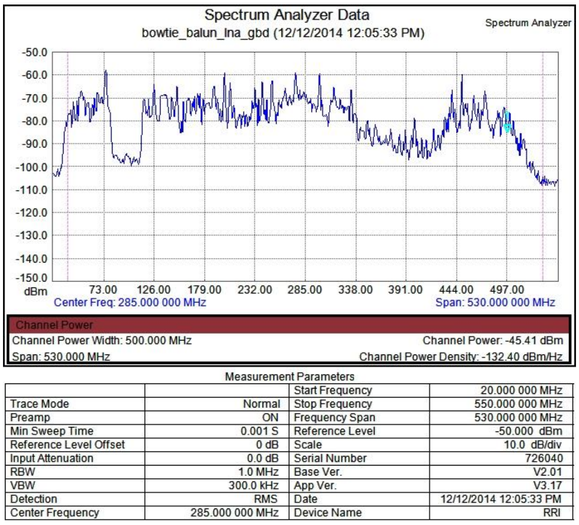
Measurements carried out at Gauribidanur Field Station



Measurement Parameters

		Start Frequency	50.000 000 MHz
Trace Mode	Normal	Stop Frequency	550.000 000 MHz
Preamp	ON	Frequency Span	500.000 000 MHz
Min Sweep Time	0.001 S	Reference Level	-50.000 dBm
Reference Level Offset	0 dB	Scale	10.0 dB/div
Input Attenuation	0.0 dB	Serial Number	726040
RBW	1.0 MHz	Base Ver.	V2.01
VBW	300.0 kHz	App Ver.	V3.17
Detection	Peak	Date	12/12/2014 11:58:39 AM
Center Frequency	300.000 000 MHz	Device Name	RRI

Diploe – Balun – Output



Channel Power
Channel Power Width: 500.000 MHz Channel Power: -45.41 dBm
Span: 530.000 MHz Channel Power Density: -132.40 dBm/Hz

Measurement Parameters

		Start Frequency	20.000 000 MHz
Trace Mode	Normal	Stop Frequency	550.000 000 MHz
Preamp	ON	Frequency Span	530.000 000 MHz
Min Sweep Time	0.001 S	Reference Level	-50.000 dBm
Reference Level Offset	0 dB	Scale	10.0 dB/div
Input Attenuation	0.0 dB	Serial Number	726040
RBW	1.0 MHz	Base Ver.	V2.01
VBW	300.0 kHz	App Ver.	V3.17
Detection	RMS	Date	12/12/2014 12:05:33 PM
Center Frequency	285.000 000 MHz	Device Name	RRI

Dipole – Balun – ILNA –Output

6 Conclusions

This technical report describes the development of a low- noise amplifier with FM signal rejection, can be used for radio sky observations. The module integrates the FM notch filter which ensures the suppression of strong FM radio interference signal much before the amplification so that the saturation of low noise amplifier is avoided, hence higher the dynamic range. The gain and noise figure of the single stage low noise amplifier is around 20dB and 0.6 to 1.1dB respectively. The high- pass and low -pass filter combination forms the band- pass filter which is embedded into it.

Acknowledgements

Many thanks to Ibrahim and Srinivas in the basement workshop for making. amplifier chasis.

References

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Noise Figure Measurement Principles and Applications ,Hewlett Packard, 1989.

ANNEXURE

Mechanical Dimensions of the Integrated LNA