ABSTRACT

150 MHz is one of the major frequency bands of observation for GMRT. The band alloted for the radio astronomical purpose is from 152 – 155 MHz with a center frequency of 153 MHz. Even though the alloted bandwidth is only 3 MHz, observation is generally done with a center frequency of 150 MHz with bandwidth of 6 MHz. This is for increasing the sensitivity.

Observations at 150 MHz are severely affected by strong man-made interferences nearby frequency band of observations. However, with the broad band coverage of the existing system many interferences comes into picture. The major interfering signals are MARR (Multi Access Rural Radio) system, T.V. Transmission, F.M. Radio, police wireless and civil aviation communication. Therefore it is essential to separate the desired signal from undesired signals. The process of separation of desired signals/informations from that of undesired one is called "Filtering" and the circuit which performs this filtering is called as "Filter".
And this separation is done by filters. Filters are one of the most important components used in the instruments in Radio Astronomy. They are used to select certain frequency channels for observation or to minimize unwanted man-made radio interferences.

The objective of the project is not only to replace the existing BPF with HPF-LPF combination for better rejection at stop frequency but also to suppress major interferences falling in the desired frequency band by incorporating notches at interference frequencies falling in the desired band. The project involves mass production of LPF,HPF and notch filter tunning of the same for desired response, implement it in Front-end box, testing of the FEB in lab and then install the FEB and test at ABR.

ACKNOWLEDGMENT

To carry out a task successfully, it is very important to have a good vision and good guidance . My guide provided me the same. I am very thankful to my project guides at GMRT-TIFR , Mr. A. Praveen Kumar and Mr. Anil Raut for their valuable guidance ,throughout the project. I express my deep gratitude to them for their constant encouragement and support throughout the project.

I am thankful to Mr. Ajit Kumar who designed the notch filters, HPF and LPF and proved it's usefulness for RFI rejection by doing necessary testing. My project was to implement the same in FEB. I am also thankful to Mr. S. Joardar for providing necessary information regarding RFI around the frequency band of interest. I thanks to Mr. G. Sankar for his help.

I am thankful to V.B. Bhalerao, S. Ramesh, Mrs. Parate (FE-Lab), Sandeep Parkhee, Mr. Hande & Ramdas (BB Lab) for providing me the necessary help whenever needed.

My special thanks to my friends at GMRT Sanjay, Jayanta, Manisha, Abhay, Ramchandra, Aparna, Sachin P., Sachin S., Vishal, Laurent, Tauji, Vinod, Zinjad with whom I had memorable moments.

I thank everybody who directly or indirectly helped me for this project. I thank to entire staff at GMRT for their help and co-operation at various levels.

Last but not least , I wish to thank my family for their affection and inspiration.

Sandeep C. Chaudhari

Chapter 1

INTRODUCTION

1.1 Brief Introduction Of GMRT

Radio Astronomy is a part of observational Astronomy. It is the study of of planets, stars,galaxies and other astronomical objects using radio waves they emit. Radio astronomy is the study of celestial phenomena by measuring the characteristics of radio waves emitted by physical processes which occur in extraterrestrial environments. Because radio waves are much longer than light waves, radio astronomy requires large antennas such as GMRT.

Giant Meter wave Radio Telescope (GMRT) is a project run by the National Center for Radio Astrophysics (NCRA) under Tata Institute of Fundamental Research (TIFR) INDIA. It is one of the largest radio telescope observatory in the world operating at meter-wavelengths. GMRT is situated at Khodad 80km North of Pune. It has 30 fully steerable giant parabolic dishes of 45m diameter each, spread over distance of about 25km.

The Main objective of GMRT is to study interesting phenomenon which can be observed at meter wavelength. The location of antennas and their number was optimized to meet the principal astrophysical objectives which require sensitivity at high angular resolution as well as ability to image radio emission from less fused extended regions. Fourteen of the thirty dishes are located more or less randomly in a compact central array in the region of about 1 sq km. The remaining sixteen antennas are spread out along the 3 arms of an approximately 'Y'-shaped configuration over a much larger region. Currently GMRT operates in four frequency bands centered at 233, 327, 610 and 1420 MHz. At all these feeds the dual polarization outputs are available.

1.2 Scope Of Work

Scope of my project is

- To mass produce the filter units for 12 number of antennas.
- Tuning each individual filter for the desired performance.
- Assembling in the 150 FEB.
- Testing and certification of the FEB in the lab for field installation.
- Installation of FEB on antennas, testing at ABR.
- And Documentation of test reports.
- Also thermal cycling of Notch filter unit

1.3 Introduction To Interferences At 150 MHz

Observations at 150 MHz are severely affected by strong man-made interferences nearby frequency band of observations. With the broad band coverage of the existing system many interferences comes into picture. The major interfering signals are MARR (Multi Access Rural Radio) system, T.V. Transmission , F.M. Radio, police wireless and civil aviation communication.

- **Major Interferences Summary** :-

The major sources of interference within this band are as listed below. These are referred from the report RFI REJECTION FILTER AT 150 MHz by Mr. Vinod Toshniwal under the guidance of Mr. Ajitkumar B.

1. MARR(Multi Access Rural Radio)	121,127,132.3,137.8 &144.3 MHz	
2. Pager	146 MHz	
3. Police wireless	159.5,163,164.3 MHz	
4. T.V. Communication	Picture	Audio
a. Channel 5	175.5MHz	180.75 MHz
b. Channel 6	182.25 MHz	187.25 MHz
c. Channel 7	189.25 MHz	194.75 MHz

Thus from the above table and the plot presented in the report of Mr. Vinod, major interferences frequencies of concern are :-

a. 101 MHz : Pune FM Radio.
b. 130 MHz : Aeronautical Radio-navigation.
c. 146.6 MHz : Pager.
d. 159 MHz : Police wireless.
e. 163 MHz : Rural Police.
f. 175.25 MHz : Pune TV video.
g. 180.75 MHz : Pune TV audio.

1.3 Filter Basics

Real world signals contain both wanted and unwanted signals / informations. Therefore it is essential to separate the two. The process of separation of wanted signals / informations from that of unwanted one is called “Filtering” and the circuit which performs this filtering is called as “Filter”.

1.3.1 Filter Classification :-

Filters can be classified on the basis of the type of components/devices used, the band of frequencies they select, and the nature of the transfer function which tries to approximate the ideal characteristics.

Depending upon the passband and stop band locations filters are basically divided into four types as:-

1. Low-pass
2. High-pass
3. Band-pass
4. Bandstop

Ideal Filter :-

An ideal filter is the one, which transmits frequencies in its pass band without attenuation and phase shift , while not allowing any signal components in the stop-band to get through i. e. Stop band attenuation as infinity .Also ideal filter has a sharp transition.

Real World (Non-Ideal) Filters :-

Ideal filters are not realizable. In order to approximate the "Brick wall" frequency response of the ideal filter we have to use some approximations. These approximations are nothing but mathematical transfer functions which approximate the ideal behavior. Depending upon transfer function response of the best amplitude or phase, filters can be classified into two basic categories , **Amplitude Filters** and **Phase Filters** .

Amplitude filters are designed for the best amplitude response for a given situation. e. g. Zero ripple is in passband the amplitude response.

The classification of amplitude filter is as follow :-

1. **Butterworth** :-

Butterworth filters are characterized by the fact that it has no ripple in the passband or stop band and has monotonically decreasing passband. These filters are all-pole filters

2. **Chebyshev** :-

The Chebyshev response is characterized by the presence of ripple in the passband and no ripple in the stop band. The ripple can be controlled and is directly proportional to the SWR and Reflection coefficient. The cutoff frequency is specified at an attenuation equal to passband ripple. The Chebyshev response is more selective than Butterworh response at the expense of insertion loss and greater group delay.

3. **Elliptic** :-

The Elliptic response is characterized by the presence of ripple in both passband as well in stop band. The Elliptic response is more selective than Chebyshev but exhibit more group delay variation in the passband.

Phase filters are designed for desired phase response, such as linear phase with frequency throughout the filter passband. Bessel filter is the best example of this. It is a (**Bessel)** linear phase filter providing very little delay distortion (constant group delay) in the passband. They show no overshoot in response to the step input. However frequency response is much less selective than other filters types. This restricts the use of these filters where transient properties are the major consideration.

1.3.2 Selecting The Right Analog Filter :-

Choosing the correct filter for a particular application requires defining properties of the incoming signal that the filter must remove, as well as the properties that it must retain. In most situations, there is some overlap between these two areas, demanding a degree of compromise.

Time Domain Waveform Presentation :-

Filters for such applications must have a linear phase response in the passband, and must not introduce ringing or overshoot. To Preserve signal waveform while removing undesired components,the filter must also pass many harmonics of the incoming signal's base frequency. “Noise” components that the filter removes must be at substantially higher frequencies than these necessary harmonics. Bessel filter works best in these cases.

High Selectivity in the Frequency Domain :-

Situations where removal of undesired components is the overriding concern and some distortion in the time domain of the signal's shape is of less importance generally require sharper roll-off filters with Butterworth or Chebyshev or elliptic transfer functions. e. g. Spectrum analysis is only concerned to the amplitude of input frequency components.

Compromise Filters :-

Although linear phase filters preserve critical information, many applications also require rapid transition-band roll-off. A balance between these mutually exclusive requirements can often be achieved by phase-derived types and amplitude-compensated versions of phase filters.

Chapter 2

FRONT-END SYSTEM

2.1 Existing 150 MHz Front-End Receiver System

The existing system of front-end receiver gets it's input from two orthogonal pairs of folded thick dipoles at a spacing of approximately half wavelength placed in a quad formation over a plane reflector. This arrangement is called "Boxing Ring " arrangement. Two pairs of dipoles one to receive vertical polarized signal (V) and another to receive horizontally polarized signal (H) are used.

The linearly polarized signals V and H are then converted into circular polarization viz CH1 and CH2 or LCP and RCP using QHDC. The signal is then amplified by LNAs which are having a gain of 32 dB and a bandwidth in excess of 100 MHz.

The signal is band limited by a Bandpass filters placed immediate after LNA with a center frequency of 150 MHz with bandwidth of +/- 16 MHz.

The signal is then amplified by post amplifier. Thereafter, the signal is modulated with Walsh function using phase switching to reduce the effect of coupling between the two channels.

Rf on/off facility is provided for connecting and disconnecting a channel by means of RF switch. The front end box output signal is sent to the common box, which incorporates band-selector, solar attenuator, swap switch and broadband amplifier for further amplification.

2.2 Necessity Of Up gradation In Front-End System

The filter present in the existing Front-End system is a bandpass filter as mentioned above and have asymmetric and gradual roll-off (especially on higher frequency sides) characteristics which is insufficient to block out of band strong interferences. These strong out of band interfering signals may beat with inband as well as with out of band signals in the mixer stage and produce many inter-modulation products (IMD), which may fall inside the desired frequency band of observation. Therefore in order to provide large rejection for the out of band signals we need to have maximum attenuation in stop band with very sharp roll-off for the filter. This can be achieved by combining an elliptic LPF in series with an elliptic HPF to produce a sharp cut-off bandpass filter.

2.3 Modified 150 MHz Front-End System

2.3.1 Reason Of Selection Of LPF And HPF Combination

The main reasons for selecting LPF and HPF combination instead of BPF are as follow :-

Individual tuning of the filter makes it possible to adjust the response characteristics without affecting the individual response of the another filter. Thus tuning becomes very easy. Also by adjusting the transition band of the filters on lower as well as upper side of frequencies individually, it is easy to make a filter symmetric around the center frequency. Thus filter response symmetry can be achieved. This response symmetry results in the symmetry in group-delay, which ultimately results in simplified group-delay equalizer design. For large bandwidth it is preferable to have LPF and HPF combined as BPF.

2.3.2 Modified 150 MHz Front-End Receiver

To suppress strong in band interfering signals notch filter has to be incorporated. The interfering signals for which notch is to be put is based on the strength of the signal and as well the location of the interfering signals which may again produce third order IMD falling inside the desired frequency band.

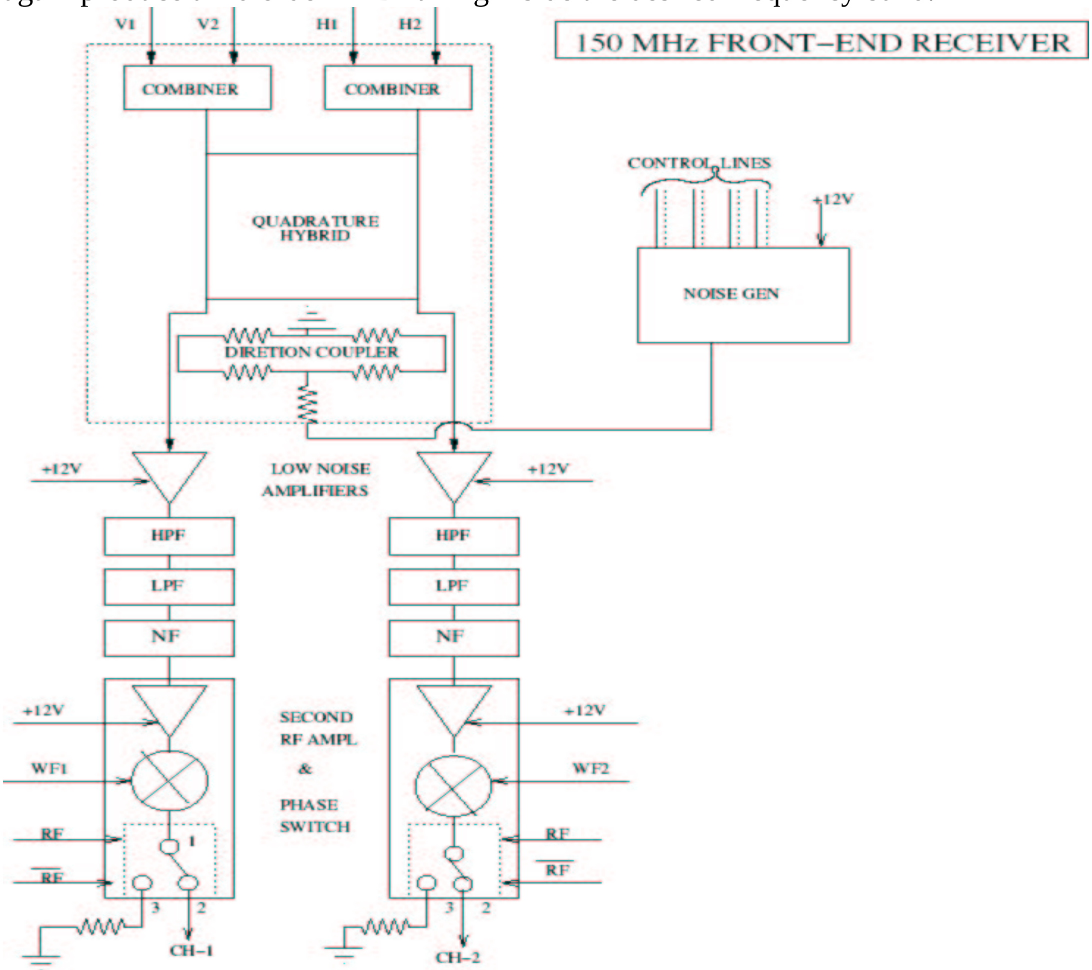


Fig. 2.1 150MHz Front-End Receiver Block diagram.

The modification is done only by replacing the Bandpass filter in the existing front end system by LPF+HPF and Notch Filter combination as shown in fig. above ,with all the other blocks untouched.

2.2.3 Notch Frequency Selection

The notch frequencies are decided on the basis of the information available reggarding the interference sources (Ref. Section 1.2) and the RFI data acquired by Mr. S. Joardar using his RFI monitoring instrument. The location of the notch was fixed at 133.35, 146.6, 159 MHz, which falls in the desired frequency band.

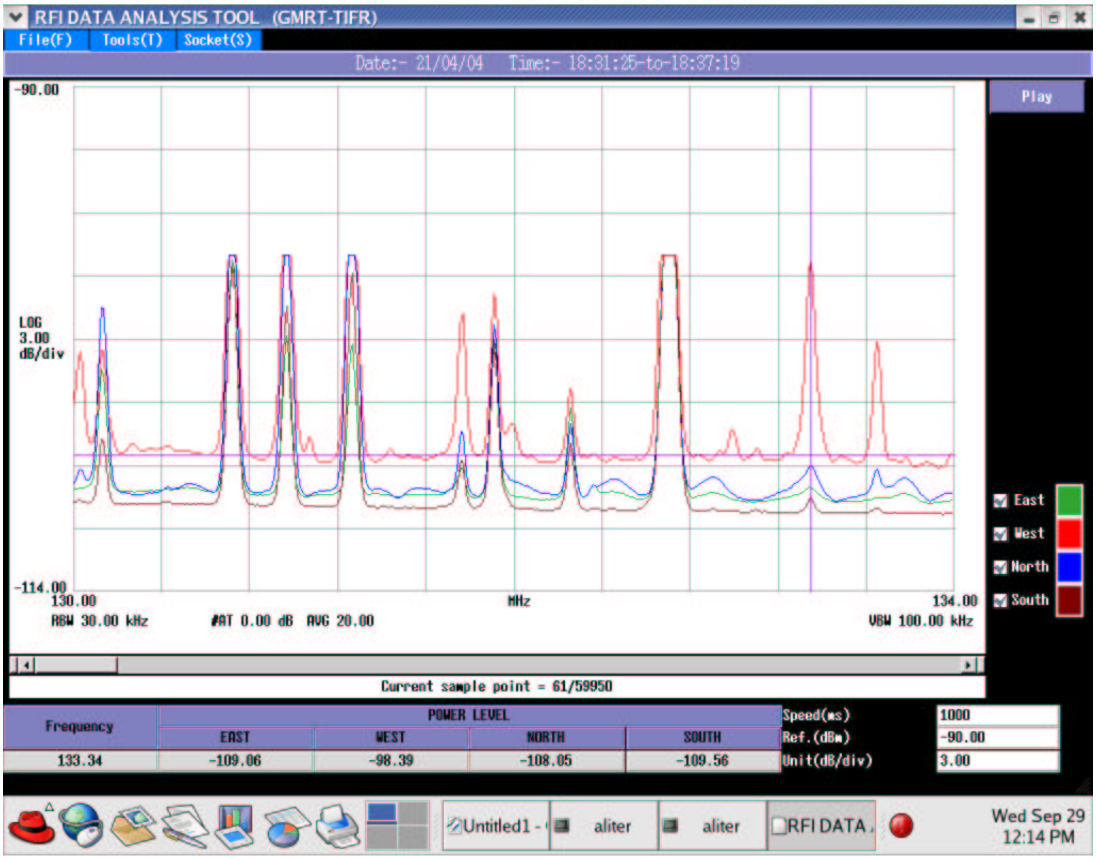


Fig. 2.2 RFI Detection And Analysis Tool Plot

Thus the selected notch frequencies 133.35, 146.6 and 159 MHz along with one out-band signal 175 MHz produce third order IMDs , of which some fall in the required frequency band as given below:

For f1 = 133.35 MHz and f2 = 146.6 MHz, then IMD's are

1. 2xf2 - f1 = 2x146.6 - 133.35
   = 159.89 MHz which falls within desired freq. Band.
2. 2xf1 - f2 = 2x133.35 - 146.6
   = 120 MHz & this doesn't fall within desired one.

Similarly for f1 = 146.6 MHz and 159 MHz these are

1. 2xf2 - f1 = 2x159 -146.6
   = 171.4 MHz & this doesn't fall within desired one.

2. 2xf1 - f2 = 2x146.6 - 159
= 134.2 MHz which falls within desired freq. Band.

And for f1 = 159 MHz and 175 MHz these are

1. 2xf2 - f1 = 2x175 -159
= 191 MHz & this doesn't fall within desired one.

2. 2xf1 - f2 = 2x159 - 175
= 143 MHz which falls within desired freq. Band.

Chapter 3

NOTCH FILTER DESIGN

3.1 Specifications :-

1. Center Frequency = 150 MHz
2. 3dB Band-width = 4 MHz
3. Stop band Attenuation = 25 dB
4. Stop band Band-width = 500 kHz
5. Insertion loss < 1 dB
6. Passband ripple = 0.1 dB
7. I/P and O/P impedance = 50 ohms

Filter Type Selection :-

Chebyshev Full Transformed Elliptic filter of T-section type.

It is used to get very narrow stop band band-width at a particular frequency as well as sharp roll-off.

3.2 Interleaving Technique

3.2.1 Practical Filter Design Difficulties :-

The filter is designed using Eagle-ware GENESYS software. The main concern is to realize the component values. The filter doesn't have all realizable elements ,especially series branch inductors have value of few hundred picohenry(pH) and shunt branch capacitor having value of few hundred femtofarad(fF).

To make these element realizable a technique is used called “Interleaving Technique”. With this technique a notch is embedded in the LPF to realize unrealizable element without changing the characteristics of filter in the band of interest. The realization is done by using “Dipole Transform”.

3.2.2 Solution To Practical Filter Design Difficulty :-

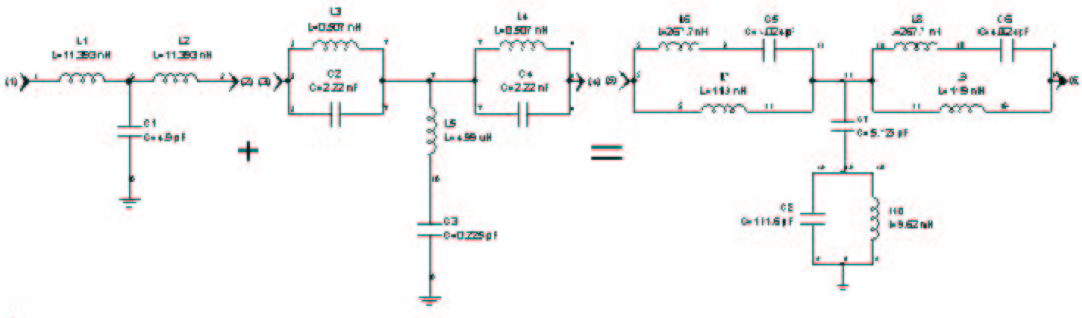
Interleaving Technique :-

➢ **Why to use interleaving technique?**

-> Usually numeric design of bandstop filter with the given specifications at RF frequencies can't be built as a practical lumped element filter because of their extreme element spread i. e. ratio of max. element value to the min. element value is very high. The second reason is that very low values of inductors usually have very poor Q at RF frequencies ,if built. So to reduce the extreme element spread and make numerical values of elements to the practical values “Interleaving Technique” is used.

- **What is interleaving technique?**

-> Interleaving is the technique of reducing the element spread by embedding a notch in the another filter passband . The filter may be LPF / HPF / BPF depending upon the requirement and accordingly the dipole transform changes. The technique in which two ladders of the same size are interleaved by combining the corresponding shunt branches in parallel, and series branches in series as shown in **fig. 3.1** respectively.



LPF to reduce element spread+Numerical Bandstop Filter =Realizable Notch Filter

Fig. 3.1 of Interleaving tech.

- **What is dipole transform?**

-> When series as well as shunt branches of LPF and NF are combined then to get the realizable element values and to reduce inductance spread we have to apply transforms to series as well as to shunt branches which makes the series/shunt branch elements realizable. The shunt circuit and series circuit transforms are shown in **fig.3.2**.

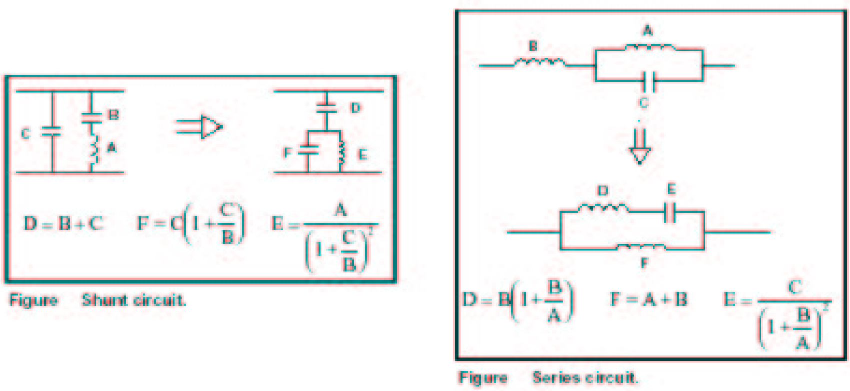
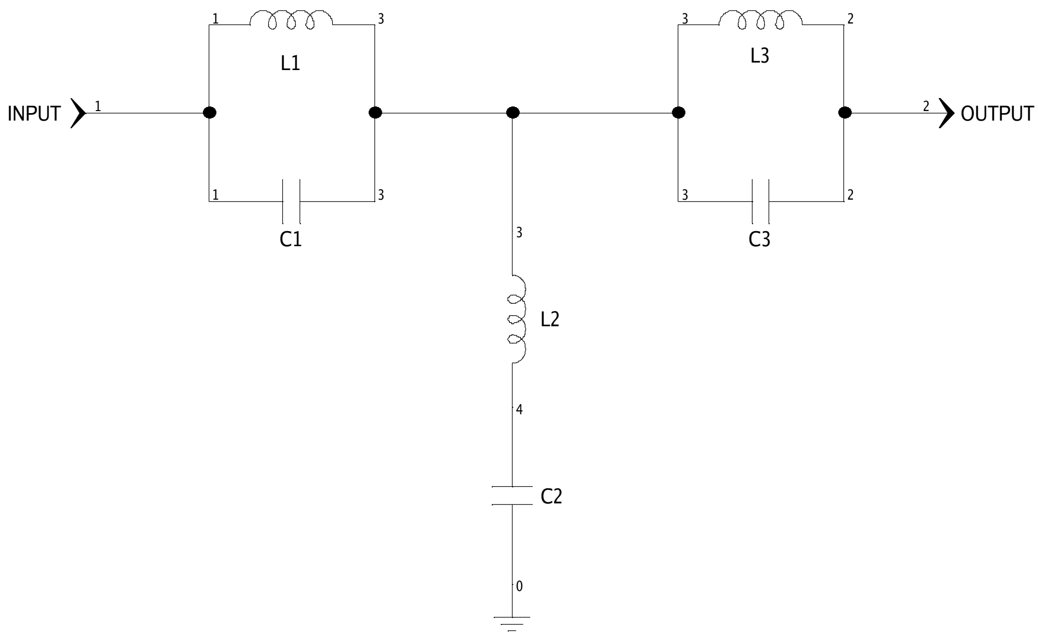


Fig. 3.2 Dipole Transformation Circuit Diagram with Formulas

3.3 Numerical NF (Bandstop Filter) Design

Numerically designed Bandstop filter, with above specifications is shown in **fig. 3.3** below. The filter is designed using Eagle-ware GENESYS Software.



Where values of components are as follows :-

L1,L3 = 0.507 nH
C1,C3 = 2.22 kpF
L2 = 4.99 uH
C2 = 0.225 pF

Fig. 3.3 Numerically Designed Bandstop Filter

So it's obvious that the numerically calculated values are not practically possible and the design is totally inflexible .Let's see the series arm inductors having values < 1nH which is very difficult to construct using lumped components & it also have a drawback that if construct such an inductor it's Q-factor will be very very poor. Also the shunt branch capacitor has very small and inductor has very large value.

The most important thing is the element spread. In this design the total inductor spread and capacitor spread are as follows

Inductor spread = (4.99 uH) / (0.507 nH) = 9842 --------(1)

Capacitor spread = (2.22 kpF) / (0.225 pF) = 9867 ---------(2)

This element spread is too large and need to be optimized. This can be done using a process called Interleaving. With this technique the notch is embedded in the LPF and then using dipole transform element spread can be minimized. For this a LPF has to be designed in order to optimize the spread.

3.4 Practical NF Filter Realization

3.4.1 Optimizing Element Spread :-

If y = inductance spread , and
x = band-edge frequency of the LPF
Then y is a function of x as Y = f(x).

To evaluate this function for a given band-edge frequency, x , begin by finding the low pass element values for chosen value of x. Bandstop element values are fixed, so incorporate low pass element values into the design to optimize the design. Then perform the dipole transformation as shown in above **fig.3.1** and **fig.3.2** . Finally calculate the element spread thus obtained i. e. the function value.

If this procedure is performed several times to plot the smooth curve,it will become apparent that it has a definite minimum. The band-edge frequency that produces this minimum is the optimal value for the practical filter.

3.4.2 Interleaving NF And LPF :-

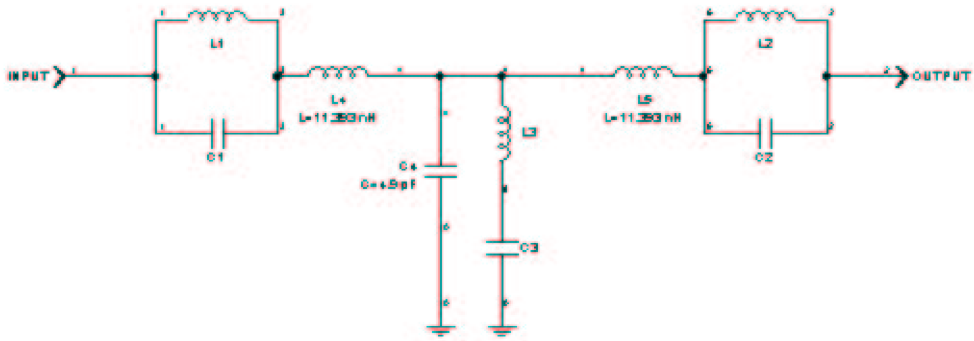


Fig. 3.4 Interleaved Bandstop and LPF

Where, L1,L2 = 0.507 nH
C1,C2 = 2.22 kpF
L2 = 4.99 µF
C2 = 0.225 pF

With the simulation of above circuit and making the values of LPF elements variable the flat response up to required frequency range can be obtained and then predict that this is the LPF which produces definite minimum. The LPF obtained from above method is as shown in **fig.3.5** given below.

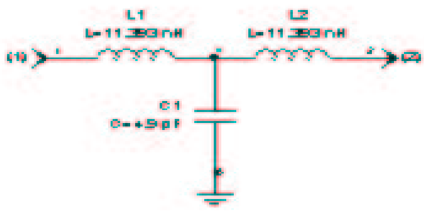


Fig. 3.5 Circuit Diag. OF LPF

The specifications of the LPF are as given below :-

Specifications:-

1. Filter Type = Butterworth
2. Order = 3
3. 3 dB cut-off frequency = 1 GHz

Now the combined filter as described in interleaving technique is as shown in above **fig. 3.4**.

3.4.3 Dipole Transform To Interleaved Filter :-

Now apply dipole transform to the filter in order to find out the element values, as follows.

Series Dipole Transform:-

From the fig.3.2 (1) of series dipole Transform component values are calculated as :-

Where B = 11.393 nH
A = 0.507 nH
C = 2.22 kpF

1. D = B(1+B/A)
   = 11.393 nH (1 + 11.393 nH / 0.507 nH)
   = 267.7 nH
2. F = A+B
   = 0.507 nH + 11.393 nH
   = 11.9 nH
3. E = C / $(1+B/A)^2$
   = 2.22 kpF / $(1 + 11.393 \text{ nH} / 0.507 \text{ nH})^2$
   = 4.024 pF

Shunt Dipole Transform:-

From the fig.3.2 (2)of shunt dipole transform component values are calculated as :-

Where B = 0.225 pF
A = 4.99 µF
C = 4.9 pF

1. D = C+ B
   = 4.9 pF + 0.225 pF
   = 5.125 pF
2. F = C (1 + C/B)
   = 4.9 pF (1 + 4.9 pF / 0.225 pF)
   = 111.6 pF
3. E = A / $(1 + C/B)^2$
   = 4.99 µF / $(1 + 4.9 \text{ pF} / 0.225 \text{ pF})^2$
   = 9.62 nH

The transformed circuit using these values is as shown in **fig.3.6**.

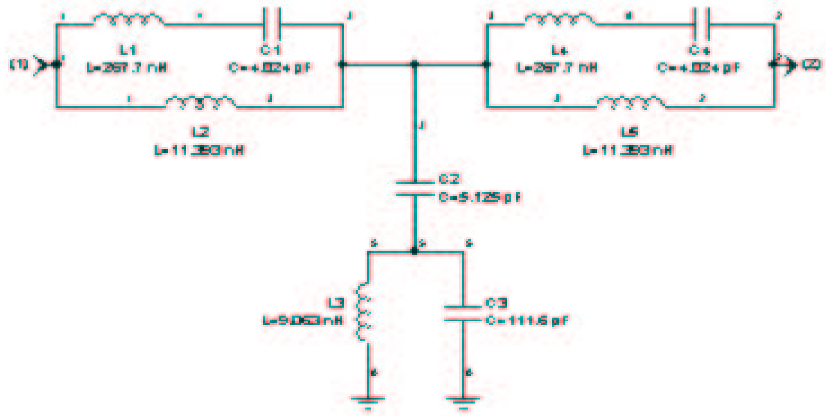


Fig. 3.6 REAL Bandstop filter

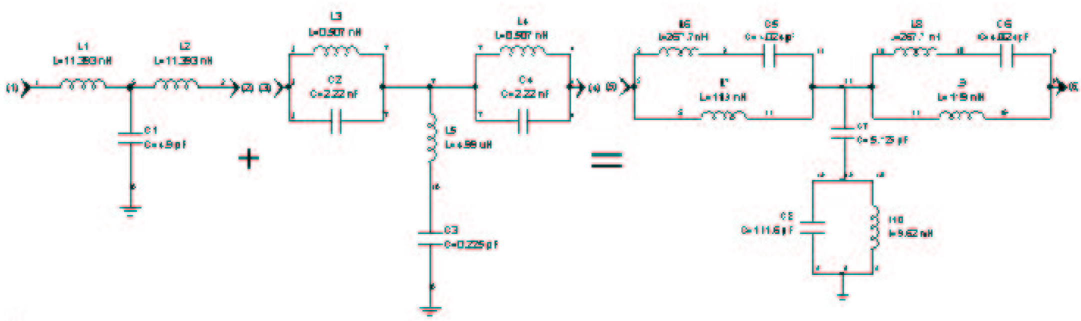
It is apparent from the following figures that the element spread has reduced drastically after using the interleaving technique.

Inductor spread = 267.7 nH / 9.62 nH = 27.83 ----------(3)

Capacitor spread = 111.6 pF / 4.024 pF = 27.73 ----------(4)

Thus the Interleaving technique is used to realize a practically unrealizable Bandstop filter.

Following diagram shows the step by step implementation of realizable Bandstop filter.



LPF + Numerical Bandstop filter = Interleaved Bandstop Filter

Fig. 3.7 Interleaving Technique Used For Bandstop Filter

NOTE :- Here all simulated results of filters are with element Q-factor of 100. If Q of individual element is increased then the rejection of the bandstop filter will increase accordingly.

3.5 Simulation Results :-

3.5.1 Simulated Filter Response Of Numerically Designed Notch Filter

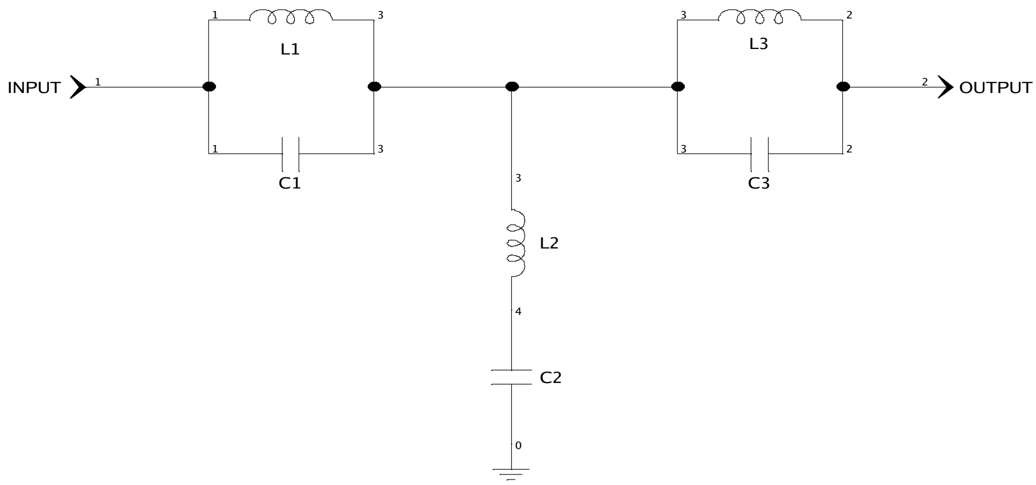


Fig. 3.8 Circuit Diagram Of Numerically Designed Bandstop Filter

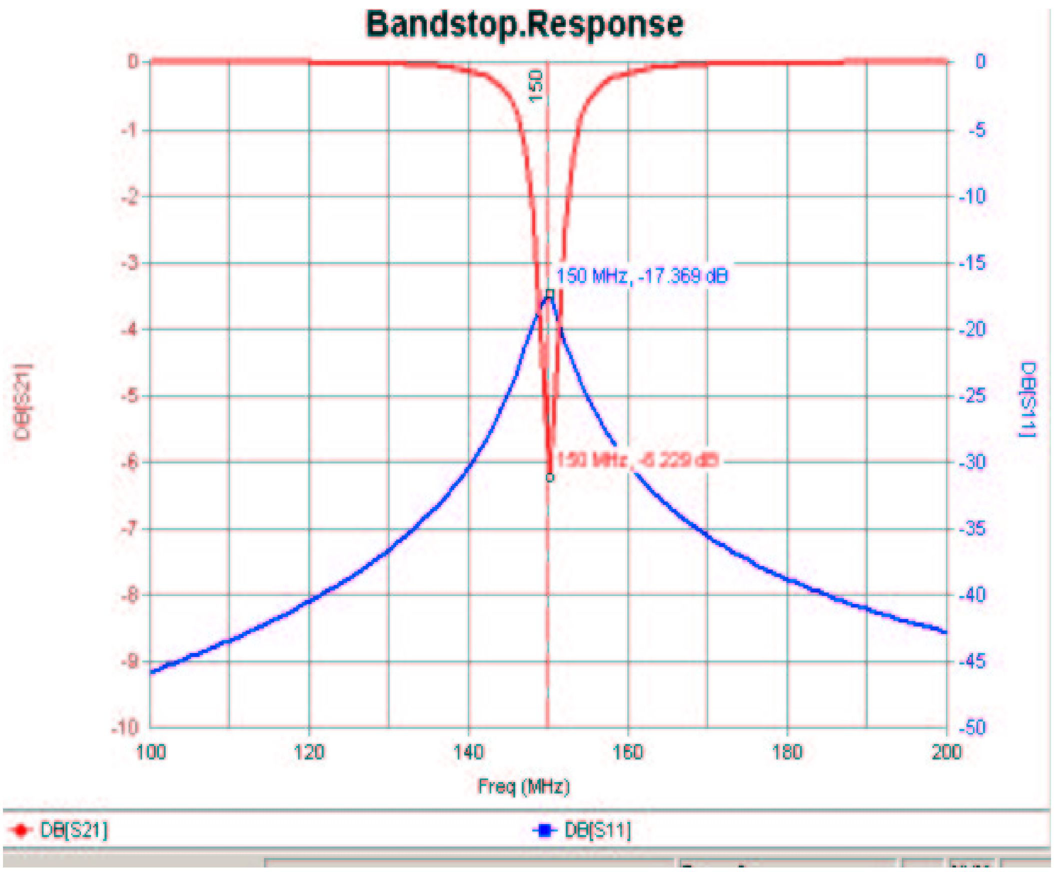


Fig. 3.9 Numerically Designed Bandstop Filter Response

3.5.2 <u>Simulated Filter Response Of LPF Used For Interleaving</u> :-

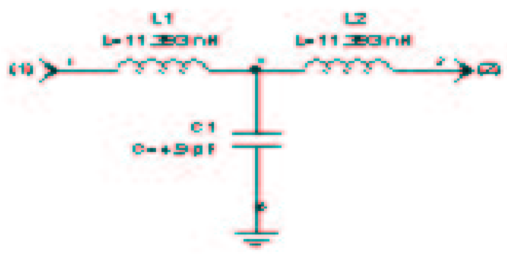


Fig. 3.10 LPF Circuit Diagram

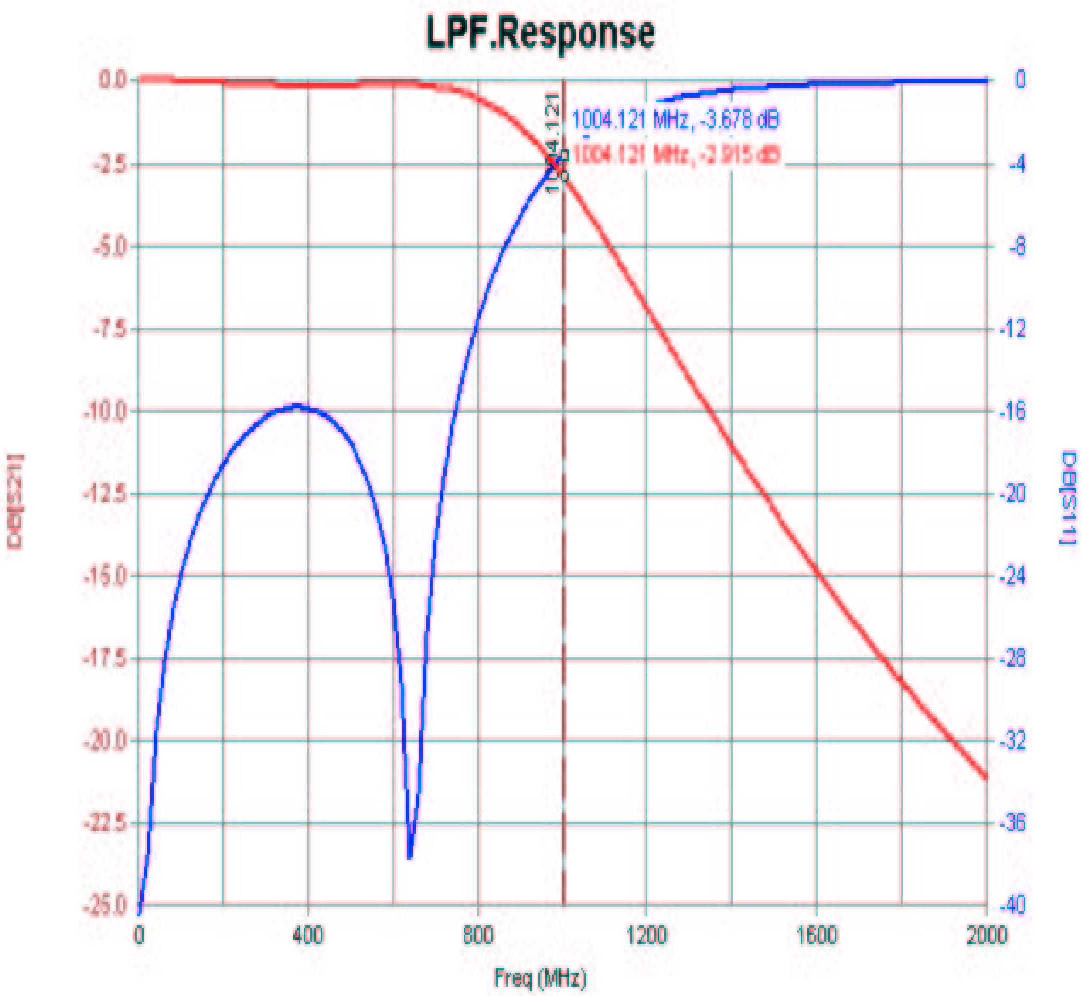


Fig. 3.11 LPF Filter Response

3.5.3 Simulated Filter Response Of Interleaved Notch Filter :-

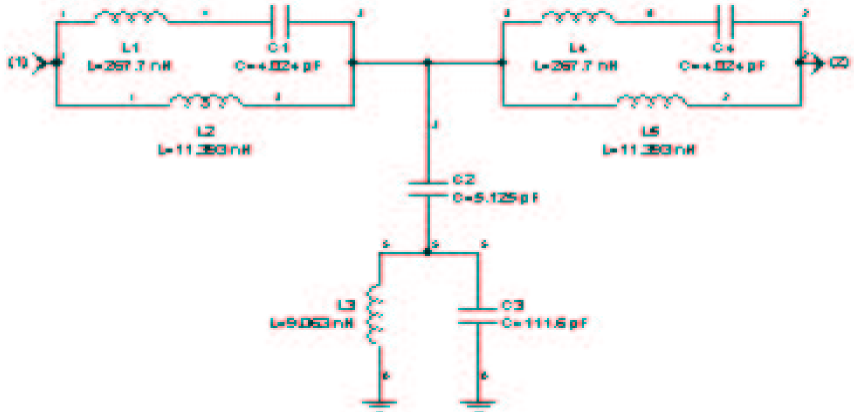


Fig. 3.12 Realizable Bandstop Filter

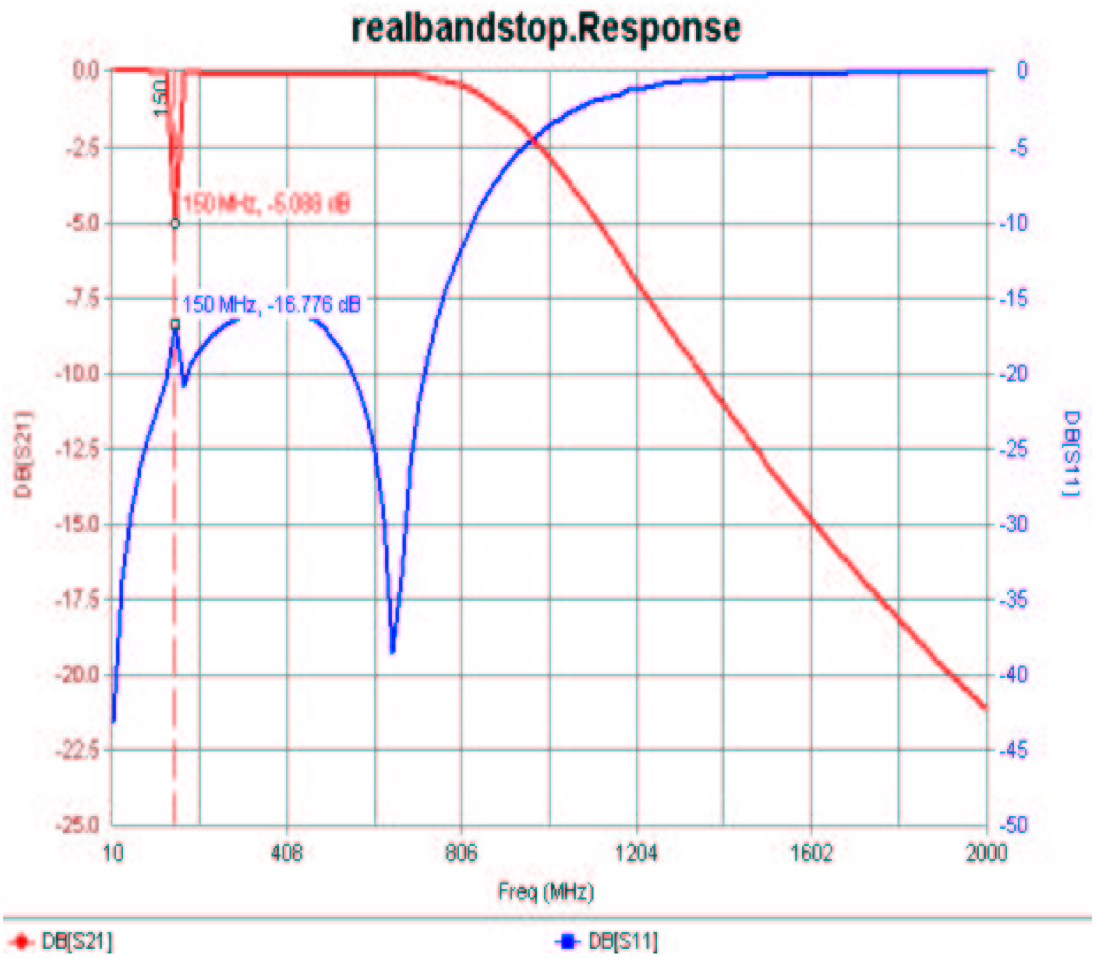
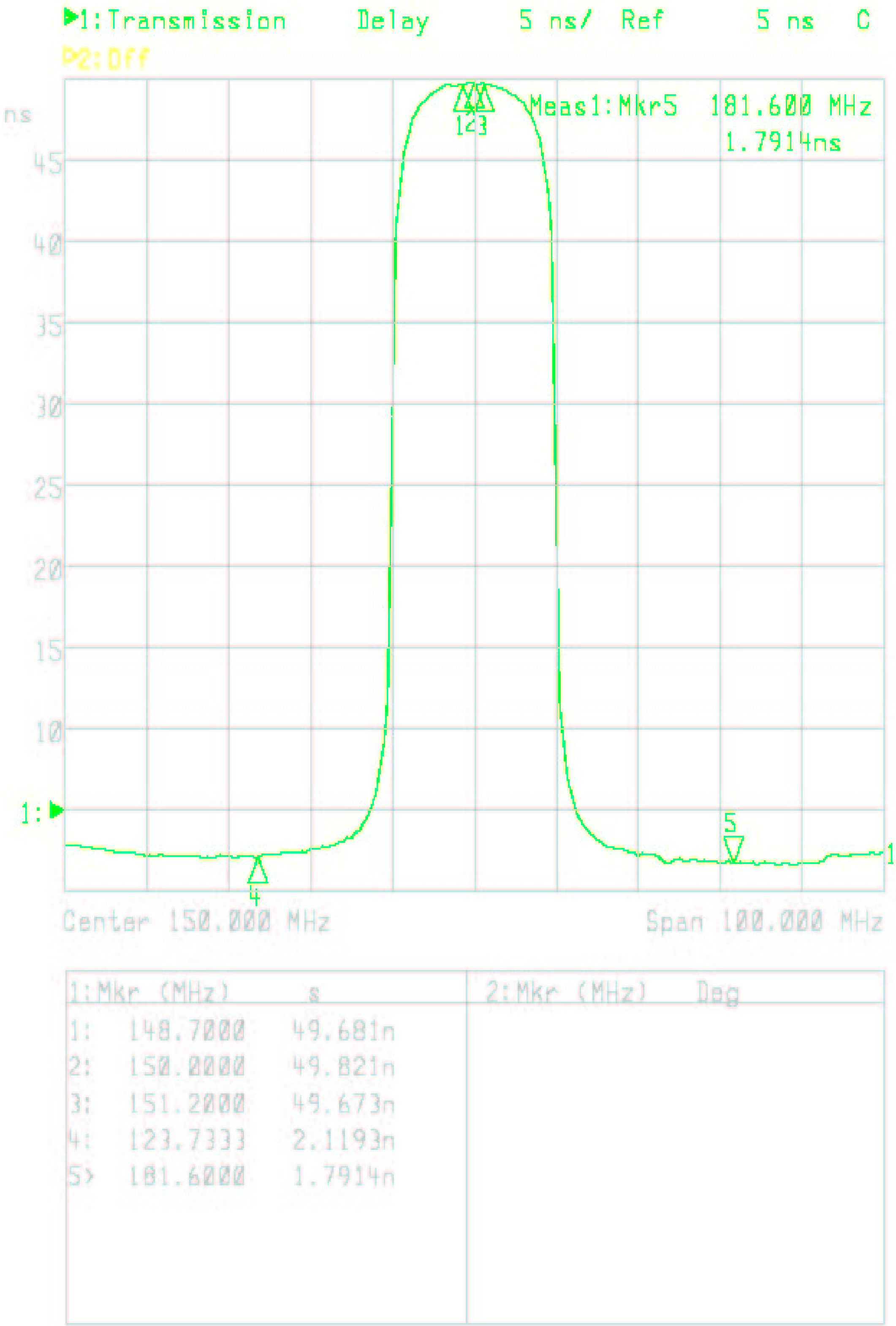


Fig. 3.13 Realizable Bandstop Filter Response

3.6 Practical Bandstop Filter Response :-

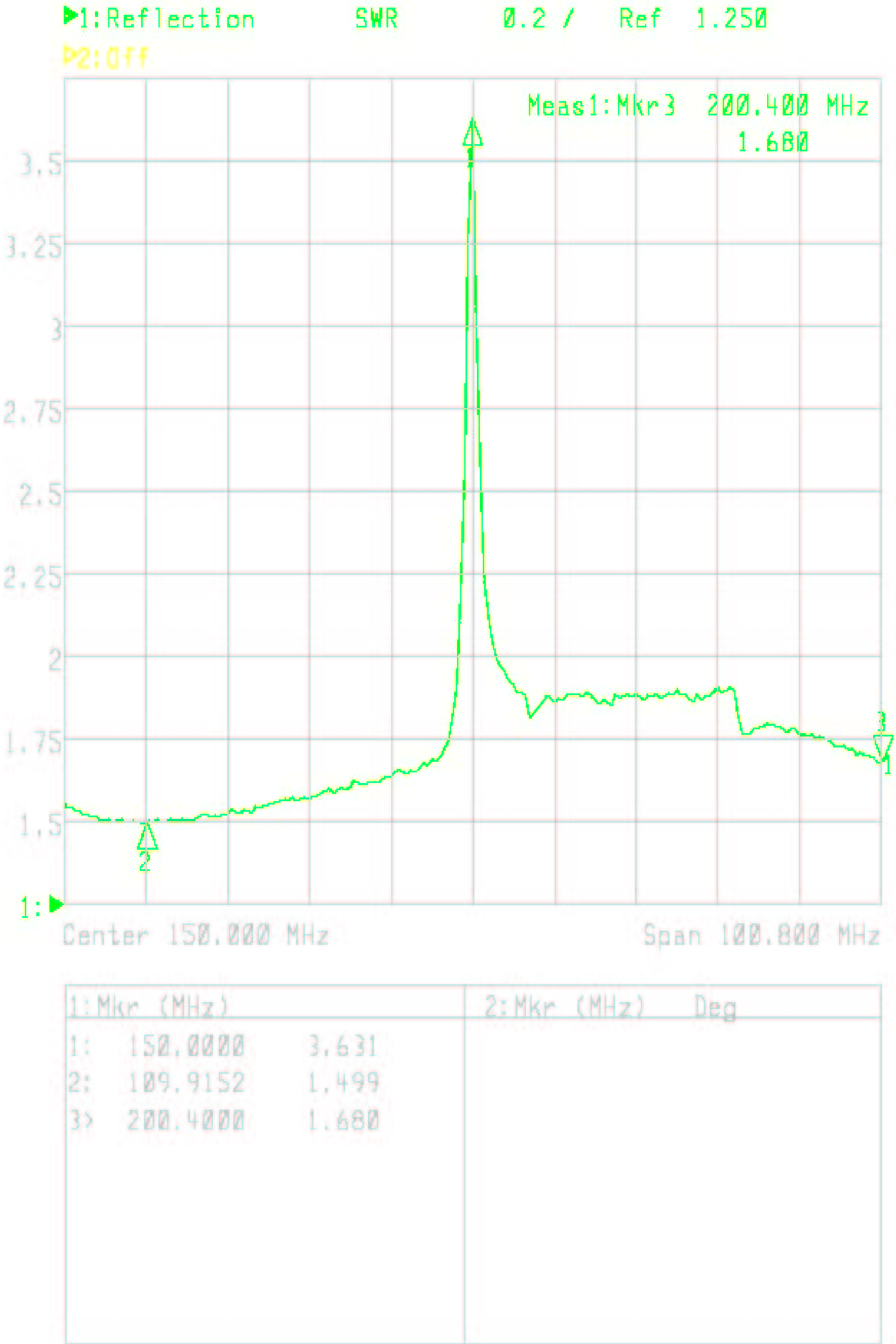
3.6.1 Rejection at 150 MHz :-

3.6.2 Delay Characteristics Of Bandstop Filter :-

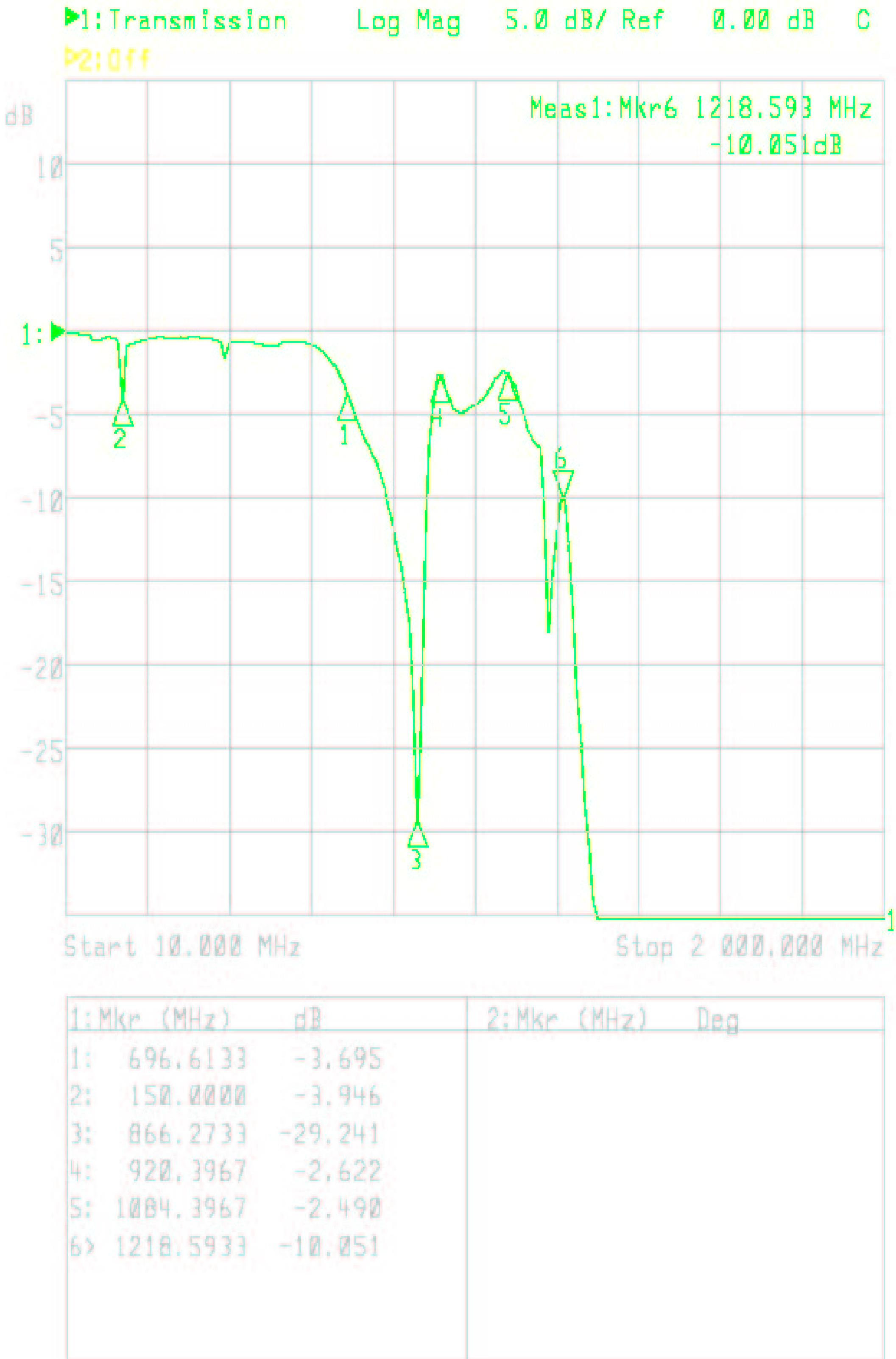


3.6.3 Phase Characteristics Of Bandstop Filter :-

3.6.4 VSWR Format Of Bandstop Filter :-



3.6.5. Response Of Bandstop Filter From 10 MHz to 2 GHz :-



3.7 Thermal Cycling Of Band-stop Filter :-

The purpose of thermal cycling of the bandstop filter is for analyzing variation in notch rejection values as well as frequency drift of the notch frequency w.r.t temperature.

Initially notches are adjusted at the desired frequencies of 133.35, 146.6 and 159 MHz. The rejection values at different notch frequencies at room temperatures are recorded as

133.35 MHz ----- -29.937 dB
146.6 MHz ----- -28.402 dB
159.0 MHz ----- -38.391 dB

Then the tuned filter is kept in environmental chamber for thermal cycling. The temperature was varied from as cool as 15°C to as hot as 55°C & readings for notch rejection are taken after every 5°C change in temperature with a settling time of around ½ hours.

First the temperature is increased from room temperature to 55°C (HEAT-1 Cycle) & then again reduced up to 15°C (COOL-1 Cycle) in steps of 5°C. At every 5°C change in temperature notch rejections for 3 different notch frequencies are recorded.

This procedure is repeated 3 times to get three sets of thermal cycles as HEAT-1/2/3 and COOL-1/2/3.

Temperature in °C	**Attenuation in dB**			**Cycle**
	133.35 MHz	146.6 MHz	159 MHz	
27	-29.94	-28.4	-38.39	HEAT-1
35.9	-13.2	-21.4	-33.29	
39	-10.42	-19.26	-27.67	
48.9	-7.4	-16.72	-21.78	
50.5	-6.94	-16.27	-20.71	
57.1	-5.91	-15.38	-18.65	

Temperature in °C	**Attenuation in dB**			**Cycle**
	133.35 MHz	146.6 MHz	159 MHz	
47	-6.38	-16.13	-18.8	COOL-1
47	-6.91	-17.06	-19.13	
40	-8.11	-18.95	-17.8	
35.5	-12.02	-26.88	-22.6	
29.6	-17.3	-29.72	-24.36	
26.8	-31.03	-23.36	-26.53	
22.8	-17.73	-19.72	-29.62	
18	-13.38	-17	-34.89	

Temperature in °C	Attenuation in dB			Cycle
	133.35 MHz	146.6 MHz	159 MHz	
27.5	-16.63	-19.63	-41.54	HEAT-2
33.7	-21.64	-28.15	-31.62	
38.3	-14.21	-28.34	-27.43	
42.2	-11.02	-22.85	-24.7	
48	-8.96	-19.84	-22.79	
55	-6.99	-17.16	-20.42	

Temperature in °C	Attenuation in dB			Cycle
	133.35 MHz	146.6 MHz	159 MHz	
47.9	-7.27	-17.98	-20.2	COOL-2
44.1	-8.39	-20.32	-20.77	
35.6	-12.83	-31.54	-23.08	
30.5	-20.51	-23.95	-25.44	
27.6	-18.76	-18.19	-31.32	
25.6	-16.09	-16.71	-34.04	
21.3	-13.11	-14.97	-45.37	
18.2	-11.48	-12.53	-34.76	
14.6	-13.17	-9.9	-26.37	

Temperature in °C	Attenuation in dB			Cycle
	133.35 MHz	146.6 MHz	159 MHz	
22.5	-12.56	-15.59	-48.51	HEAT-3
26.6	-15.09	-18.74	-37.23	
29	-16.22	-19.57	-37.5	
35	-21.04	-25.85	-31.57	
40	-14.43	-31.13	-27.48	
46	-9.51	-21.05	-22.88	
52.3	-7.38	-17.88	-20.55	

Temperature in °C	Attenuation in dB			Cycle
	133.35 MHz	146.6 MHz	159 MHz	
48	-7.62	-18.55	-20.34	COOL-3
44	-8.29	-20.18	-20.63	
40.3	-9.68	-23.47	-21.38	
35.5	-14.08	-31.59	-23.57	
29.2	-18.62	-17.75	-31.29	
26.4	-16.86	-16.81	-32.21	
21.7	-12.71	-14.32	-43.22	
17.3	-11.64	-12.96	-38.62	

Temperature in °C	Attenuation in dB			Cycle
	133.35 MHz	146.6 MHz	159 MHz	
29	-14.63	-16.98	-37.78	HEAT-4

Variation of notch rejection w.r.t. Temp. was recorded and plotted in environmental chamber test for 3 different notches tuned at frequencies as 133.35 MHz, 146.6 MHz & 159 MHz.

Inference from plots of Notch filter Thermal cycling :-

From the notch filter thermal cycling curves plotted in MATLAB, as shown below, there is no notch drift from tuned notch frequency, but only variation is in the notch rejection with variation in temperature is observed at extreme higher and lower temperature.

Plots show some sort of repeatability, especially for 146.6 MHz and 159 MHz and for 133.35 the notch it is not that much repeatable.

Also there is definitely variation of notch rejection w.r.t. Temperature. For 146.6 and 159 MHz and from temperature variation from 15°C to 40°C rejection is in the acceptable range. Only there is a abrupt change in rejection for 133.35 MHz notch in the above mentioned temp. range.

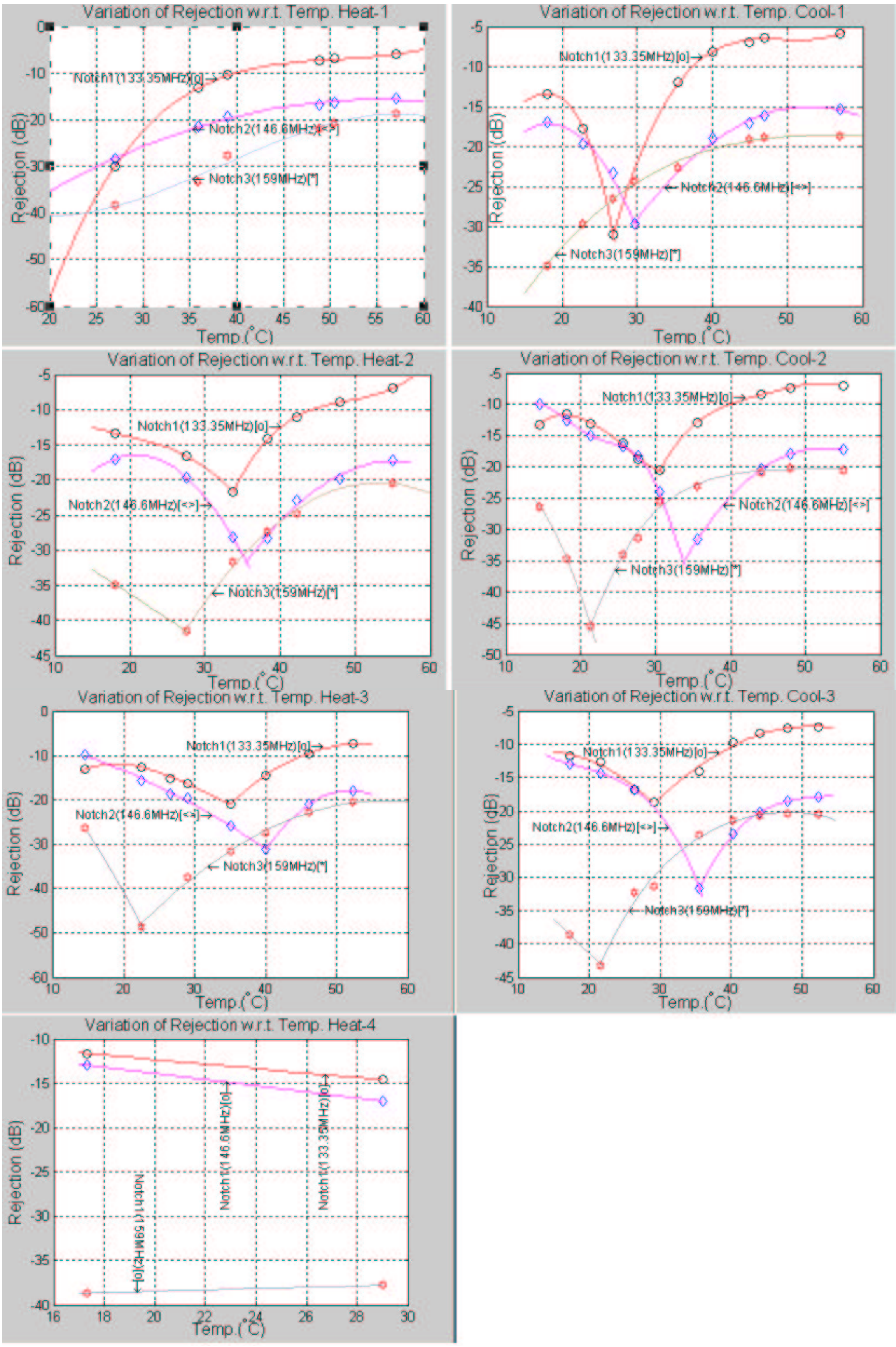


Fig. 3.14 Notch Filter Thermal Cycling Curves

Chapter 4

LOW-PASS FILTER DESIGN

4.1 Low-pass Filter Design procedure :-

1. List out the specifications like type of filter,cutoff frequency, i/p impedance,stop-band frequency,stop-band attenuation etc.
2. Estimate the order for the given type of filter by standard procedure.
3. Design a normalized LPF filter having cutoff frequency of 1Hz, and input and output impedance of 1 ohm.
4. Then frequency scale as well impedance scale the above designed filter components by appropriate inductor and capacitor formulas
   like for capacitor
   C' = C / (FSF * Z)
   And for inductor
   L' = L * Z / FSF
   Where FSF is Frequency scaling factor given as
   FSF = 2* *f_c , f_c – cutoff frequency

4.2 Low-pass Filter Specifications :-

1. Minimum inductor elliptic.
2. Cauer-chebyshev Normal.
3. 3 dB cutoff at a frequency of 163MHz.
4. Input & Output impedance is 50 ohms.
5. Stop band frequency is 175MHz.
6. Stop band attenuation minimum = 40 dB.

4.3 Order Estimation :-

From cutoff frequency and stop band frequency the steepness factor (As) for LPF can be calculated as follows

$A_s = f_s / f_c$ where f_s – stop band frequency
and f_c – cut-off frequency

$A_s = 175 / 163$
$= 1.0736$

Steepness factor is $Ø = \sin^{-1}(1/A_s)$
$= \sin^{-1}(1/1.0736) = 68.66^{o}$

With Amin = 40 dB and As <= 1.0736, choose reflection coefficient Ro = 20% which corresponds to VSWR = 1.5 , the worst case pass-band VSWR.

Ro = (VSWR -1) / (VSWR + 1)
So VSWR = (Ro + 1)/ (Ro -1)

= 1.2 / 0.8

= 1.5 ....The worst case VSWR.

And passband ripple R_{dB} is related to reflection coefficient Ro as

R_{dB} = -10 log (1-(Ro)^2)

Therefore R_{dB} = -10 log (1-(0.2)^2) = 0.1773 dB

Thus Ro = 20% corresponds to A(Ro) = 13.9 dB

Therefore total attenuation is As + A(Ro) = 40 +13.9

= 53.9 dB

Now from the curve for estimating the order of the elliptic function filter design* at an As = 1.0736 a filter order n = 7 provides required attenuation.

Therefore n = 7 is the required order.

Return Loss is given as

RL = 20 log (1/R_o)

= 20 log (1/0.2) = -13.979 dB

- Expected Filter Response Properties : -

1. VSWR = 1.5
2. Return Loss = -13.979 dB
3. Stop Band Attenuation = -40 dB
4. Passband ripple = 0.1773 dB

4.4 Normalized LPF Design :-

This is the procedure in which first LPF components are found out for the cutoff frequency of 1Hz,which are tabulated in the standard format in the Arthur williams " Electronic Filter Design Handbook".

Now we have steepness factor As = 1.0736 from which we can calculate the angle of steepness Ø = sin^{-1} (1/ As) = sin^{-1} (1/ 1.0736)

= 68.66º

Take Ø = 66º as a compromise between attenuation and steepness, with priority to attenuation. So for the given Ø the attenuation is 41.1 dB.

So the LPF can be expressed as

C n Ro Ø = (C7 20 66º),

where C – Cauer filter
n – order
Ro – reflection coefficient
Ø – Steepness angle

Now from these specifications of LPF the normalized values of the filter elements are taken from Arthur Williams book for normalized LPF component values for elliptic filter design and shown in the diagram below:-

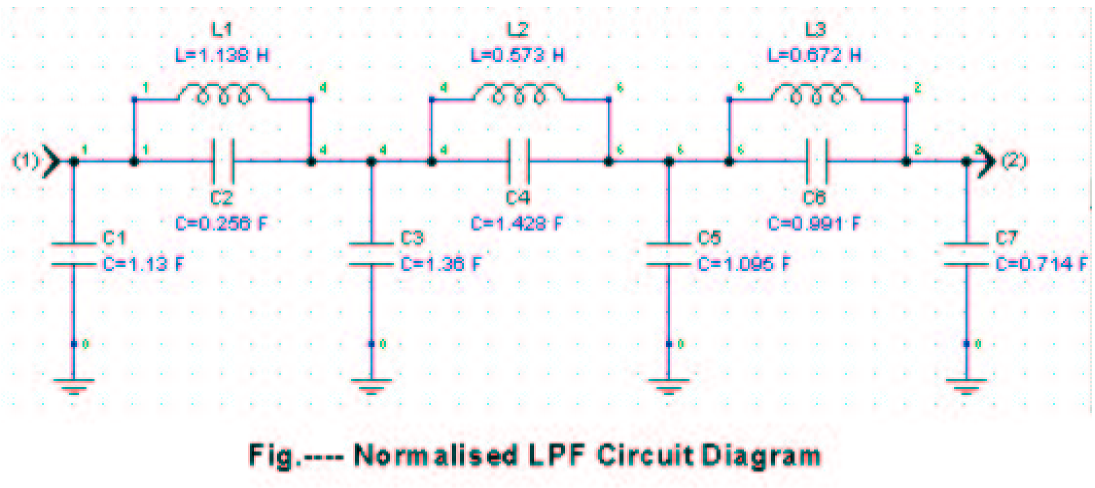


Fig. 4.1 Normalized LPF Circuit Diagram

4.5 Frequency And Impedance Scaling :-

Now this normalized filter is having cutoff frequency of 1Hz, therefore to frequency scale the given filter to the required cutoff frequency, multiply filter filter elements by a frequency scaling factor (FSF), as mentioned in above design procedure. For this circuit it is

FSF = 2*   * 163MHz

= 0.10242* 10^{10}

and impedancd scaling factor is Z = 50.

Therefore for capacitor C' = C / (FSF * Z)

Therefore actual circuit capacitor values become as

C1' = 1.13 / (0.10242* 10^{10} *50)
= 22 pF
C2' = 4.997 pF
C3' = 26.56 pF
C4' = 27.89 pF
C5' = 21.38 pF
C6 = 19.35 pF
C7' = 13.94 pF

Also same way for Inductor L' = L * 50 / FSF

Therefore the actual circuit inductor values become as

L1' = 1.138 * 50 / 0.10242* 10^{10}
= 55.56 nH
L2 = 27.98 nH
L3 = 32.817 nH

With the above impedance and frequency scaling, the actual LPF with the given specifications can be synthesized. The circuit diagram is as shown below. Also which series branch parallel resonant section produces zero at what frequency is shown in fig. :-

*Curve for estimating filter order is given in Arthur williams " electronic Filter Design Handbook" on Pg. No. 2.80 and fig. No. 2.86

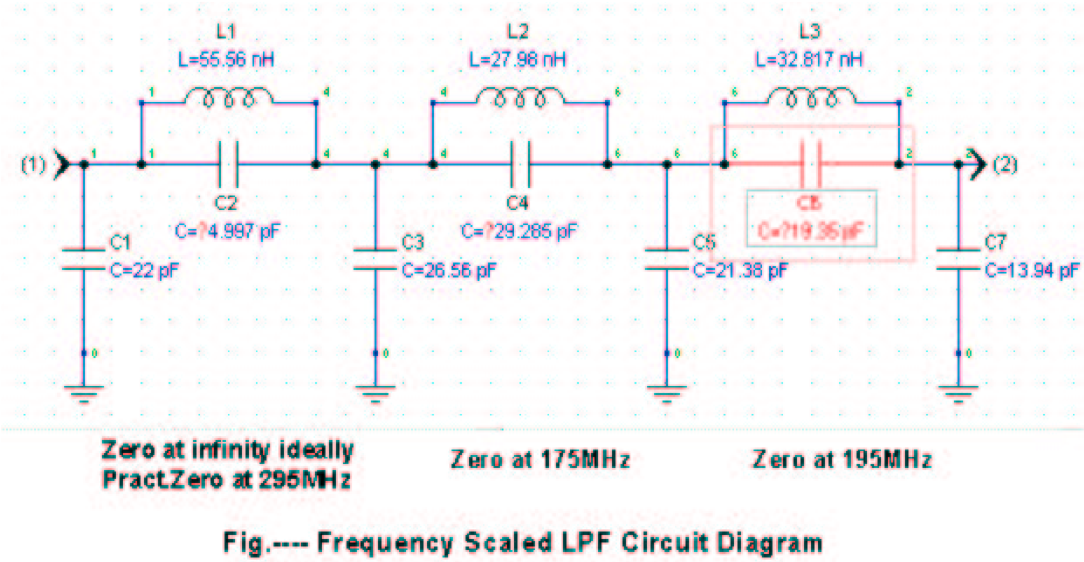
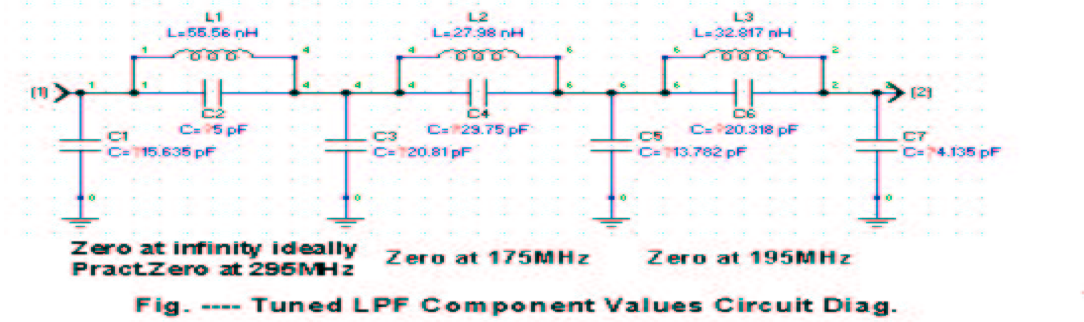


Fig. 4.2 Frequency Scaled LPF Circuit Diagram

This is the theoretical filter design as per the specifications. This doesn't meet the desired specifications, therefore components were tuned using the simulation software “Eagle ware”.The final filter circuit with simulation software is as shown below:-



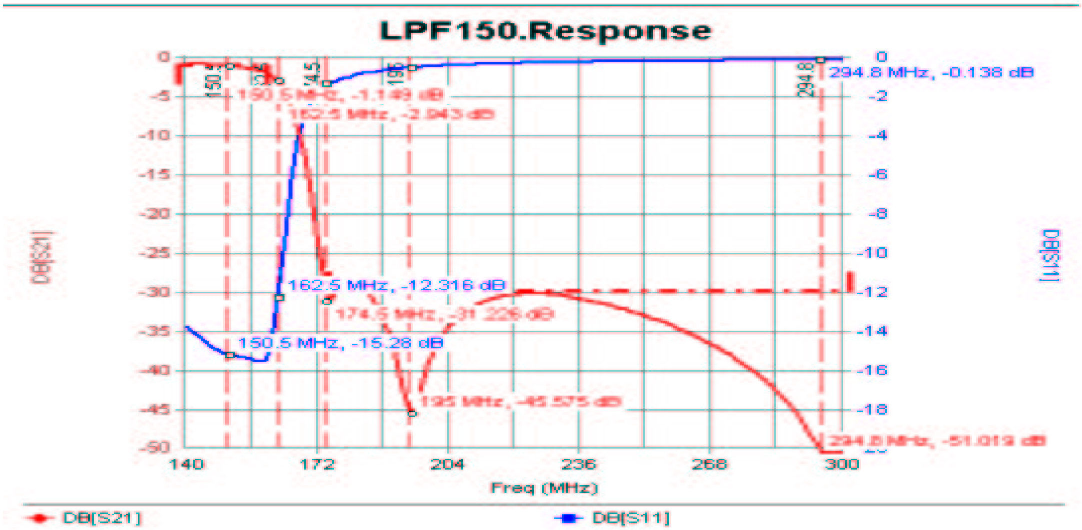


Fig. 4.3 Simulated Filter Response of LPF on Eagleware after Tuning

Chapter 5

HIGH-PASS FILTER DESIGN

5.1 HPF Filter Design Procedure :-

1. List out the specifications like type of filter,cutoff frequency, i/p impedance,stop-band frequency,stop-band attenuation etc.
2. Estimate the order for the given type of filter by standard procedure.
3. Design a normalized LPF filter having cutoff frequency of 1Hz, and input and output impedance of 1 ohm.
4. Replace capacitor by inductor and inductor by capacitor in the circuit and invert the values found out for the normalized LPF.
5. Then scale the circuit for and impedance scale the above designed filter components by using following formulas for components scaling
   for capacitor
   C' = C / (FSF * Z)
   for inductor
   L' = L * Z / FSF
   Where FSF is Frequency scaling factor given as
   FSF = 2*   *fc , fc – cutoff frequency

5.2 High-pass Filter Specifications :-

1. Minimum inductor elliptic.
2. Cauer-chebyshev Normal.
3. 3 dB cutoff at a frequency of 120MHz.
4. Input & Output impedance is 50 ohms.
5. Stop band frequency is 101MHz.
6. Stop band attenuation minimum = 40 dB.

5.3 Order Estimation :-

From cutoff frequency and stop-band frequency angle of steepness (As) for HPF can be calculated as follows

$A_s = f_c / f_s$ where f_s – stop band frequency
and f_c – cut-off frequency

$A_s = 101 / 120$
$= 1.188$

Steepness factor is

$Ø = \sin^{-1}(1/A_s)$
$= \sin^{-1}(1/1.0736) = 68.66^{o}$

With Amin = 40 dB and As <= 1.188, choose reflection coefficient Ro = 20% which corresponds to VSWR = 1.5 , the worst case pass-band VSWR.

Ro = (VSWR -1) / (VSWR + 1)

Therefore VSWR = (Ro + 1)/ (Ro -1)
= 1.2 / 0.8 = 1.5 ....The worst case VSWR.

And passband ripple R_{dB} is related to reflection coefficient Ro as

$R_{dB} = -10 \log (1-(Ro)^2)$

Therefore $R_{dB} = -10 \log (1-(0.2)^2) = 0.1773$ dB

Thus Ro = 20% corresponds to A(Ro) = 13.9 dB

Therefore total attenuation is As + A(Ro) = 40 +13.9
= 53.9 dB

Now from the curve for estimating the order of the elliptic function filter design* at an As = 1.188 a filter order n = 7 provides required attenuation.

Therefore n = 7 is the required order.

Return Loss is given as RL = 20 log $(1/R_o)$

= 20 log (1/0.2) = -13.979 dB

- Expected Filter Response Properties :-

1. VSWR = 1.5
2. Return Loss = -13.979 dB
3. Stop Band Attenuation = -40 dB
4. Passband ripple = 0.1773 dB

5.4 Normalized LPF Design :-

This is the procedure in which first LPF components are found out for the cutoff frequency of 1Hz,which are tabulated in the standard format in the Arthur williams " Electronic Filter Design Handbook".

Now we have steepness factor A_s = 1.0736 from which we can calculate the angle of steepness

$Ø = \sin^{-1} (1/ A_s) = \sin^{-1} (1/ 1.188)$
$= 57.32^o$

Assuming Ø = 57º as here there is no compromise between attenuation, as attenuation for this Ø is 527 i.e. > 40 dB and is 52.7 dB.

This normalized LPF can be expressed as

C n Ro Ø = (C7 20 57º),

where C – Cauer filter
n – order
Ro – reflection coefficient
Ø – Steepness angle

Now for these specifications of LPF, the normalized values for the filter elements are chosen from Arthur Williams book. And are as shown in the circuit below:-

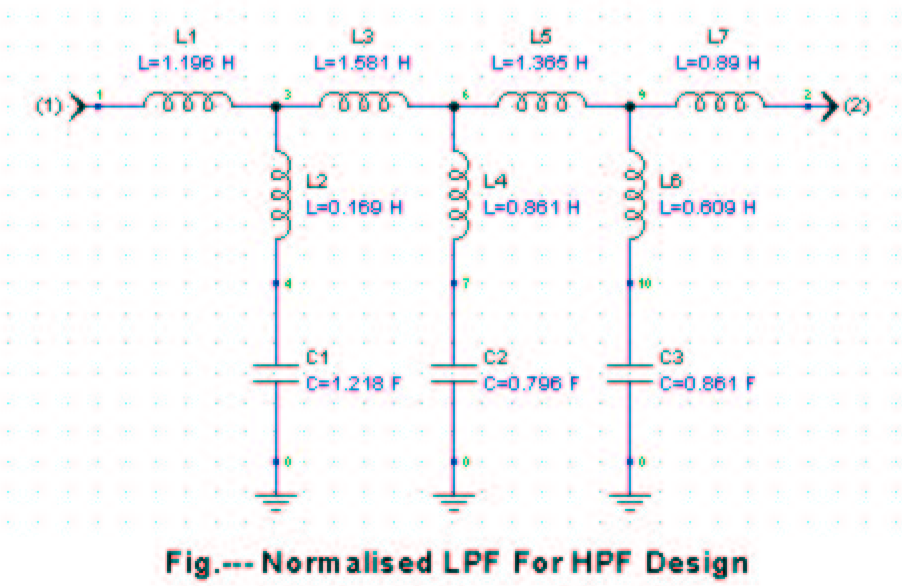


Fig. 5.1 Normalized LPF For HPF Design

5.5 <u>Normalized</u> <u>HPF</u> <u>Design</u> :-

normalized HPF can be designed from the normalized LPF by just replacing capacitors by inductors and vice versa. The values for inductors and capacitors are found by taking reciprocal of the corresponding capacitor and inductor in the normalized LPF circuit. The normalized HPF filter circuit is as shown below :-

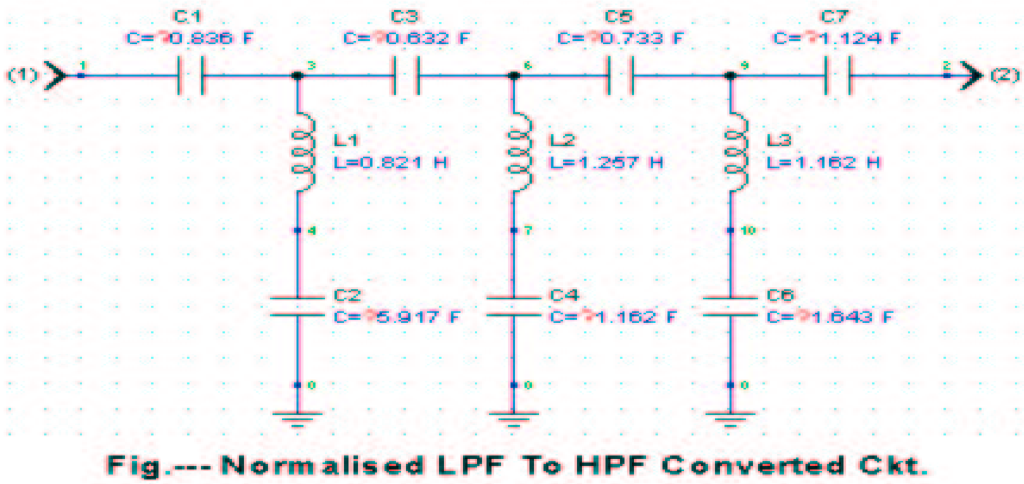


Fig. 5.2 Normalized LPF To HPF Converted Circuit

5.5.1 Frequency And Impedance Scaling :-

The designed normalized filter has a cutoff frequency of 1Hz and impedance Z =1 ohm. In order to scale the circuit for frequency and impedance replace capacitors and inductors with scaled values as follows. The frequency scaling factor (FSF) for the circuit is

FSF = 2* * 120MHz

= 0.075398* 10^{10}

and impedance scaling factor is Z = 50.

C' = C / (FSF * Z)

Therefore actual circuit capacitor values become as

C1' = 0.836 / (0.075398* 10^{10} *50)
= 22.18 pF
C2' = 156.95 pF
C3' = 16.78 pF
C4' = 30.82 pF
C5' = 19.43 pF
C6 = 43.58 pF
C7' = 29.81 pF

Inductor L' = L * 50 / FSF

Therefore the actual circuit inductor values becomes

L1' = 0.821 * 50 / 0.075398* 10^{10}
= 54.44 nH
L2 = 83.34 nH
L3 = 77.06 nH

With the above impedance and frequency scaling the actual HPF is designed for the given specifications. The circuit diagram is as shown below, also resonant frequency of each parallel branch series resonant section that produces zero at definite frequency is also shown in fig. :-

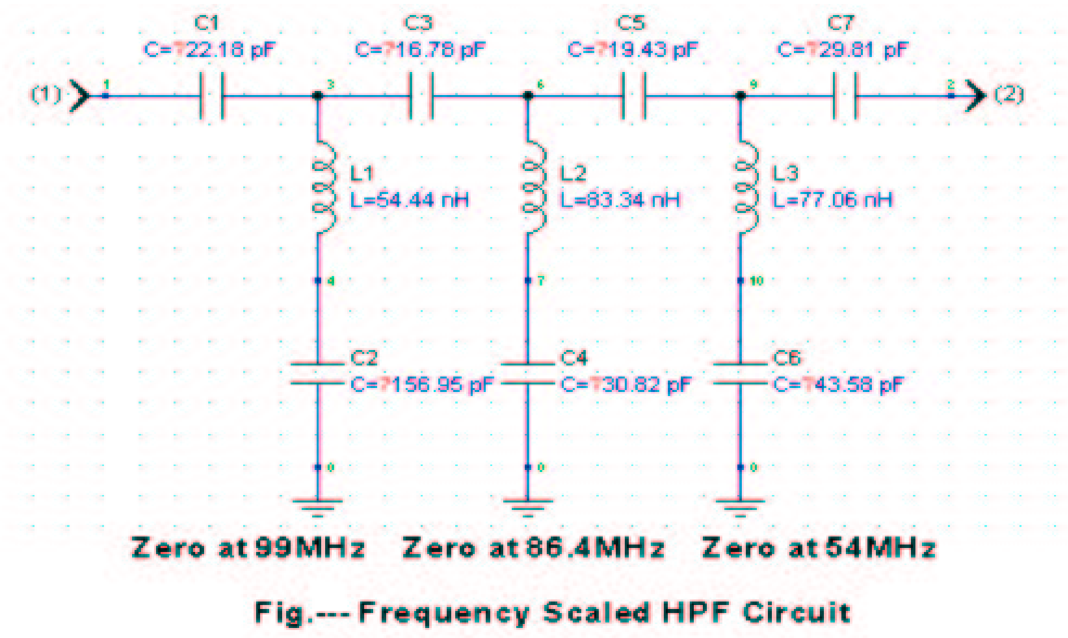


Fig. 5.3 Frequency Scaled HPF Circuit

These finite zeros are added to increase the steepness of the filter response. This filter design doesn't meet the required specifications, therefore component values were tuned using “Eagle ware” software. The circuit diagram along with response for tuned component values is as shown below :-

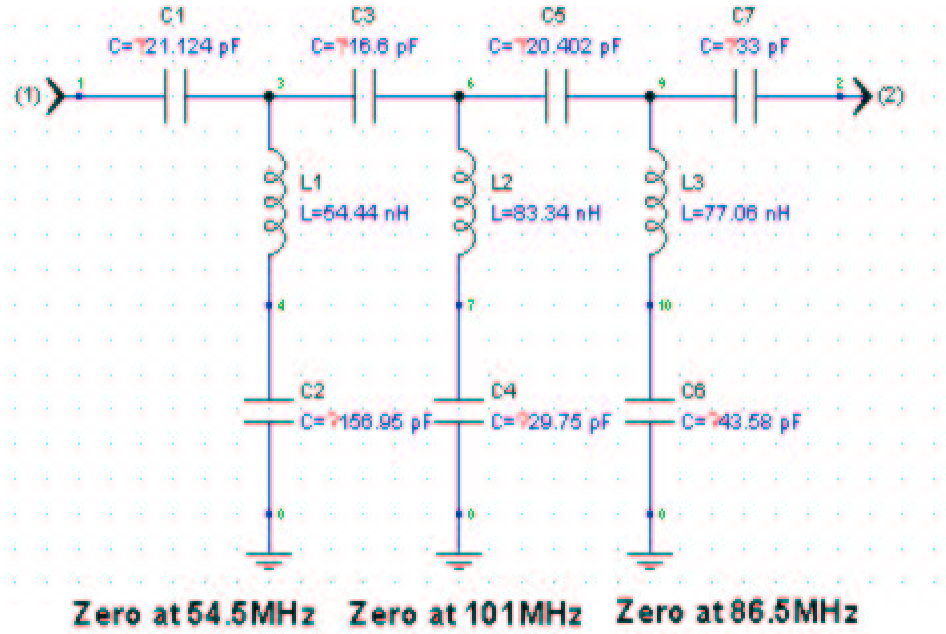


Fig. --- Tuned HPF Component values Circuit Diag.

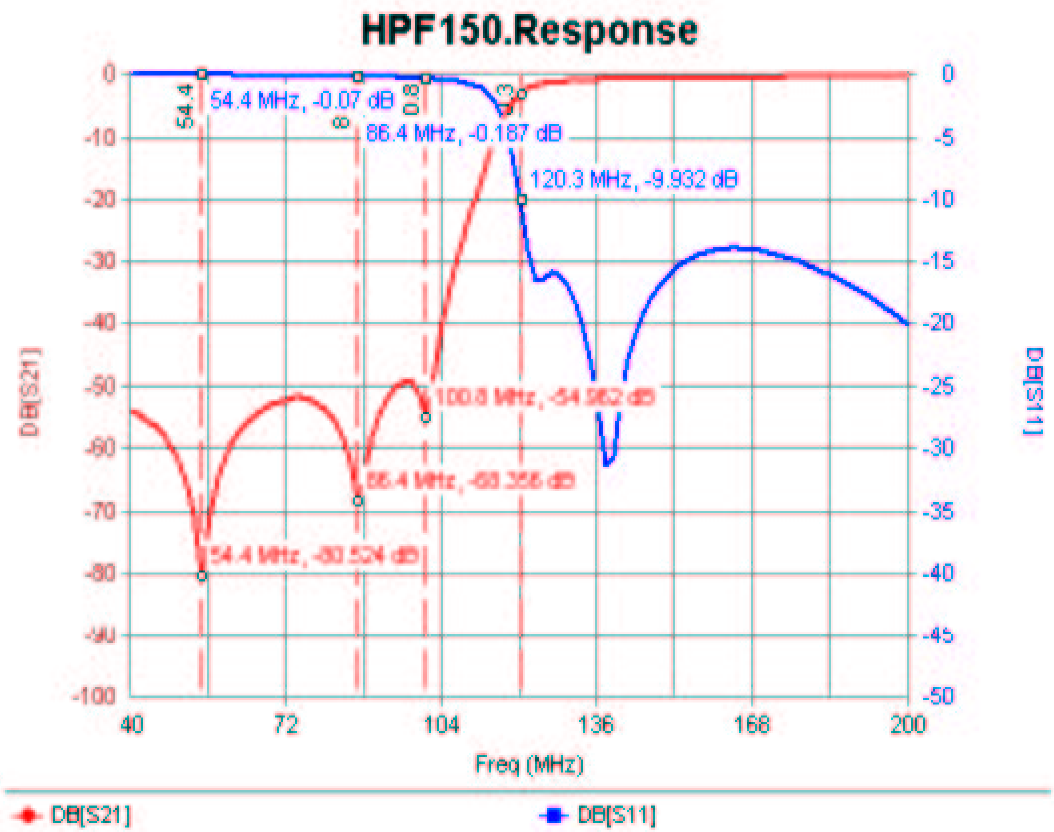


Fig. 5.4 Simulated Filter Response of HPF on Eagleware after Tuning

Chapter 6

FILTER TUNING

6.1 Practical Band-stop filter Tuning :-

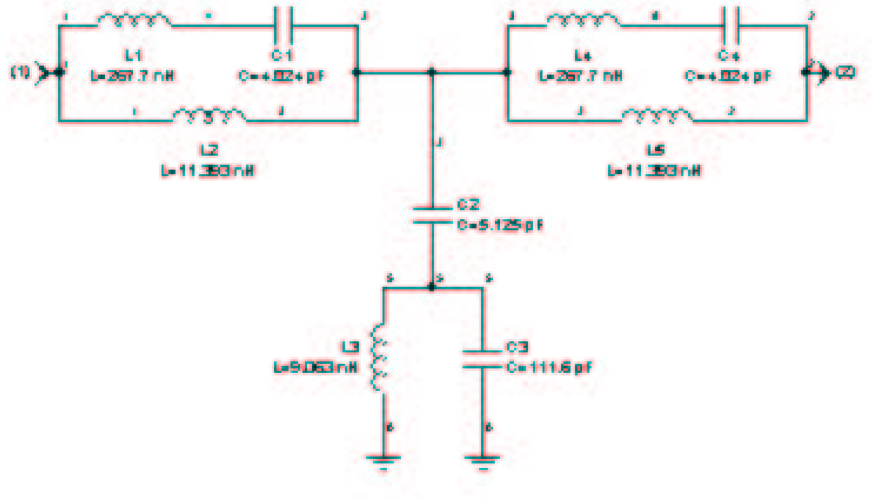


Fig. 6.1 Realizable Band-stop filter

Two series arms of the bandstop filter provides a null or zero at a given frequency. So to reject a given frequency series arm should be tuned properly. Here is a tunning procedure.

1. Adjust the null at the specified frequency by one of the series arm resonant circuit capacitor tuning say C1.
2. Then by the same way adjust null for the another series arm resonant circuit capacitor say C4, so as to get maximum rejection at the given frequency.
3. Then capacitor C2 is the rejection adjustment capacitor for the notch,adjust it to get optimum rejection without any insertion loss.
4. Shunt resonant circuit is tuned to adjust the cutoff frequency of the LPF in which notch is embedded, so by tuning C3 we can improve the out of band response of the bandstop filter.

6.2 Practical Low-pass filter Tuning :-

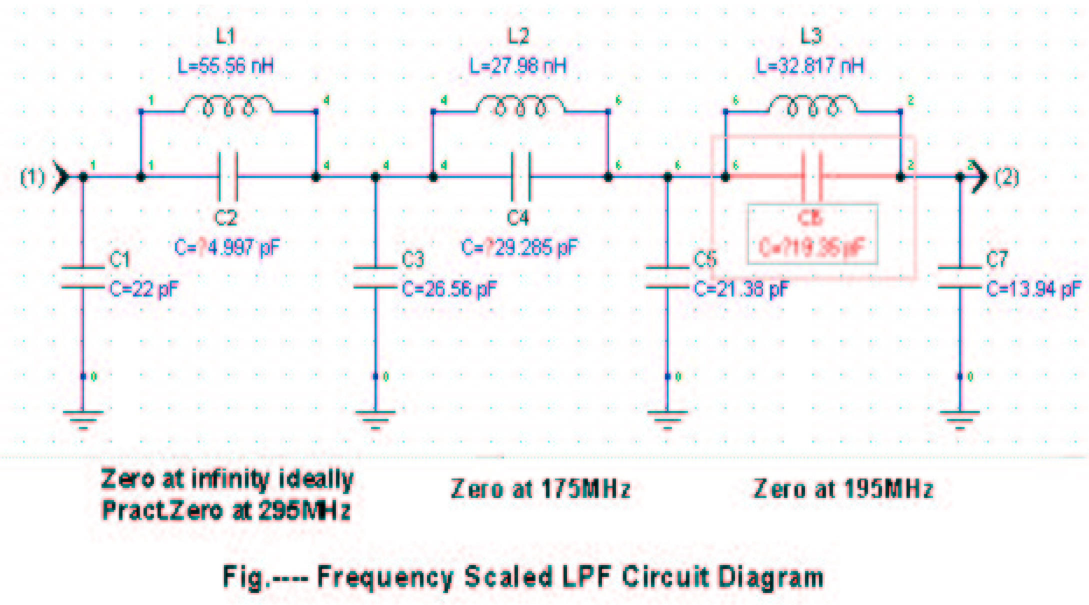


Fig. 6.2 Frequency Scaled LPF Circuit

Target Tunning :-

3 dB cutoff frequency = 163MHz.
Maximum rejection at 175MHz.
Insertion loss > -1dB from DC to 160MHz i. e. in the pass band.
Return loss < -10 dB from DC to 160MHz i. e. in the pass band.

In the low pass filter major tuning part is the series arm circuits, which provide a zero/null at particular frequencies and thus provide a required degree of steepness.

1. First series arm parallel resonant circuit(L1,C2) provides null at infinity. So by adjusting this arm capacitor C2 improves rejection on higher frequency side. Adjust this capacitor so as to get the size of side lobes minimum.
2. Second series arm parallel resonant circuit(L2,C4) provides null at 175MHz. So adjust this arm capacitor C4 to get optimum rejection at 175MHz .
3. Third series arm parallel resonant circuit(L3,C6) provides null at a finite frequency of 190MHz. So adjust it so as to get the cut off at 163MHz .
4. Capacitor C1 and C7 are input and output capacitors respectively. These are used to match impedances of input and output circuit to whom they are connected. Thus adjust them so that insertion loss and the return loss is optimum.
5. Capacitor C3 and C5 are impedance matching capacitors in between two series arm parallel resonant circuits to optimize insertion and return loss.

6.3 Practical High-pass Filter Tuning :-

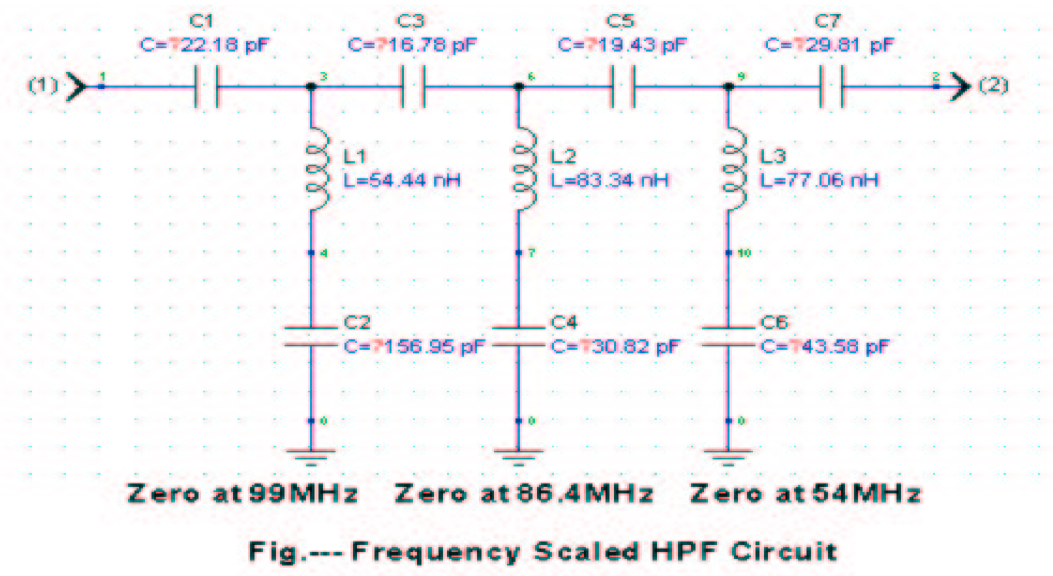


Fig. 6.3 Frequency Scaled HPF Circuit

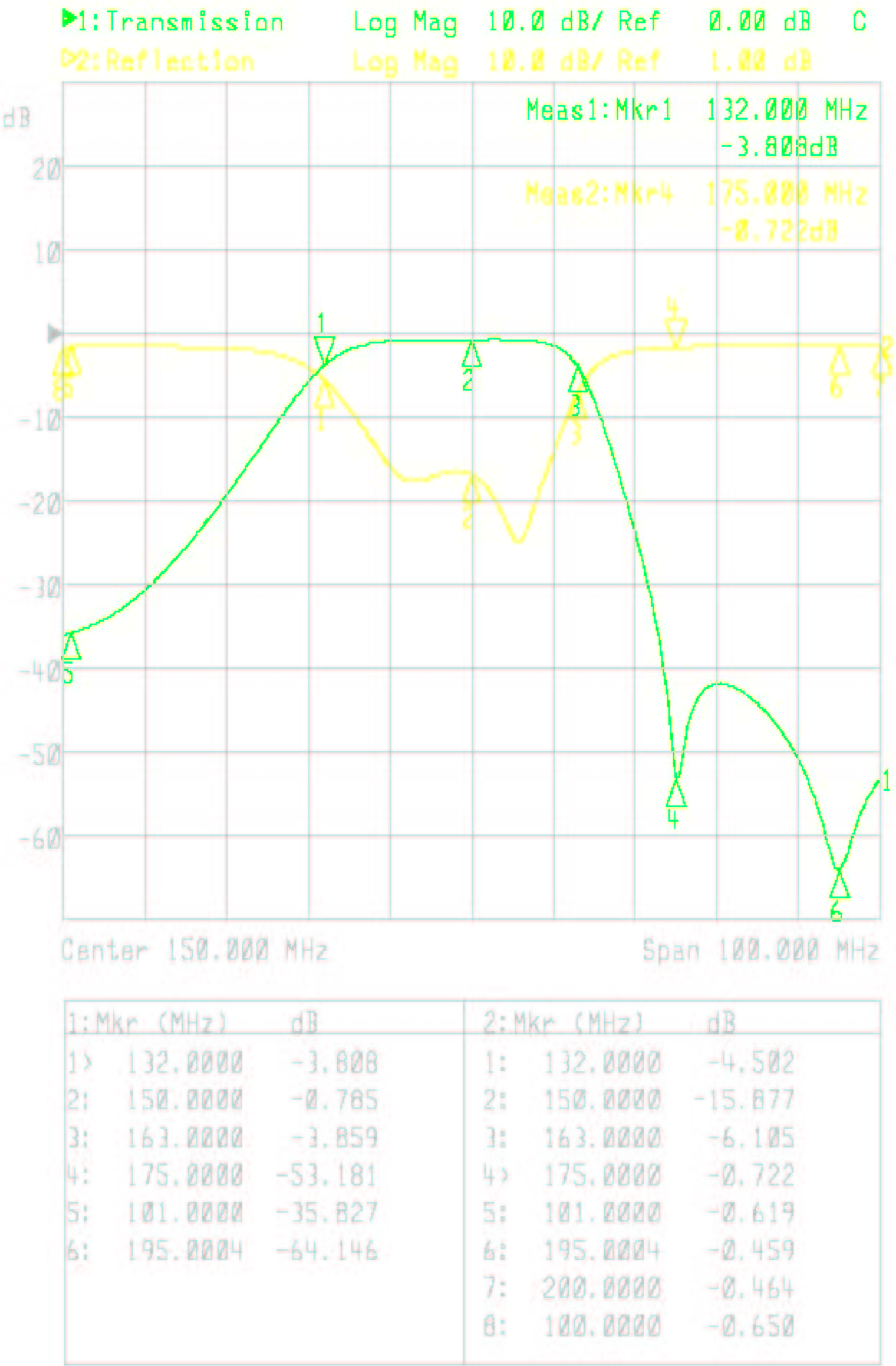
Target Tunning :-

3 dB cutoff frequency = 132MHz.
Maximum rejection at 101MHz.
Insertion loss > -1dB from 134 MHz to infinity i. e. in the pass band.
Return loss < -10 dB from 132 MHz to infinity i. e. In the pass band.

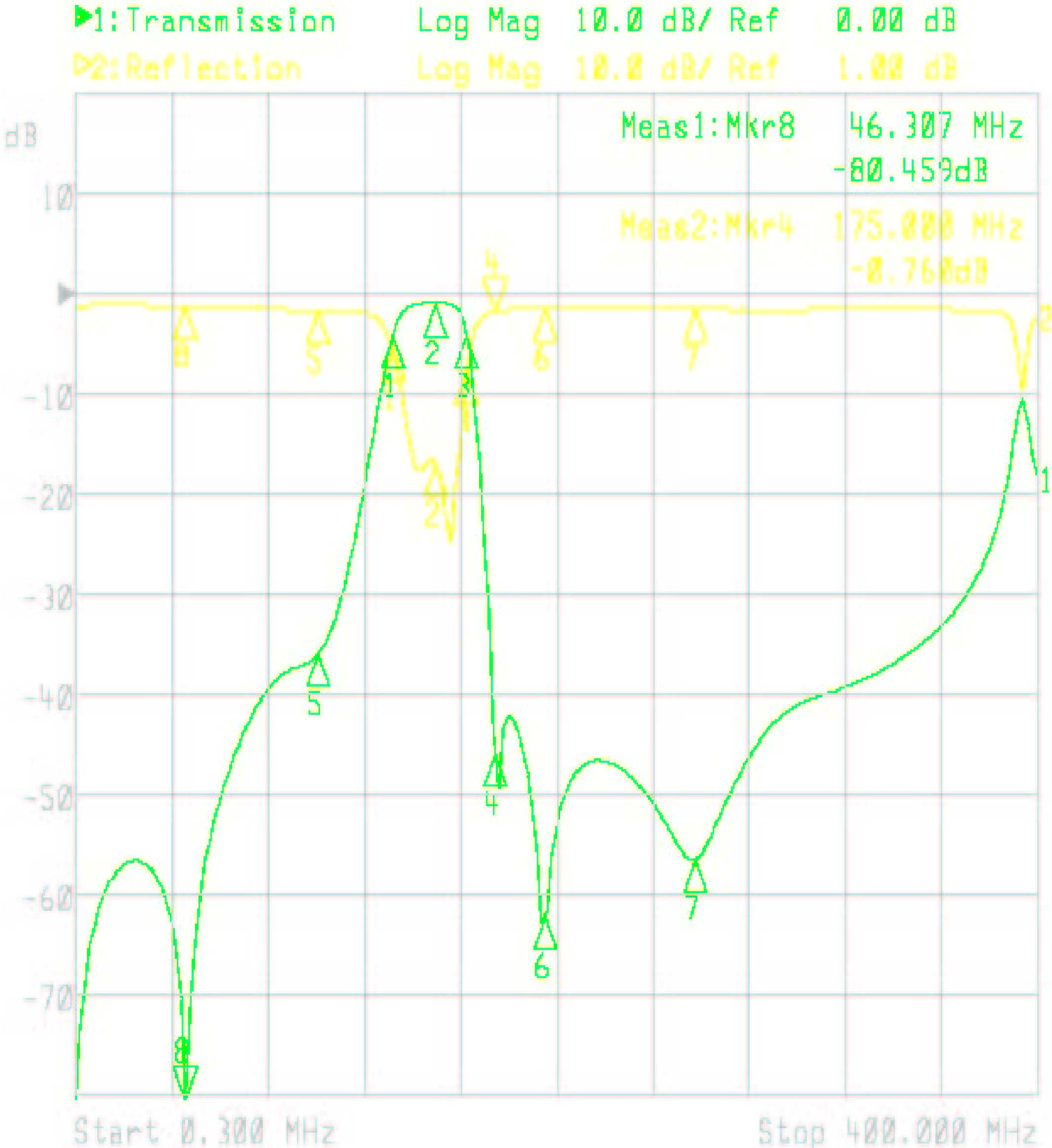
In the high pass filter major tuning part is the the shunt arm series resonant circuits,which provide a null/zero at a finite frequencies and thus provide a required degree of steepness.

1. First shunt arm series resonant circuit(L1,C2) provides null/zero at finite frequency of 46.6MHz . It provides a finite steepness to the high pass filter in it's transition band. Here this arm component values are kept fixed to provide finite frequency null at 46.6MHz only.
2. Second shunt arm series resonant circuit(L2,C4) provides null/zero at a finite frequency of 101MHz . So by adjusting capacitor C4 provides desired rejection at 101MHz . So optimize it to get good rejection at the specified frequency.
3. Third shunt arm series resonant circuit(L3,C6) provides null/zero at DC to improve rejection on lower frequency side. This arm component values are also kept fixed as it doesn't affect the filter response in the desired frequency range,but is necessary to improve rejection on lower frequency side.
4. Capacitor C1 and C7 are input and output capacitors respectively. These are used for input output impedance matching, thus reducing insertion loss and return loss.
5. Capacitor C3 and C5 are impedance matching capacitors in between two shunt arm series resonant circuit to optimize the return loss and insertion loss .

- **LPF And HPF Practical Response** :-

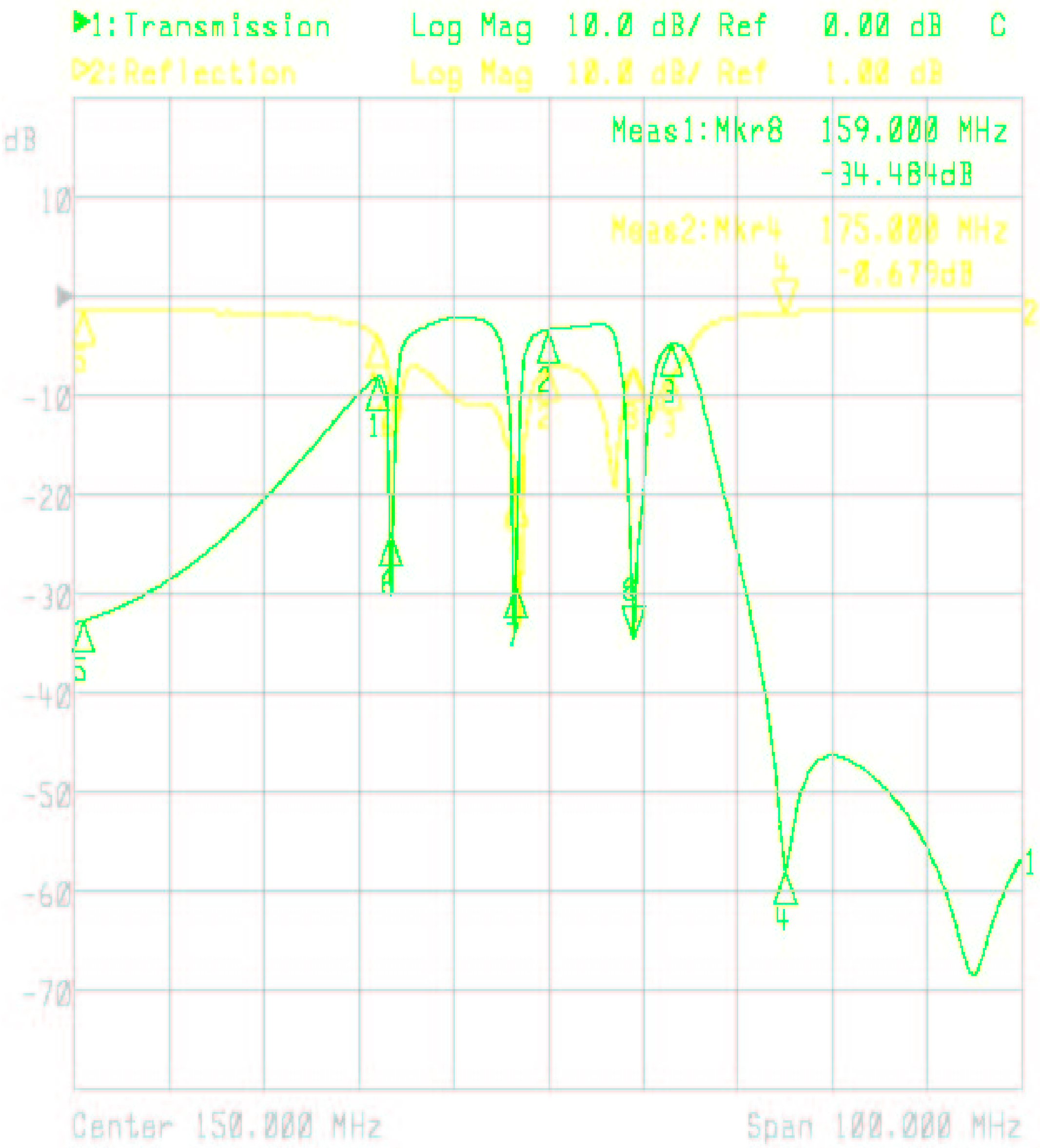


- **<u>LPF And HPF Out Of Band Response</u> :-**



1:Mkr (MHz)	dB	2:Mkr (MHz)	dB
1: 132.0000	-4.192	1: 132.0000	-4.531
2: 150.0000	-0.984	2: 150.0000	-15.922
3: 163.0000	-4.145	3: 163.0000	-6.874
4: 175.0000	-45.902	4> 175.0000	-0.760
5: 101.0000	-36.013	5: 101.0000	-0.672
6: 195.0004	-62.284	6: 195.0004	-0.470
7: 257.5568	-56.504	7: 257.5568	-0.547
8> 46.3070	-80.459	8: 46.3070	-0.308

- **<u>LPF</u> +<u>HPF</u>+<u>NF</u> <u>Combined</u> <u>Response</u> :-**



1:Mkr (MHz)	dB
1: 132.0000	-8.140
2: 150.0000	-3.384
3: 163.0000	-4.844
4: 175.0000	-57.959
5: 101.0000	-32.740
6: 133.3500	-24.088
7: 146.6000	-29.183
8› 159.0000	-34.484

2:Mkr (MHz)	dB
1: 132.0000	-3.051
2: 150.0000	-6.336
3: 163.0000	-6.902
4› 175.0000	-0.679
5: 101.0000	-0.596
6: 133.3500	-7.283
7: 146.6000	-18.637
8: 159.0000	-6.285

- **Notch Filter Attenuation Summary :-**

S. No.	Filter No.	Antenna No.	Attenuation In dB		
			133.35 MHz	146.6 MHz	159 MHz
1	B34/01	C-04	-28.98	-29.23	-28.64
2	B34/02	C-09	-30.87	-26.81	-34.56
3	B34/03	W-01	-19.18	-21.79	-25.63
4	B34/04	C-08	-28.53	-22.62	-28.88
5	B34/05	C-11	-18.24	-24.69	-33.95
6	B34/06	C-03	-18.33	-26.46	-25.28
7	B34/07	C-02	-22.98	-22	-34.68
8	B34/08	W-05	-28.24	-31.32	-40.81
9	B34/09	S-04	-23.51	-28.98	-32.83
10	B34/10	S-01	-18.59	-21.58	-24.87
11	B34/11	-	-26.57	-31.9	-47.99
12	B34/12	E-02	-29.46	-33.25	-46.14
13	B34/13	E-04	-27.33	-28.19	-37.42

Notch Filters are implemented in six central square antennas and two in each arm antennas along with LPF and HPF combination. The above table gives summery of notch filter attenuation at various notch frequencies and filter unit no. implemented in which antenna.

Chapter 7

CONCLUSION

7.1 Conclusion :-

The project of implementation of modified filter bank in twelve antennas is completed successfully. Filter units are tuned,tested and implemented in 150 MHz front-end box.

LPF and HPF is having sharp roll-off characteristics ,that provide enough attenuation for the out of band strong interferences like FM and TV communication.

Notch filters are implemented to suppress in-band interferences and tuned to such frequencies that have strong interferences which may saturate the receiver or may beat with each other and produce inter-modulation products that might be falling inside the desired band. Thus the possibility of receiver saturation and inter-modulation products due to in-band strong interferences is avoided by implementation of notch filter in the pass band of LPF and HPF combination.

The spectrum obtained from the antennas shows that most of the strong in-band interferences are suppressed quiet good by notch filter. Also LPF & HPF combination provides a very good solution to previously implemented bandpass filter.

7.2 Future Scope :-

Filter tuning for LPF and HPF is quiet easy, but major difficulty arise while tuning notch filter, which can be overcome by minimizing the tuning range of variable capacitors.

Also notch at each frequency is not stable from the point of view of attenuation. Attenuation changes widely with temperature variation. This can be overcome by using very low temperature coefficient variable capacitors.

The filter elements can also be realized by using micro-strip lines, as in case of micro-strip line low values of capacitors and inductors can be realized easily without any transformation as used in notch filter designing.

This filter bank provides a temporary solution to the current trends. In future if interferences increase to more than existing and which may affect the observation then it becomes difficult to implement so much of notches at every required interferences. System will become bulky and also tuning work become extensive and time consuming. So it is better way to go for digitized filter.

Bibliography

[1] Vinod Toshniwal, “RFI Rejection Filter At 150MHz” , STP project report.

[2] Arthur B. Williams and Fred J. Taylor, “Electronic Filter Design Handbook”.

[3] Phillip R, Geffe, “Novel Design For Elliptic Band Stop Filters” RF Design Journal, Pg. No. 75-76, February 1999.

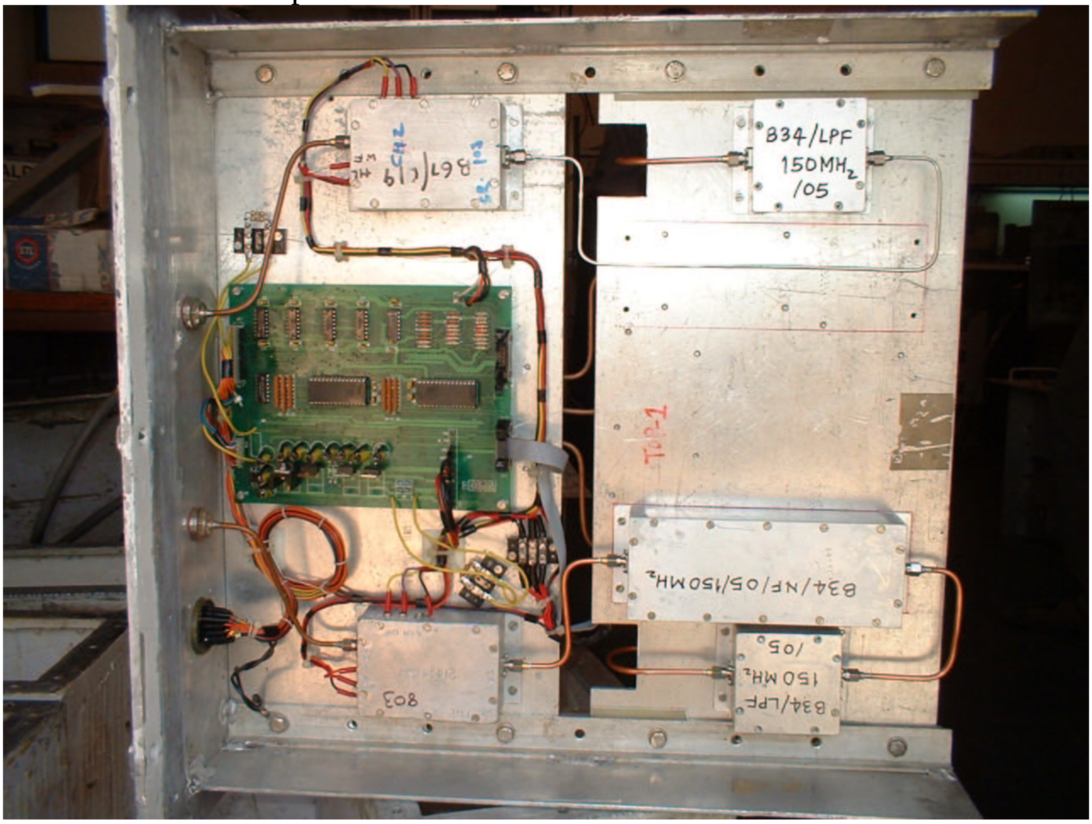
[4] Eagle-ware GENESYS software manual for M-Filter design.

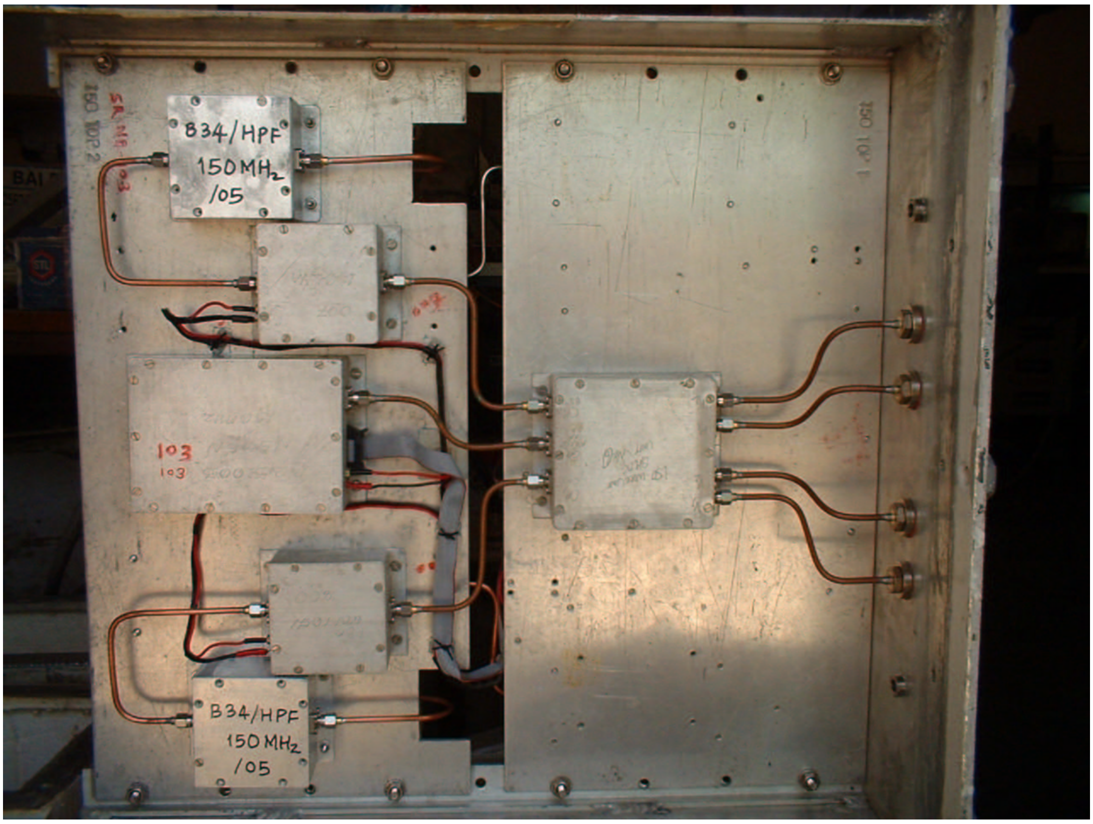
[5] Pratap, R. “Getting Started With MATLAB 6” ,Oxford University Press, 2002.

[6] Prof. Govind Swarup, “Survey Of RFI At GMRT Site From Terrestrial Transmitters”, GMRT RFI-Report Part IV.

Appendix I

150 MHz Filter Implemented Front-End Box

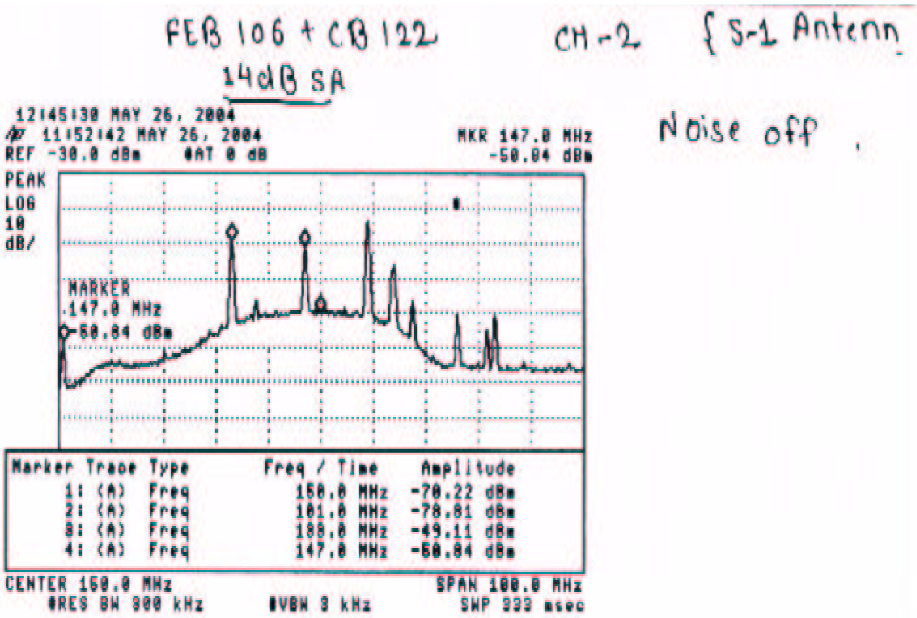


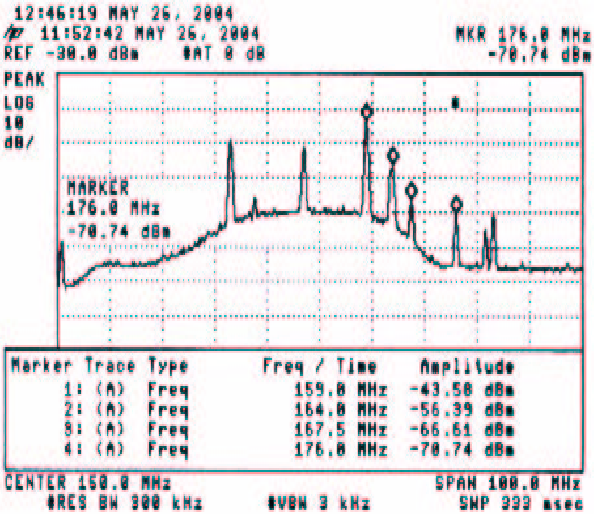


Appendix II

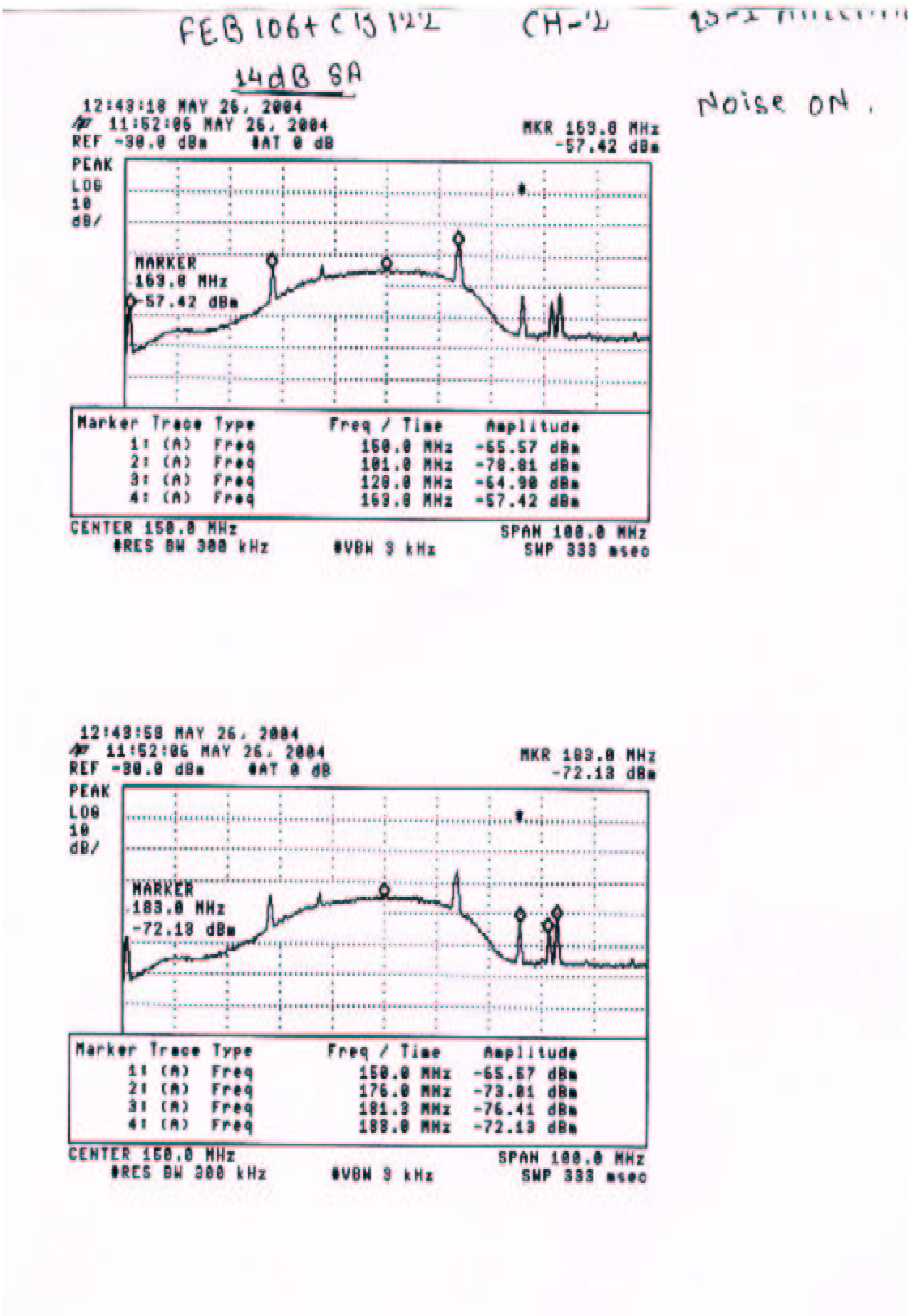
150 MHz Front-End Output For Antenna - S01:-

1. Antenna ->(S-1) ,Channel – 2, FEB 106, CB 122, Solar Attn. -14dB, Noise On/Off :-





2. Antenna ->(S-1) ,Channel – 2, FEB 106, CB 122, Solar Attn. -14dB, Noise Off :-



3. Antenna ->(S-1) ,Channel – 1, FEB 106, CB 122, Solar Attn. -14dB, Noise ON :-