Circuit Theory and Electronics Fundamentals

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Laboratory 5

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1 Introduction

The objective of this laboratory assignment is to design a Band-Pass filter, using the knowledge we have acquired in the theoretical classes (lecture 22, 23 and 24). Based on the information given, the Band-Pass filter has to have a Gain of 40dB and to be centred at 1KHz. It receives an alternating current (AC) with 0.01V and a frequency of 1KHz.The primal objective was to create a Band-Pass filter with the highest possible merit figure.

This Merit Figure is given by:

$$M = \frac{1}{Cost(VoltageGainDeviation + CentralFrequencyDeviation + 10^{-6})} \tag{1}$$

- cost = cost of resistors + cost of capacitors + cost of transistors;
- cost of resistors = 1 monetary unit (MU) per kOhm;
- cost of capacitors = 1 MU/μF;
- cost of transistors = 0.1 MU per transistor;

To implement the Band-pass Filter we were only allowed to use the following components:

- One 741 OPAMP;
- At most three $1k\Omega$ resistors;
- At most three $10k\Omega$ resistors;
- At most three $100k\Omega$ resistors;
- At most three $220nF$ resistors;
- At most three 1μF resistors;

In Section 3, a theoretical analysis of the circuit is presented. In Section 2, the circuit is analysed by simulation, and the results are compared to the theoretical results obtained in Section 3. In Section 4 we did a Side by Side comparison between the simulation and the theoretical results and then we have computed the Figure of Merit as is shown in section 5. The conclusions of this study are outlined in Section 6.

2 Simulation Analysis

2.1 Bandpass filter

This type of filter, with the characteristics that were mentioned in the Introduction, has several applications:

- BPFs (Bandpass filters) are extensively used in wireless transmitters and receivers. The main function of this filter in a transmitter is to limit the bandwidth of the o/p signal to the band allotted for the transmission. This avoids the transmitter from interfering with further stations.
- In a receiver, a Band-Pass filter allows signals within a selected range of frequencies to be heard or decoded, while preventing signals at unwanted frequencies from getting through.
- A Band-Pass filter also optimizes the signal-to-noise ratio and sensitivity of a receiver. This filters are used in all types of instruments as well as in Sonar, Seismology and even medical applications like EEGs and Electrocardiograms. These filters are also extensively used in optics like lasers, LIDARS, etc.
- A BPF (Band-Pass Filter) permits an exact frequency range to pass, while blocking frequencies that are lower and higher. A good application is in Audio Signal Processing, where a particular range of frequencies of sound is required while removing the rest.
- Band-Pass filters are used in communication systems for selecting a specific signal from a range of signals.

2.2 Implementation

The first implementation consisted in an High-Pass filter at the input of the OPAMP, an OPAMP with negative feedback, so that the gain was 100, and a Low-Pass filter at the output. In this way we were able to obtain the Band-Pass filter with the desired gain.

After this first implementation, we realized that the OPAMP itself, due to the components it contained, cut the high frequencies. In this way, we removed the low pass filter at the OPAMP output, because of the components redundancy and to reduce the cost.

The implemented circuit and the values of its components are shown in the figure and tables below:

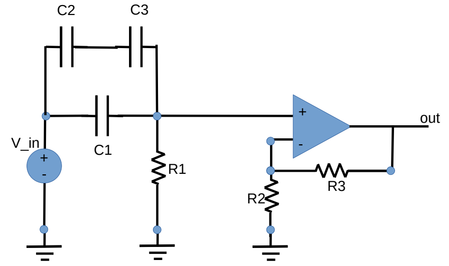

Figure 1: Band-Pass Filter circuit

Name	Value [kΩ] or [uF]
R1	1
R2	1
R3	100
C1	1
C2	1
C3	1

Table 1: Values of the components

2.3 Frequency Response

After the circuit implementation, its behaviour was analyzed as a frequency function. As we expected, the circuit behaves like a Band-Pass filter with a center frequency of approximately 1kHz and a gain of 100.

The graphs below show the magnitude and phase response in relation to the frequency:

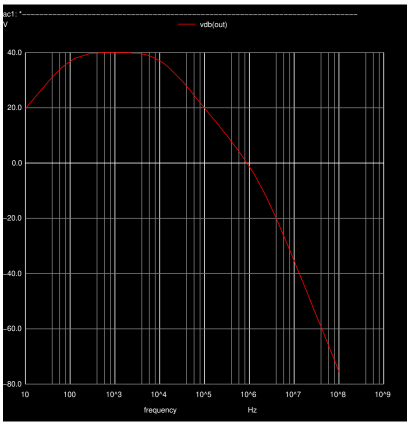

Figure 2: Magnitude frequency response

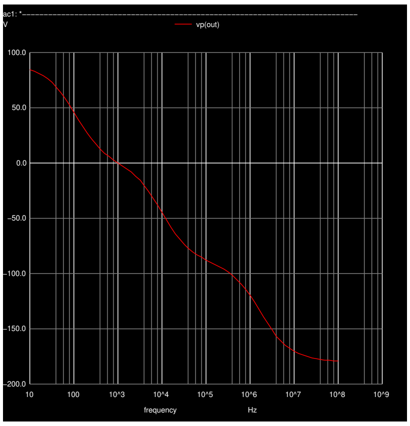

Figure 3: Phase frequency response

2.4 Voltage gain deviation

One of the requirements of the implementation was that at the frequency of 1000Hz, the gain should be 400dB, which means that the ratio between the output and input signal was 100. To measure this value in the simulation, the measure function was used to analyse the frequencies. The results are shown in table 2:

Name	Value [dB] or non-dimensional
centralgain	9.987576e+01
centralgaindb	3.998920e+01

Table 2: Values of Gain

As can be seen the value of our gain is very close to 100, that was the objective.

2.5 Central Frequency Deviation

The second requirement was that the central frequency was 1kHz. To determine this central frequency, we proceeded to measure the lower and upper frequencies where the gain dropped 3dB from its maximum. Subsequently, the central deviation frequency was computed from a geometric mean, that is, the root of the product of the upper and lower frequencies. In the following tables, we present the results that we have obtained.

Name	Value [Hz]
freqlow	1.050228e+02
freqhigh	1.011716e+04
centralfreq	1.030792e+03

Table 3: Values of Gain

2.6 Input and Output impedance

These two parameters are very important to predict the behavior of the implemented circuit. At the frequency we are working on, we want the input impedance to be as high as possible, and the output impedance as low as possible so that there is no signal degradation when we implement it in other circuits.

2.6.1 Input impedance

To determine the input impedance it was necessary to place a very large Load ($Z_L = \infty$) and remove the components upstream of the OPAMP, C1 and R1. After placing this load at the output of the circuit, the v_I, v_- and the current entering the non-inverting input were measured. The calculation was done with the following expression:

$$Z_L = \left.\frac{v_I}{i_I}\right|_{Z_i=\infty} \tag{2}$$

The obtained value is adequate to the intended one, however it doesn't fit reference interval.(1-10M Ω)

Name	Value $[M\Omega]$
zinput	5.121429e+02

Table 4: Value of Zi

We also made the input impedance plot (Figure 4) to verify the behavior. As noted, the input impedance value does not change much with frequency.

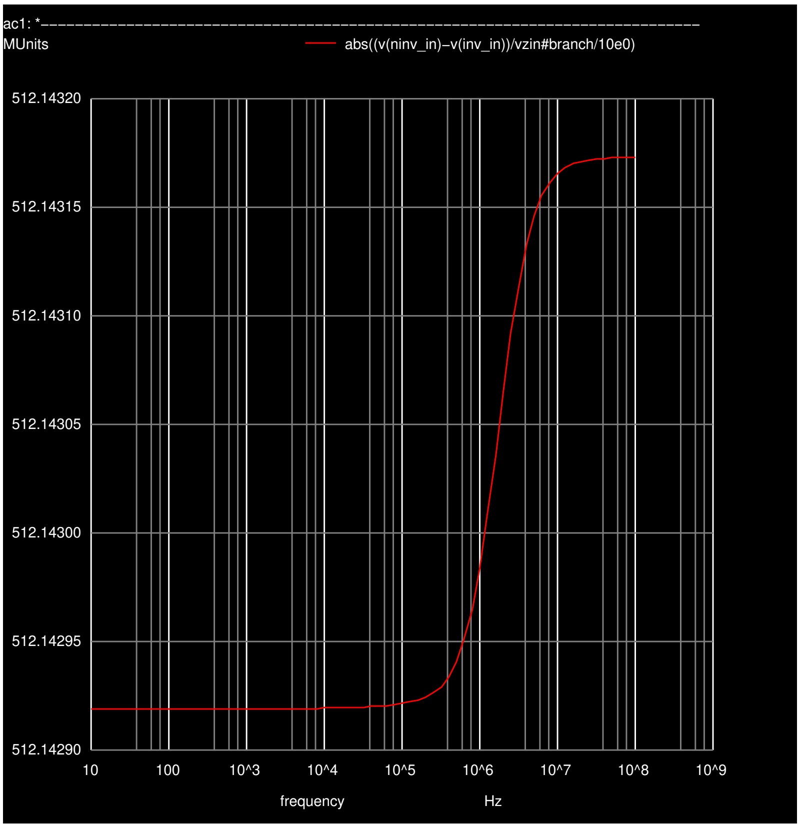

Figure 4: Frequency response of input impedance

2.6.2 Output impedance

To determine the input impedance it was necessary to implement a slightly different circuit. The signal source was placed at the OPAMP output, and the current and voltage at the OPAMP output were measured, from its ratio, the output impedance was determined.

$$Z_O = \left.\frac{v_O}{i_O}\right|_{v_i=0} \tag{3}$$

The obtained value is again adequate to the intended one, and is slightly lower than the reference values of the OPAMP (10-100 Ω).

Name	**Value** $[\omega]$
zoutput	5.038123e+00

Table 5: Value of Z_O

We also made the output impedance plot (Figure 5) to verify its behavior. As we noted, the output impedance, after reaching values close to 10kHz, increases substantially.

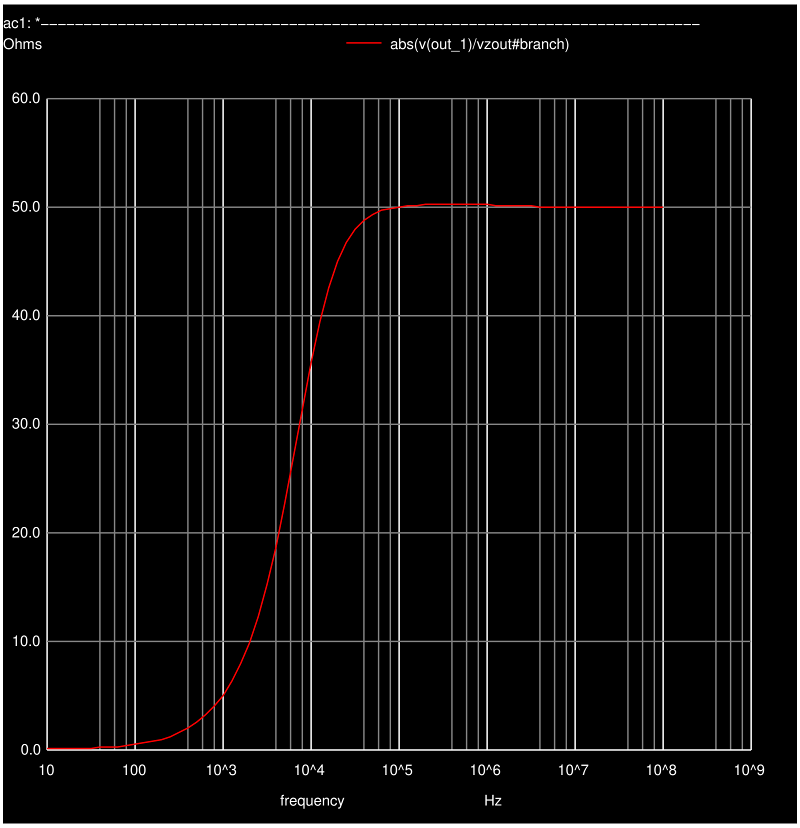

Figure 5: Frequency response of output impedance

3 Theoretical Analysis

In this section, we used a suitable theoretical model that was able to estimate the circuit behavior in response to frequency.

3.1 Ideal OPAMP analysis

In this subsection we used the characteristics of an ideal OPAMP to determine the behavior of the circuit. We considered:

$$\frac{v_0}{v_I} = -\frac{R_2}{R_1} \tag{4}$$

$$Z_I = R_\infty \tag{5}$$

$$Z_O = 0 \tag{6}$$

3.1.1 Circuit Transfer Function

By determining the above-referenced parameters, we were able to compute the transfer function of our ideal circuit:

$$\frac{v_o(s)}{v_i(s)} = \left(1 + \frac{R3}{R2}\right) \times \frac{R1 \times C1 \times s}{1 + (R1 \times C1 \times s)} \tag{7}$$

With the frequency response as follows:

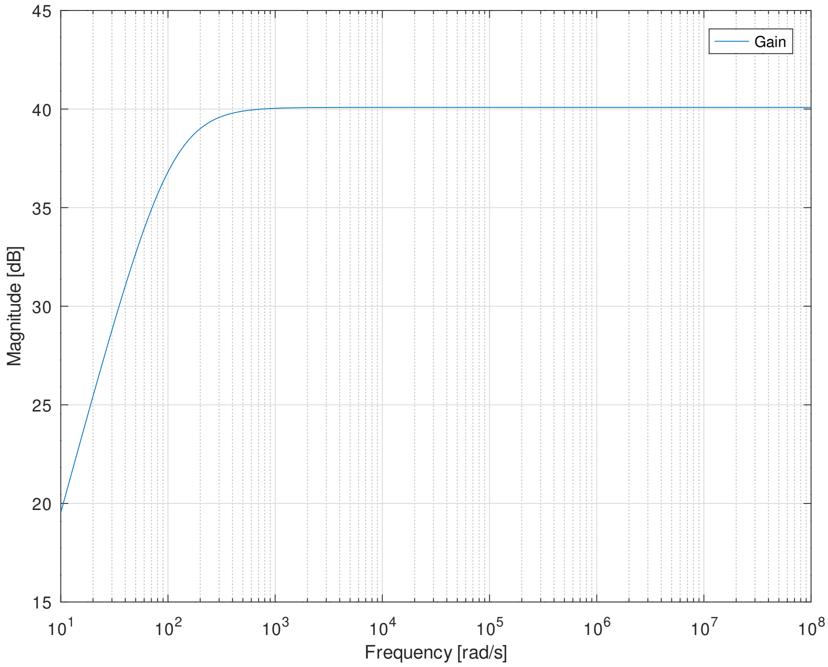

Figure 6: Gain stage circuit (from lecture 17 TCFE)

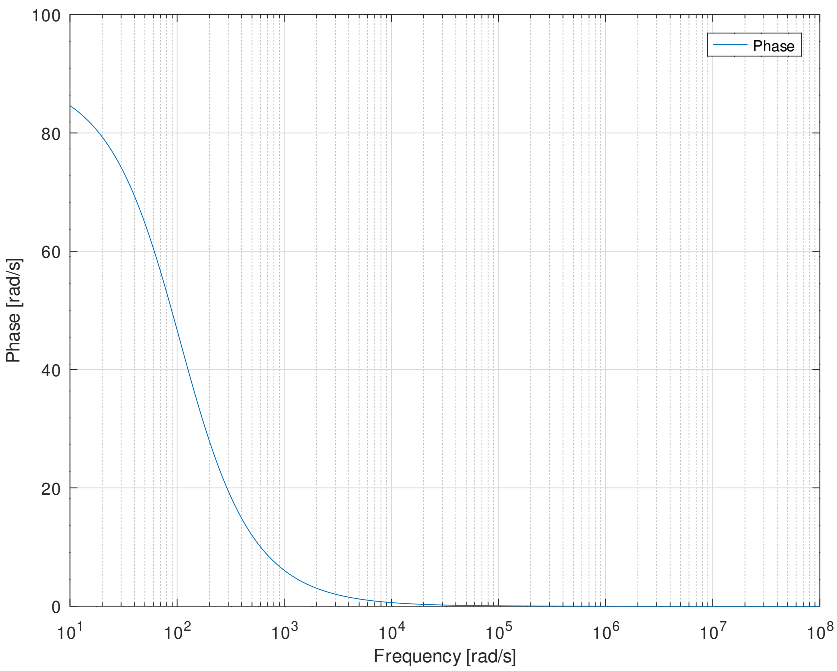

Figure 7: Gain stage circuit (from lecture 17 TCFE)

As we can see, the ideal behavior of the OPAMP does not equals the simulated behavior. This is because, the ideal behavior does not take into account that the OPAMP has two poles, which end up making the response to be a Band-Pass and not just an high pass. having said that, we had to use a more adequate model for its theoretical analysis.

3.2 Circuit analysis

For a more adequate analysis, and taking into account the non-ideal behavior of OPAMP, we implemented a circuit in order to be able to predict the location of the poles of the OPAMP transfer function. Thus, we verified that the OPAMP has two poles, one at 10^4 and the other at 10^6. It was possible to perceive this through the magnitude and phase Bode plots. As you can see, the slope changes in 10^4 to -20 dB per decade, and in 10^6 to -40 dB per decade.

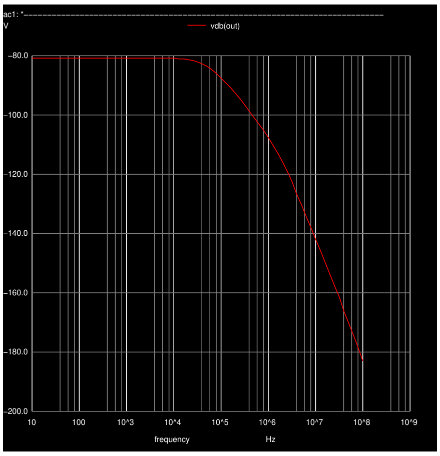

Figure 8: OPAMP frequency response: magnitude

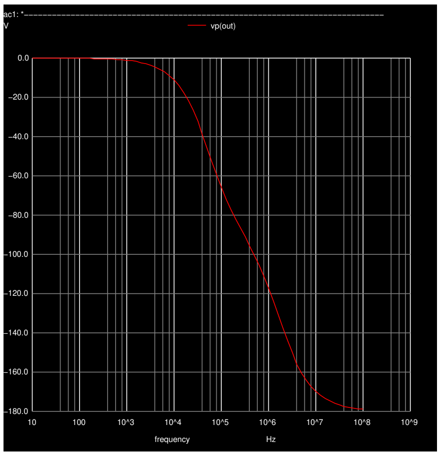

Figure 9: OPAMP frequency response: phase

3.2.1 Circuit Transfer Function

In this way, it was possible to correct the previously computed transfer function in order to incorporate the non-ideal behavior of OPAMP. The obtained FT is:

$$\frac{v_o(s)}{v_i(s)} = 1 + (\frac{R3}{R2}) \times \frac{R1 \times C1 \times s}{1 + (R1 \times C1 \times s)} \times \frac{10e10}{(s + 10e6) \times (s + 10e4)} \tag{8}$$

And the response is:

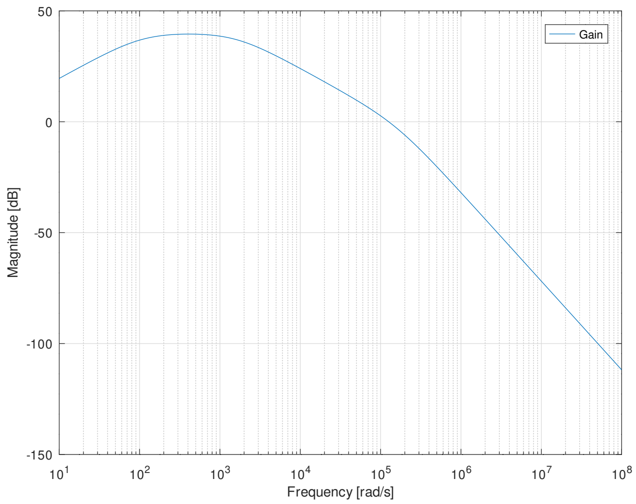

Figure 10: Frequency response: magnitude

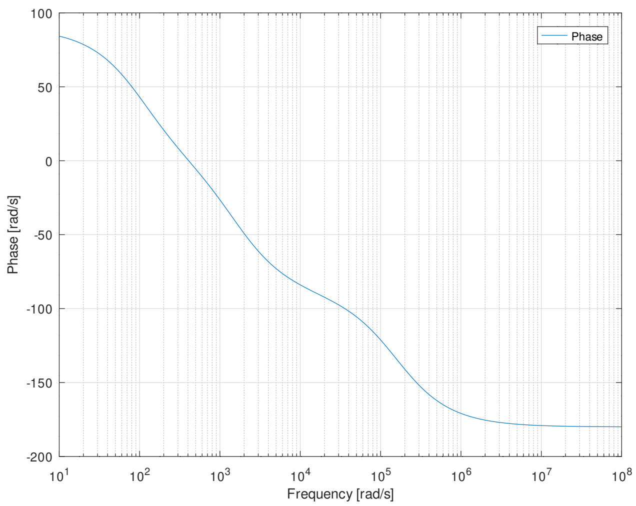

Figure 11: Frequency response: phase

4 Side by Side comparison

In this section we are going to analyse and compare the response generated with the Ngspice simulation and with the Octave tool (Theoretical analysis).

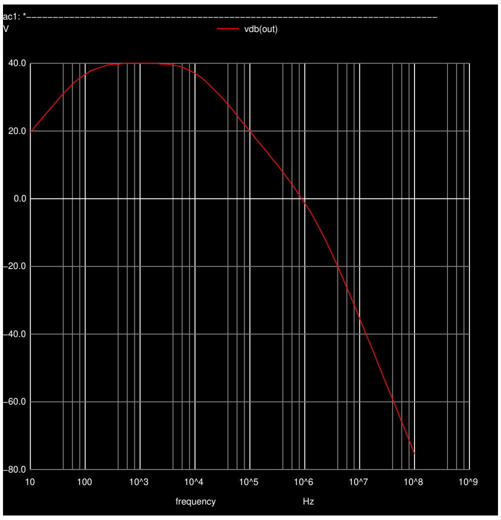

Figure 12: Simulation response

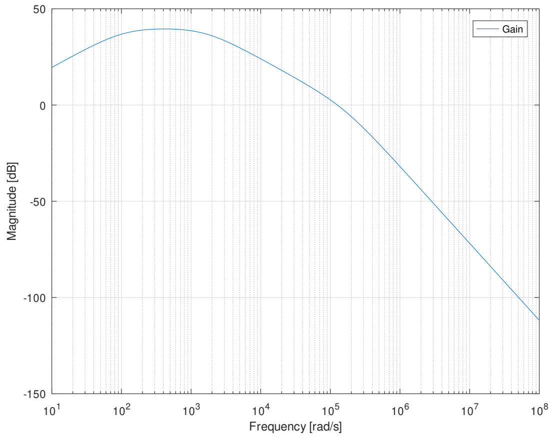

Figure 13: Theoretical response

As we can see, the simulation and theoretical analysis responses are very similars. The fact that the visualization is being done in logarithmic scales makes small discrepancies completely impossible to visualize.

5 Figure of merit

The final objective was to obtain a figure of merit as high as possible. In this section, we present the final result, after we performed all the analysis The merit figures is given by:

$$M = \frac{1}{Cost(VoltageGainDeviation + CentralFrequencyDeviation + 10^{-6})} \tag{9}$$

Name	Value [Hz]
OPAMP	13322.58000
CIRCUIT	105
TOTAL	13427.58000

Table 6: Values of Gain

Name	Value [Hz]
GAIN	99.876
GAINDEV	0.12424
CENTRALFREQ	1030.8
CENTRALFREQDEV	30.792
COST	13427.58000
FM	0.0000024089

Table 7: Values of Gain

Finally, we obtained the important values to calculate the Merit Figure, which we present in the table above. The values used were those of the simulation, since they represent a more accurate approximation of reality.

The Figure of Merit has a very low value. The main reason for this is because the cost of the OPAMP is quite high, in fact, is two orders of magnitude higher than the cost of the rest of the circuit.

Even so, the gain and centre frequency values achieved were very close to the intended values.

6 Conclusion

In this laboratory assignment, the objective was to implement an Band-Pass Filter with the highest Merit Figure as possible (this merit figure depends on the price of the components, the Voltage Gain Deviation and the Central Frequency Deviation), using the Octave Math tool and by running a simulation using the Ngspice tool.

In this laboratory we obtained similar values in the two analysis. This was due to the fact that the theoretical analysis was based in the values of the simulation itself. To conclude, the objective was achieved, since we built an band-pass filter with similar gain and central frequency to the values required.