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Abstract

Microwave Cavity Filters are widely used in RF systems for high Q signal filtering. But their bulky sizes at lower operating frequencies make them quite inconvenient to be used especially in the frequency range 1-4 GHz, which is the range of most of the commercial wireless applications. This thesis work aims to enhance the usability of cavity filters in these lower frequency ranges, by exploring a unique re-entrant structure for the cavity filter design. The study further explores the use of superconductors in the design to for improve the performance of the filters by reducing the associated losses. After verifying the basic workability of the concept, a coupled re-entrant cavity filter design is proposed with an equivalent high Q.

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List of symbols

Quantity	Symbol
Quality Factor	Q
Bandwidth	BW
	ω
Magnetic Permeability of Free Space	μ_0
Electric Permittivity of Free Space	ϵ_0
Center Frequency of Resonance	f_0
Roots of Bessels' function	ρ
Roots of First Derivative of Bessel's Funtion	ρ'
Relative Permeability of Medium	μ_r
Relative Permittivity of Dielectric Medium	ϵ_r
Wavelength in Free Space	λ_0
Wavelength in Dielectric Medium	λ_g
	δ
Attenuation Constant	α_c
Propagation Constant	β
Current due to Capacitive Reactance	I_c
Current due to Inductive Reactance	I_L

Chapter 1

INTRODUCTION

Filter is one of the most crucial components in any communication system. The quality of the signal and hence the data is highly dependant on the selectivity of the filter employed.[1] As the data rates employed in communication systems are increasing exponentially, the need for precise and highly accurate filters is also increasing. Researchers are periodically coming up with newer, better and more efficient designs, which has made filter design a very competitive field in itself.

The filters used in different systems vary extensively depending on the application for which the filter is employed. Some of the important characteristics considered in selection of a filter for a system are size, low insertion loss, high selectivity, bandwidth and noise margin.[2][3] But the communication system and its components present several constraints, which prevent an optimal design solution. Hence the choice of a filter is always a trade-off amongst the filter characteristics depending on these constraints.

Cavity resonator filters are widely employed in wireless communication systems. With the advance in MMIC development, filters of very small size can be employed in most applications. But despite the availability of smaller sized filters, what makes the bulky cavity filters useful is their Quality Factor, which is several times high as compared

to all other filter types. They also have minimum insertion loss for a given fractional bandwidth. The filter characteristics of a high quality filter are very sharp at the cut off frequencies. The sharper the edges are, the better is the ability of the filter to eliminate interference from neighboring channels. Thus by employing a high quality filter, the requirement for extensive signal processing to eliminate noise, can be greatly reduced.

However in addition to being bulky, they also have the limitations of being useful over only a limited frequency range because of the possibility of excitation of higher modes. Hence, such filters are employed in applications where the size of the filter is not a big constraint and the system operates over a smaller frequency range, but the selectivity of the filter is very important. Typically, cavity resonator filters find applications in base-stations of mobile and wireless communication systems, satellite transmissions systems and radars, where quality of the signal is of paramount importance and size is not important.[1]

Problem Definition:

The cavity resonators used in filtering applications can provide high quality of filtering but the major limitation which prevents more sporadic use of cavity resonators is their bulky size in the range of frequencies in which most wireless applications operate. Most wireless systems cover the frequency range of 800 MHz to 5 GHz. For a cavity resonator to be used at 2 GHz, its length can be around 75 mm. Hence the use of these filters is limited to places like base stations where space is not a constraint, while quality of filtering is of great importance. The aim of this research is to improve the disadvantage

introduced by conventional cavity filters, and thus enhance the chances of its possible utility in today's communication systems.

The thesis work presented here strives to provide a method to reduce the size of the cavity filters by use of a re-entrant cavity structure. Though the structure is relatively lossy, the results presented here show that with the use of superconducting material in the filter structures, the losses are drastically reduced and in fact an even better filter characteristic are obtained, thus enhancing the selectivity of the filter. Finally, a tunable wide-band cavity resonator, using re-entrant design, with highly accurate filter performance is presented.

Chapter 2

Filter Theory

Microwave Filters are used to control the frequency response in a system by passing signals within specific frequencies and eliminating all other signals. Depending on the frequency response of the filters, they are classified as high-pass, low-pass, band-pass and band-reject. Filters are one of the essential parts in transmitters, receivers and in many other RF circuitry such as multiplexers.[2]

2.1 Theory of Filters:

An ideal filter has at least one frequency, where there is zero attenuation..[3] But depending on the overall losses, the attenuation increases over a small range, rather than increasing instantaneously. Due to this, the filter characteristic is not very sharp. By using higher order of the poles, sharper frequency response can be achieved.

A typical filter circuit consists of alternating series and shunt resonators. In microwave structures, the effect of alternating series and shunt resonators is achieved by using impedance inverters. These impedance inverters are usually strips or gaps in between two consecutive resonating structures. They can be modeled into some corresponding lumped elements for design convenience.[4]

Two important parameters which are considered in the design of a resonant circuits are the quality factor (Q) and the bandwidth (BW). The quality factor (Q) is a measure of the power loss in a resonant circuit. It is defined as

$$Q = \omega (\text{average energy stored})/(\text{average loss/second}) \quad \dots\dots (2.1)$$

The fractional bandwidth (BW) of a circuit is the frequency band for which the power is greater than half of the maximum power.

$$\text{B.W.} = 1/Q \quad \dots\dots (2.2)$$

2.2 Cavity Resonators:

By definition, a resonant cavity is any space completely enclosed by conducting walls that can contain oscillating electromagnetic fields and possess resonant properties. Resonators can be constructed from closed sections of transmission lines. Open ended waveguides cause loss of energy due to radiation, while closed sections of waveguides or cavities act as shorts. Cavity resonators built for different frequency ranges and applications can have a variety of shapes, but, the basic principles of operation are the same for all.

Resonant cavities have a very high Q and can be built to handle relatively large amounts of power. There are two variables that determine the primary frequency of any resonant cavity. The first variable is the physical size. The second controlling factor is the

shape of the cavity. Electric and magnetic energies stored inside the cavity resonate at the resonant frequencies which is a characteristic of the cavity.[2] Resonant frequency is determined by the geometrical shape of the cavity. Depending on the types of the TE or TM mode, the resonance also occurs at different frequencies. Cylindrical cavity resonators have been used for the purpose of ease of experimentation in this research work. The theory of cylindrical cavity resonators has been briefly discussed below.

2.3 Cylindrical Cavity Resonators:

A cylindrical cavity resonator can be constructed from a section of circular waveguide shorted at both ends. A circular waveguide supports TE and TM modes of propagation. From electro-magnetic analysis of a circular waveguide, the propagation constants of the propagating waves depend on the roots of Bessel's functions and the diameter of the cavity. In the case of TE modes, they depend on roots of the first derivative of Bessel's function, $J_n'(k_c\rho)$ and in the case of TM modes, they depend on the roots of the Bessel's function of the first kind $J_n(k_c\rho)$. The cut-off frequencies of propagating waves are given by

$$f_{c,nm} = \frac{\rho'_{nm}}{2\pi a \sqrt{\mu\epsilon}} \quad \dots\dots (2.3)$$

$$f_{c,nm} = \frac{\rho_{nm}}{2\pi a \sqrt{\mu\epsilon}} \quad \dots\dots (2.4)$$

where,

n and m are integer values,

ρ_{nm}' : Zeros of the function $J_n'(x)$,

ρ_{nm} : Zeros of the function $J_n(x)$,

a : Radius of cylindrical cavity,

d : Height of cylindrical cavity.

Since the cylindrical cavity is a shorted section of circular waveguide, the resonant frequencies for the TE_{nml} modes are given by

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{\rho_{nm}'}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad \dots\dots (2.5)$$

Here, $l = 1, 2, 3, \dots\dots$

And the resonant frequencies for TM_{nml} mode are given by

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{\rho_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad \dots\dots (2.6)$$

Here, $l = 0, 1, 2, 3, \dots\dots$

The other important parameter for a cavity resonator is the quality factor. The overall Quality Factor (Q_U), known as the unloaded Q of a filter can be written as

$$\frac{1}{Q_U} = \frac{1}{Q_{cond}} + \frac{1}{Q_{diel}} \quad \dots\dots (2.7)$$

where,

Q_U is the unloaded Q and

Q_{cond} is the Q due to conductive losses

Q_{diel} is the Q due to a dielectric material.

The unloaded Q_U is dependant only on the losses in the in the cavity itself. If a dielectric material fills the cavity, it contributes to the unloaded Q of the cavity and the associated Q is given by

$$Q_{diel} = \frac{1}{\tan \delta} \quad \dots\dots (2.8)$$

where, $\tan \delta$ is the loss tangent in the waveguide.

The Q_{cond} is a function of the ohmic losses in the waveguide walls and is related to the ratio of the frequency in the dielectric to the frequency in vacuum

$$Q_{cond} = \frac{\pi}{\lambda_g \alpha_c} \quad \dots\dots (2.9)$$

where,

λ_g = Wavelength in the waveguide with the dielectric, guide wavelength,

α_c = Attenuation constant

The cavity is connected to an external system by a probe or aperture to utilize the filtering characteristics of the cavity. The external circuit introduces an additional Q and is known as Q_{ext} .

The experimentally measured Q of a cavity is the loaded Q and is related to the Q_U and Q_{ext} by the relation.

$$\frac{1}{Q_L} = \frac{1}{Q_U} + \frac{1}{Q_{ext}}$$

From the measured S parameters, Q_L , Q_U and Q_{ext} are calculated.

2.4 Equivalent Circuit Modeling:

Any cavity resonator can be modeled using lumped elements to obtain its AC equivalent circuit. A cavity filter can be represented as an equivalent parallel RLC tank circuit, resonating at the center frequency of the filter.[2] The typical circuit and its characteristic are shown in figure 2.1

Figure 2.1

Parallel RLC circuit and its characteristic

Thus, the equivalent circuit of the resonator can be used to understand the working of a resonator and also to predict the performance of the filter..

A cross section of a cylindrical cavity can be represented to be equivalent to a shorted quarter wave section of a transmission line. The corresponding equivalent circuit is given in Figure 2.2(b).. The other cross sections of the the cavity are also represented as quarter wave sections in parallel. Since the quarter wave sections are in parallel, the resonance frequency remains the same, but the increase in the number of sections, increases the Quality Factor of the resonator. The capacitor in the center is due to the contribution of the top and bottom plates.

Figure 2.2

Equivalent circuit for a Cylindrical Cavity Filter

The value of the equivalent circuit components can be determined by analyzing the source of each component. The capacitance in the equivalent circuit is due to the lines of electric fields in the cavity. The upper and the lower faces of the cylinder act like the parallel plate capacitor enclosing the dielectric in between them. Hence the equivalent capacitance can be given as

$$C = \epsilon \frac{A}{h} = \epsilon \frac{\pi r^2}{h} \quad \dots\dots (2.10)$$

Where,

ϵ is Dielectric permittivity of the medium,

r is the radius of the cylinder,

h is height of the cylinder,

The inductive component in the equivalent circuit is due to the magnetic lines of field in the cavity. The inductance can therefore be given as

$$L = \frac{\mu h}{2\pi} \ln(r) \quad \dots\dots (2.11)$$

where,

μ is the magnetic permeability of the medium

Based on these concepts, equivalent circuit models can be generated for any type of cavity resonator and its characteristics and performance can be predicted.

2.5 Experimental Analysis Method:

The cavities in which the experiments were performed were given excitation by a probe through its top surface. The fundamental mode in the cavity was transverse magnetic i.e. TM_{010} . [2][3] This mode was independent of the height of the cavity and hence was the best choice for this experiment. A Matlab program was written to calculate the theoretical value of the resonant frequencies for the cavity under test, using Bessel's functions. The program is attached as Appendix A

The responses of cavity filters were tested using Vector Network Analyzer. The data obtained was read into a file using GPIB interface. The file was then edited to make it a file of strictly numerical data and the data was analyzed using another Matlab program. This program was written based on the theory presented in [5]. The Matlab program, which was used to calculate the Q factor from experimental data, is attached as Appendix B.

Chapter 3

Re-entrant Cavity Filter

3.1 Re-entrant Cavity Structure:

A re-entrant structure was originally used in Klystrons for generation of modest microwave signal generation. Nowadays they find a variety of applications in microwave devices such as electron beam tubes and filters.. The basic re-entrant structure used in the design of resonator is shown in Figure 3.1. The coaxial part acts as an inductor and the top part acts as a capacitor resonating at the design frequency of the cavity. In Klystrons, the central post is hollow and the top plate of the main cylinder and the top surface of the post are made of fine mesh grids so that the electron beam can go through between the two grids under the influence of a relatively uniform electric field. The short distance between the plates allow the electron beam to travel through the plates with a very short transit time which is essential in generating the high frequency microwave signal. [6] In the cavity filter application, the increased capacitance provides a reduction in the resonant frequency.

Figure 3.1

Re-entrant cavity structure

3.2 Theory of a Re-entrant cavity:

The objective of the thesis work was to design a cavity resonator to work at lower frequencies while keeping its size small. From the discussion in section 2.3, we can see that the frequency of resonance can be reduced by either increasing the capacitance or the inductance. The inductance in the cavity is dependent on the ratio of the radius of the outer cylinder and the radius of the post as well as the length of the shorted equivalent coaxial line. The capacitance is inversely dependant on the distance between the top surface of the cylinder and the surfaces of the post. Hence capacitance increases as the gap between the two plates decreases.

The equivalent circuits for the re-entrant cavity resonator can be obtained by rigorous solution of the electromagnetic fields inside the cavity.[7]. But for design

purposes, the cavity can be approximated by a capacitance in parallel with an inductor.

The values of L and C can be approximated as

$$L = \frac{\mu h}{2\pi} \ln\left(\frac{a}{b}\right) \quad \dots\dots (3.1)$$

$$C = \varepsilon_0 \left[\frac{\pi a^2}{d} - 4a \ln \frac{2d}{\varepsilon \sqrt{H^2 + (a-b)^2}} \right] \quad \dots\dots (3.2)$$

where,

a is the radius of the cavity

b is the radius of the inner post

H is the height of the cavity

h is the height of the inner post

d is the gap between the top surface of the cylinder and the post ($H-h$)

The introduction of a cylindrical post within an empty cavity therefore, increases the capacitance but decreases the inductance. But, inductance is directly dependant on natural logarithm of the radius, while capacitance is inversely dependant on the gap between the top and bottom surfaces of the plates of capacitor. Hence, the increase in capacitance is much more than the decrease in inductance. As a result the frequency of resonance decreases.

3.3 Design of the Re-entrant Cavity Resonator:

In the earlier stages of use of re-entrant structures, the design of re-entrant cavities was usually done based on design curves developed by Hansen.[7] These curves illustrate the relationship between the cavity dimensions and the resonant frequency of the cavity. For a given combination of dimensions, the resonant frequency can be predicted for the structure from these curves. The cavity can thus be designed for the required resonance frequency using the data from the curves. This method was first published by the Sperry Gyroscope company in 1944. A typical Sperry Gyroscope Curves Data is shown in Figure 3.2. The Sperry curves have to be employed with great care owing to the high level of analytical approximations involved with the modeling effect of gap incorporated into the original Hansen theory. Also, due to extent of the frequencies covered by the graphs can become a lengthy process of trial and error to obtain the correct dimensional ratio.

Figure 3.2

Sperry Gyroscope Data Curves for Cylindrical Re-entrant Cavity [8]

Nowadays, more accurate modeling can be done using computer simulations employing finite element methods.[8] In the frequency domain finite element method (FEM) analysis, the electromagnetic field distribution in a structure is expressed as a wave equation derived from Maxwell's equations.[9] The wave equation is then solved as an eigenvalue problem using several hundred degrees of freedom. [10][11] The frequencies of the resonant cavity structure are obtained as the eigenvalues of the wave equation.

In this thesis work, FEM analysis is performed on the designed structure using Ansoft's HFSS (High Frequency Structure Simulator) simulation software. This software creates a mesh of tetrahedrons along the structure design and executes a full solution of FEM analysis.[12] The software automatically creates a more dense mesh along areas of greater field strengths, which gives a better FEM analysis result.[13] In addition to this, the mesh can be made more concentrated, manually, to increase the accuracy of computation. This provides a lot of control over the analysis and increases the accuracy of results.[14][15]

Another advantage of using Ansoft's HFSS in simulation of the cavity is that the structures can be modeled in a manner which can give a more realistic representation of the actual experiment. For example, the modeling done in our simulation considers the realistic losses which occur at the ports, energy feed into the cavity and the coupling iris.

The simulations conducted in HFSS, not only give quantitative values of resonant frequencies and Q values but also provide a pictorial view of the 3-dimensional fields in the structure obtained from the FEM analysis.

Two modes of simulations are used in HFSS for different purposes; the Eigenmode simulation and the Driven simulation. The driven solution uses the finite element based solver to generate a solution for any structure that is “driven” by a source. The eigenmode solver is used to calculate the quality factor of a resonating structure through extensively solving of the fields in the structure. This solution also gives us the directions and relative strengths of fields in the structure.

Figure 3.3

Re-entrant cavity structure drawn in HFSS

Though, the actual structures fabricated had different dimensions, for the purpose of standard references to drawing conclusions, all simulations presented throughout the thesis are with reference to dimensions given below:

Radius of outer cylinder (a) = 10mm

Height of the outer cylinder (h) = 10mm

Different simulations were conducted to match the actual dimensions of fabricated structure to verify the practical results with simulation results. The results of those simulations are shown wherever necessary to verify the experimental data, but they are not discussed in detail.

3.4 Simulations:

The simulation results for the simple cylindrical cavity of radius 10mm and height 10mm are shown in Figure 3.4..

Figure 3.4 (a)

Simulated Structure of Cylindrical Cavity (With Meshing in HFSS)

Figure 3.4 (b)

E-Fields in the cylindrical cavity

Figure 3.4 (c)

S_{11} for the simple cylindrical cavity.

The simple cavity whose simulations are shown above was designed considering ideal source coupling and finite conductivity for the metal. From the simulations, the following results were obtained:

The resonance frequency: $(f_0) = 11.752 \text{ GHz}$

Quality Factor: $(Q) = 7940.70$

Also, the field variations within the cavity are consistent with the TM_{010} mode.

The next set of simulations was carried out for a test structure of a re-entrant cavity with the following parameters. Outer cavity dimensions kept the same as above. The inner post had height of 7mm and a radius of $b/2=3 \text{ mm}$, which generated a gap length $(g) = 3\text{mm}$. The simulation results obtained were as follows:

Figure 3.5 (a)

The Simulated Structure of Re-entrant Cavity (with Meshing)

Figure 3.5 (b)

E-Fields in the re-entrant cavity

Figure 3.5 (c)

S₁₁ graph for re-entrant cavity

Frequency of resonance (f_0) = 5.8 GHz

Quality Factor (Q) = 6479.4

A comparison of the fields of fig. 3.4 (b) and fig. 3.5(b) reveals that the simple cavity under consideration is resonating in a TM_{010} like-mode. The field lines in the re-entrant cavity present a very similar but distorted version of the same TM_{010} mode. As can be seen that the original empty cylindercical cavity resonance frequency of $f_r = 11.75$ GHz was lowered to $f_r = 5.8$ GHz in the re-entrant cavity by the presence of the central post.

Thus it has been verified from simulations that a re-entrant structure can be used as a filter at lower frequencies while keeping the volume of the structure small.

Chapter 4

Optimization of Re-entrant Cavity Resonator

The re-entrant cavity resonator concept is observed to be working but from the concept of equivalent circuit, we know that the frequency at which the re-entrant cavity resonator works will vary depending on the length and size of the re-entrant post. The size of the post is also expected to affect the quality factor (Q) of the filter. In order to be able to know the working of the re-entrant design better, we had to characterize it. This next stage was optimization of the filter structure.

A number of simulations were designed and run in HFSS to obtain a sufficient amount of data to exactly characterize the re-entrant cavity. There are two sets of two variables each. One set is the factors which affect the design structure which includes the radius (a) of the post and the height of the post (h). The other set is the factors of the filter which are influence, which includes the frequency of resonance (f_r) and the quality factor (Q). The data was collected by keeping one variable of structure design constant at a time and changing the other. The collected data was then used to plot a graph to determine the optimal structure dimensions.

4.1 Optimization of Re-entrant Cavity Parameters:

Changing the height or the radius of the inner post in the re-entrant cavity results in change of its frequency of resonance and also affects the Q factor of the cavity. Hence to find an optimal design for the cavity, these two parameters have to be optimized.

4.1.1 Optimization of Radius of Post

To find the optimal radius of the inner post, the height of the structure was kept constant at 8mm and simulations were run for various radii of the inner post, from 1mm to 9mm. The results of various simulations are summarized in Table 4.1(a). The parameters that were fixed were:

Gap between the height of post and top surface of cavity (g) = 2mm

Radius of Inner Post (b)	Resonance Frequency (f_r) in GHz	Quality factor(Q)
1 mm	6.338	3101.54
2 mm	5.728	2941.11
3 mm	5.363	2783.70
4 mm	5.166	2655.44
5 mm	5.100	2416.06
6 mm	5.168	2107.03
7 mm	5.376	1744.06
8 mm	5.803	1327.21
9 mm	6.635	928.53

Table 4.1 (a)

Frequency and Quality factors for different radii of the post with a height of 8mm

Since the results from the data of Table 4.1(a) were interestingly curious, another set of data was obtained to verify the results, but this time the height of the post was increased to 9mm (the gap was reduced to 1 mm). The results are tabulated in Table 4.1(b)

Radius of Inner Post (b)	Resonance Frequency (f_r) in GHz	Quality factor (Q)
1 mm	5.148	2606.04
2 mm	4.564	2478.36
3 mm	4.134	2328.97
4 mm	4.0345	2201.83
5 mm	3.856	1974.25
6 mm	3.920	1714.08
7 mm	4.122	1357.45
8 mm	4.537	1006.53
9 mm	5.366	760.53

Table 4.1 (b)

Frequency and Quality factors for different radii of the post with a height of 9mm

The results of Table 4.1(a) and table 4.1(b) are also drawn graphically as shown in Figures 4.1(a) and 4.1(b).

Figure 4.1 (a)

Graph of Quality Factor (Q) vs. Radius of post (b)

Figure 4.1 (b)

Graph of frequency (f_0) vs. Radius of post (b)

From these graphs, it is seen that the frequency of resonance decreases as the radius of post increases. It is minimal when the radius of the post is half the radius of the outer cylinder, but then when radius is further increased, the frequency also increases. This phenomenon can be explained by considering the equivalent circuit model as follows.

Increase in the size of the inner post decreases the equivalent inductance of the cavity. But the frequency of resonance keeps on decreasing because the increase in capacitance is much more than the decrease in inductance. When the radius of the post is more than half the radius of the outer cylinder, the inductance starts getting significantly smaller compared to the decrease in capacitance. Hence the effect of inductance on frequency becomes more dominant than the effect of capacitance, and the frequency of resonance increases.

The effect on Q , with change in radius of the post, is much more predictable and easier to explain. As the size of the post increases, the losses in the structure go on increasing, hence the Q goes on decreasing. Hence in the design of a re-entrant cavity, having an inner post with radius more than half the radius of outer cylinder has no practical use. It appears to be best to have the radius of the inner post half that of the outer cylinder, though it ought to be noted that if the Q requirements are high and the frequency of resonance is not very low, the design can be altered to suit the need, by keeping the radius of the post as small as possible.

4.1.2 Optimization of Height of Post:

For optimization of height, the radius of the inner post was fixed at 5 mm and the height of the post was varied from 1 mm to 9.75 mm. The last few data sets were taken closer to each other for better interpretation of data. The other parameters were

$$a = 10 \text{ mm}, h = 10 \text{ mm}$$

$$b = 5 \text{ mm}$$

The data obtained is tabulated in Table 4.2 and are plotted in in Figure2 4.2(a) and 4.2(b).

Gap between the heights (g)	Frequency of Resonance (f_r) in GHz	Quality factor (Q)
10 mm	12.645	8685.78
9 mm	11.098	6891.97
8 mm	10.517	6037.21
7 mm	9.297	5271.93
6 mm	8.596	4704.13
5 mm	7.651	4319.69
4 mm	6.824	4046.53
3 mm	5.927	3720.45
2 mm	5.100	3165.50
1 mm	3.856	2843.08

Table 4.2

Frequency and Quality factors for different heights of the post with radius of 5mm

Figure 4.2 (a)

Graph of frequency (f_0) vs. Gap between height of cylinder and post

Figure 4.2 (b)

Graph of Quality factor (Q) vs. Gap between height of cylinder and post

From the graphs, we can infer that as the height of the post increases, the frequency of resonance decreases. But, with the increase in height we also have an accompanying decrease in the quality factor. The deterioration of the quality factor is a very serious issue because the main reason for using a cavity resonator is a high Q-factor. It is seen that for lower heights of the post, the frequency of resonator drops significantly, while still keeping the quality factor at high values. Hence the design of a re-entrant cavity is completely dependant on the user discretion and how much he is ready to trade off the quality of filtering for convenience. Note that all the simulations presented in this chapter assumes that the cavity and the associated posts are made of Copper metal.

If the resistive losses in the re-entrant resonator can be reduced, it will be possible to design a filters with very high values of Q. These losses can be reduced by using superconducting material instead of metal to design the resonator. The following chapters explore this idea in detail.

Chapter 5

Re-entrant Cavity using a High T_c Superconductor

The re-entrant cavity performance studied in the previous chapter shows that the resonator structure is relatively lossy. As a result, the designed filter has quite low values of Q . Hence, the prime advantage of a cavity resonator as a filter is lost.[3] To overcome this disadvantage, the option of using a high T_c superconducting material for the re-entrant post structure or the whole cavity, was explored. In this chapter the theory of high T_c superconductors is discussed briefly.

5.1 History of Superconductors

The phenomenon of superconductivity was first observed in 1911, when it was observed that at a few degrees below absolute zero an electrical current could flow in mercury without any discernable resistance. But the theory which explained the phenomenon was not developed until 1957.[16][17] This theory was known as the BCS theory and explained the phenomenon of superconductivity with the help of microscopic understanding of the materials. The third era in superconductivity opened in 1986, when a class of materials completely different from the metals which had been found to be superconducting was discovered.[18] These new materials became superconducting at much higher temperatures and were known as high T_c superconductors

The research in superconductivity reached new dimensions with the discovery of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO), which possesses a critical temperature (T_c) of around 90K. After the discovery of YBCO, researchers were able to develop additional families of superconductors which included Ti and Hg based systems which had maximum T_c of 120K and 160K respectively. These high temperature superconductors find a variety of applications in RF and microwave devices like filters, low noise oscillators and some signal processing devices for fast data communications.

5.2 Phenomenon of Superconductivity

The phenomenon of superconductivity is identified by two major characteristics, zero resistance and diamagnetism (or Meissner effect). A widely accepted theory which explains the phenomenon of superconductivity is known as BCS theory.[16][17] According to this theory, the transition of a material from regular conductor to a state of superconductivity is observed because of an effective attraction between pairs of electrons of opposite spin and momentum. Below the superconducting transition temperature, T_c , the pairs form a condensate, a macroscopically occupied single quantum state, which flows without resistance and acts to screen out the modest magnetic fields. This brings about a perfect diamagnetism measured in the Meissner effect. At low temperatures, it costs a finite amount of energy to split up one of the pairs in the condensate. The superconducting state is thus characterized by the presence of a superfluid, which is the condensate.

The pairing of electrons results from a slight attraction between the electrons, related to lattice vibrations. The coupling to the lattice is called a phonon interaction. Single electrons obey Pauli's exclusion principle and hence there are a lot of collisions, leading to the resistivity which is ordinarily seen. The electron pairs however have lower energy and glide more efficiently which inhibits collisions. Hence, there is a sharp drop in the resistivity resulting in the superconducting phenomenon. This phenomenon can be visualized as the scene on the dance floor where, the couples move around smoothly, without bumping into the other couples.

5.3 The Yttrium-Barium-Copper Oxide Semiconductor:

Yttrium Barium Copper oxide ($\text{YBa}_2\text{Cu}_3\text{O}_x$), commonly called as the YBCO superconductor is one of the superconductors on which a lot of research is still being conducted. The primary reason for this is that, the YBCO superconductor becomes superconducting at a temperature as high as 92K.

The high temperature superconductors are ceramic materials with layers of copper-oxide spaced by layers containing barium and other atoms.[19] The Yttrium compound is somewhat unique as compared to the other materials in that it has a regular crystal structure. The yttrium compound is often called the 1-2-3 superconductor because of the ratio of its components. YBCO is developed as thin films for deposition on different substrates or as a single crystal.

YBCO was used in our experiments. One of the reasons why YBCO was chosen was that, YBCO can be grown as a bulk crystalline material in a very efficient manner using sintering process.[19] The bulk material can then be machined to obtain a post structure for making the re-entrant cavity; unlike most superconductors which can be efficiently grown only as thin films.[20] Another reason was the fact that it is superconducting at a fairly high temperature, below 92K so that liquified nitrogen (77K) can be used as the coolant.. Also a fair amount of research is being done on YBCO and improvements in the YBCO superconductors are highly anticipated, which can hopefully lead to a commercial use of an improved version of our filter.

Also, the project for developing the cavity filter with a superconducting material was jointly executed along with Material Science and Engineering department, which developed the superconductors and Physics department which characterized them. Hence YBCO samples were easily available to us.

5.4 YBCO Superconductor Crystal Growth:

The seeded melt-growth (SMG) technique is used to grow $\text{YBa}_2\text{Cu}_3\text{O}_x$ crystals as large as several inches. Precursor $\text{YBa}_2\text{Cu}_3\text{O}_x$ and Y_2BaCuO_5 powders are made by preparing stoichiometric mixtures of Y_2O_3 (99.999% pure), BaCO_3 (99.999%) and CuO (99.995%), then calcining in BaZrO_3 crucibles at approximately 950°C until the reaction is complete as determined by X-ray diffraction [17]. The $\text{YBa}_2\text{Cu}_3\text{O}_x$, Y_2BaCuO_5 and Platinum powders are mixed in an agate mortar under ethanol and then pressed in a

cylindrical mold under 300 MPa of hydrostatic pressure. The resulting pellet is approximately 13 mm high by 12 mm in diameter, and had a mass of approximately 10 g.

The addition of a small amount of Pt is required to prevent melt loss during growth by increasing the melt's viscosity. Without the addition of Y_2BaCuO_5 , the crystals become porous, have poor mosaic spread, and contain BaO-CuO flux inclusions. Best results are obtained when the pellet contains 2% Y_2BaCuO_5 by mass.

$\text{NdBa}_2\text{Cu}_3\text{O}_x$ is usually taken as a seed crystal for its near-perfect lattice match and for having a melting temperature 80 °C higher than that of $\text{YBa}_2\text{Cu}_3\text{O}_x$. The seed and the pellet are placed on a disc-shaped substrate, loaded into a three-zone vertical tube furnace, and subjected to the temperature program shown in figure below. After a sintering step at 990°C, a temperature gradient of 5°C is applied and the pellet is melted. It is then slowly cooled down. This effectively moves the peritectic temperature through the pellet, from seed to substrate, over the course of several days, forming a complete crystal.

Figure 5.1

Crystallization furnace program; the inset depicts the growth setup, showing the geometry of the pellet, seed and substrate

Chapter 6

Experimental Results

The proposed idea of a re-entrant structure for the cavity resonator filter was verified from several simulations carried out in HFSS. We have also seen the characterization of the cavity design to find out the optimal design for the cavity resonator. In order to verify the proposed design, we had a cavity fabricated from a professional machinist with accurate dimensions.

The fabricated cavity was larger than the prototype design considered while carrying out the simulations. The cavity dimensions were:

Outer Cavity Radius (a) = 15 mm

Height of Cavity (h) = 10 mm

Height of Inner Post = 8.5 mm i.e. $g = 1.5$ mm

Radius of Post (b) = 10 mm

Material: Brass

6.1 Design of the Cavity Filter:

The cavity was designed such that the top surface was a removable lid. For testing the characteristics of a regular cavity, we screwed the simple cap on top of the cavity to achieve a simple cylindrical cavity structure. The other cap was designed with a re-entrant post structure on it. When the second cap was screwed on top of the cavity, a re-entrant cavity resonator structure was achieved. The probes were inserted from the other surface and care was taken to ensure that they did not touch the inner post when the re-entrant structure was used. Figure 6.1 is a CAD drawing of the designed structure.

Figure 6.1
 CAD drawing for design of the fabricated cavity

Figure 6.2 is a picture of the actual fabricated cavity.

Figure 6.2

Photograph of fabricated cavity filter

6.2 Simple Cavity Resonator:

Since the structure dimensions were different from our standard assumptions, the device was first simulated in HFSS to find out the pertinent parameters. Following are the S_{11} and S_{21} patterns for the cavity. Figure 6.3(a) and 6.4(a) show the simulation for the acylindrical and the re-entrant cavities repectivley. Figures 6.3(b) and 6.(b) show corresponding experimentally measured data.

Figure 6.3 (a)

Simulation for the simple cylindrical cavity

Figure 6.3 (b)

Experimental results for the simple cavity

Results obtained from the simulation were,

Resonant Frequency (f_0) = 11.9 GHz

Quality factor (Q) = 7355.32

Results obtained from fabricated cavity were,

Resonant Frequency (f_0) = 12.15 GHz

Quality factor (Q) = 6927.86

Thus, the experimental readings for the simple cavity quite closely matched the results from the simulations. The experimental result shows a slight deviation in the frequency predicted from the simulations. Also, the Q factor is slightly smaller than anticipated. These differences are attributed to the non-ideal conditions in a practical environment in which the experiments are performed. Also in the simulations, the ports were approximated which may be different than the real port conditions.

6.3 Re-entrant Cavity Resonator:

Figure 6.4 (a)

Simulation for the re-entrant cavity

Figure 6.4 (b)

Experimental results for the re-entrant cavity.

For the re-entrant cavity data obtained from simulations is,

Resonant Frequency (f_0) = 3.4 GHz

Quality factor (Q) = 2586.42

The data obtained from experimentation is,

Resonant Frequency (f_0) = 3.48 GHz

Quality factor (Q) = 2103.52

It is seen from the simulations that the frequency of resonance drops to 3.4 GHz, and this is corroborated by the data obtained from experimental results. Thus, we have verified the workability of the concept of using a re-entrant cavity as a filter, through simulations and matching data obtained in experiments.

6.4 Cavity Filter Using YBCO Superconductor:

In order to test the workability of a superconducting material in a cavity filter, experiments were made with a cavity filter made completely of superconducting material. In this experiment, the simple cavity made of YBCO superconducting material was cooled in a cryogenic chamber and the change in Q of the filter at various temperatures was noted. Readings were taken at different temperatures during the cooling process using a programmable temperature controller. The data obtained is given below and is plotted in a graph to show the change in Q with the decrease in temperature.

Two types of superconducting cavities were experimentally investigated. The first was a conventional cylindrical cavity made from SMG YBCO. Next the cover was replaced by a cover with a plug in the center so that the assembled cavity became a re-entrant cavity.

The cylindrical High Temperature Superconducting (HTS) cavity dimensions were:

Radius (a) = 11 mm, Height (h) = 10 mm

The HTS cylindrical cavity was also simulated over a wide frequency range to observe the two lowest modes. For this simulation it was assumed that the cavity walls had an infinite conductivity. The simulated results over a wide frequency range are shown in Figure .6.5. The lowest order mode was the TM_{010} mode at 10.6 GHz and the next lower mode was the TE_{111} mode at 16.0 GHz.

Figure 6.5

1st and 2nd Resonances in the Superconducting cavity from simulation

For the experimental measurements, VNA was swept around the center frequencies of the corresponding mode predicted by the simulations. Typical VNA readings for the TM_{010} at room temperature, at 80K and 20K are respectively shown in Figures 6.6(a), 6.6(b) and 6.6(c).

Figure 6.6 (a)

Resonance of the superconducting cavity at room Temperature at 9.8 GHz

Figure 6.6 (b)

Resonance in the Superconducting cavity at 80K

Figure 6.6 (c)

Resonance in the superconducting cavity at 20K

Similar measurements made within the frequency range of the TE_{111} mode; These are shown in Figures 6.7(a), 6.7(b) and 6.7(c) at room temperature, at 80K and 20K respectively. Note that the measured values are slightly lower in frequency due to the insertion of the probe. There is a slight variation in the dimensions of the cavity. Actually, in both experiments, the temperature was varied over a wide range from room temperature down to 10K.

Figure 6.7 (a)

Second Resonance of Superconducting Cavity at room temperature at 17.5 GHz

Figure 6.7 (b)

Second Resonance of Superconducting Cavity at 80K

Figure 6.7 (c)

Second Resonance of Superconducting Cavity at 20K

The Q values were calculated from the measured values. The calculated loaded Qs and unloaded Qs at various temperatures are tabulated in Table 1. The results are also plotted in Figures 6.8 and 9.9.

Resonance of 9.8 GHz			Resonance of 17.4 GHz		
Temperature	Loaded Q	Unloaded Q	Temperature	Loaded Q	Unloaded Q
293K	148.3	1262.7	293K	86.2	726.4
100K	162.7	1318.5	100K	152.7	873.1
95K	166.7	1391.7	95K	166.7	912.9
90K	178.2	1444.6	90K	178.2	1031.5
85K	276.6	1892.8	85K	276.6	1825.7
80K	652.3	2458.1	80K	842.3	3318.5
70K	761.8	2735.6	70K	887.1	3527.6
60K	797.5	2971.5	60K	897.5	3617.8
50K	843.6	3252.8	50K	913.5	3694.4
40K	921.4	3391.2	40K	956.4	3783.2
30K	964.1	3448.1	30K	1016.9	3878.3
20K	986.3	3496.3	20K	1071.5	3912.9

Table 6.1

Loaded and Unloaded Q values at different temperatures for the Superconducting Cavity

Figure 6.8 (a)

Graph of Q vs. temperature at the resonance of 9.8 GHz

Figure 6.8 (b)

Graph of Q vs. temperature of 1st resonance zoomed in the superconducting range

Figure 6.9 (a)

Graph of Q vs. temperature at the resonance of 17.5 GHz

Figure 6.9 (b)

Graph of Q vs. temp. of 2nd resonance zoomed in the superconducting range

From the above 2 graphs it can be seen that there is a significant change in the Q factor as a function of temperature, below the critical temperature. There is a distinct and abrupt change in the quality factor at the critical temperature where the material becomes superconductor. The Q values continue to increase as the temperature is lowered but the change is much lesser.

6.5 Re-entrant Cavity using YBCO superconductor:

As it was shown in the previous chapter, the use of re-entrant cavity drastically lowered the resonant frequency of the cavity having the same internal outer dimensions. But the main hindrance in using the re-entrant structure using normal conductors was that the structure was very lossy and hence the quality factor of the filter was drastically lowered. This is a serious deterrent in the use of a re-entrant cavity as a filter. In addition to drastically lowering the resonant frequency, the presence of the center post reduced the Q factor of the cavity. The problem can be remedied by replacing either the center post with a superconducting post or completely build the re-entrant cavity from SMG HTS.

There are two ways in which the superconductor can be used to manufacture the re-entrant cavity. Either the entire structure can be machined from a single superconducting crystal or just the inner post can be made of superconducting material. In order to prove the workability of the concept, we have conducted both experiments, one using the superconducting material only for the central post and the other using a complete structure of superconducting material.

6.6 Re-entrant Cavity with a Superconducting Cylindrical Post:

A re-entrant post was fabricated. The dimensions of the post were different from the actual requirements. So, we simulated the device according to the available structure and the results of simulation and experiments are given below.

Outer Cavity Radius (a) = 15 mm

Height of Cavity (h) = 10 mm

Height of Inner Post = 8.5 mm i.e. $g = 1.5$ mm

Radius of Post (b) = 8 mm

The simulation results are given in Figure 6.10. The corresponding measured sample data at room temperature and at 80K are shown respectively in Figures 6.11(a) and 6.11(b)

Figure 6.10

The simulated re-entrant cavity filter with superconducting post

Figure 6.11 (a)

The re-entrant cavity with superconducting post at room temperature

Figure 6.11 (b)

The re-entrant cavity with superconducting post at 80K

Following data was obtained from the experiments:

The resonance frequency of the cavity is (f_r) = 4.42 GHz

At room temperature, Quality Factor (Q) = 1826.47

At superconducting temperature of 80K, Quality Factor (Q) = 4528.77

As can be seen from the graphs of figures 6.11 (a) and (b), there is a distinct change in the S_{11} characteristic. The resonance becomes sharper and hence has been magnified over a smaller range of calibration to be able to see it clearly. The data from the graph is analyzed and we can see from the Q values obtained that there is a sharp change in the quality factor of the device at the lower temperature. Thus it is seen that if the re-entrant post becomes superconducting, the losses in the structure are reduced and the Q factor increases significantly.

6.7 Complete Superconducting Re-entrant Cavity Filter:

After the experiment verified that the superconducting post in the cavity drastically improved the filter characteristics, a set of HTS re-entrant cavities were fabricated and tested to verify that the results for re-entrant cavities are consistent. These devices had the following dimensions.

Outer Cavity Radius (a) = 11 mm

Height of Cavity (h) = 10 mm

Height of Inner Post = 8.5 mm i.e. $g = 1.5$ mm

Radius of Post (b) = 7 mm

Figure 6.12 shows the simulated results assuming infinite conductivity for the cavity walls.

Figure. 6.12

Simulation Results of the superconducting re-entrant cavity

Figure 6.13 (a)

The re-entrant cavity filter at room temperature

Figure 6.13 (b)

The re-entrant cavity filter with superconductor at a temperature of 80 K

Figures 6.13(a) and 6.13(b) show the measured S parameters at room temperature and at 80K respectively.

The experimental results were:

Frequency of resonance is: 3.185 GHz

Quality Factor of the Filter at room temperature is: 2617.87

Quality factor of the Filter at 80 K is: 6388.54

Thus from both experiments, it was seen that the re-entrant cavity resonator has very high quality factors at low temperatures provided that superconducting material is used for the complete cavity. It is also seen that if the entire filter structure is made of superconducting material, there is a 40% more increase in the quality factor than it is when only the inner post is superconducting.

Chapter 7

Broadband Filter

In most practical filter applications, the filters used are required to be broadband and in general tunable. In a cavity filter, a broadband filter structure is achieved by coupling a number of cavities together which produces a broader pass-band. In this chapter, the theory of coupled cavity filters is discussed in brief and a coupled cavity design is proposed for the re-entrant cavity filter to make it usable in broadband applications. The design is simulated and results are provided, but the actual fabrication was not done.

7.1 Coupling Theory:

Just like a probe or a loop feed, aperture coupling can be used in excitation of waveguides and other transmission lines. The coupling theory through irises was first developed by Bethe in MIT Radiation Laboratory. Using the theory one can calculate the scattering of power by small irises and in a reverse manner, one can then calculate the location and dimension of irises when the amount of power to be transmitted is known.[21] The theory is perfectly applicable to waveguides in which the iris is located far from any sharp corner and the radius of curvature is large as compared to the

wavelength. The theory was later modified by Cohn and developed to be applicable in more generic cases.[22][23]

It is seen that a small aperture which lets the energy leak from one waveguide to another causes similar fields to be induced in the other waveguide. An intuitive explanation for the coupling phenomenon can be given by representing the aperture as an infinitesimal electric and/or magnetic dipole. This is valid based on the assumption that the size of the coupling aperture is very small as compared to the wavelength of the field.[24] The coupling theory discussed below is based on these phenomenological assumptions.

Consider a conducting wall separating two waveguides as shown in the figure 7.1(a). If a small aperture is cut into the conductor, the electric /magnetic field lines will fringe through the aperture as shown. The field formed on the other side of the wall will be such that polarization currents are in opposite direction. Hence an aperture excited by a normal electric field can be represented as two oppositely directed infinitesimal electric polarization currents, P_e , normal to the closed conducting wall.

$$\bar{P}_e = \epsilon_0 \alpha_e \hat{n} E_n \delta(x - x_0) \delta(y - y_0) \delta(z - z_0) \quad \dots\dots (7.1)$$

where,

α_e is defined as the dielectric polarizability of the aperture and

(x_0, y_0, z_0) are co-ordinates of the center of aperture

Figure 7.1 (a)

Similarly, magnetic lines parallel to a conducting wall with an aperture also fringe through the aperture producing a similar magnetic field on the other side of the conducting wall (Figure 7.1(b)). The magnetic field is such that the two magnetic polarization currents are parallel to the wall and in the opposite direction. Hence the polarization current is given as

$$\vec{P}_m = \alpha_m \vec{H}_t \delta(x - x_0) \delta(y - y_0) \delta(z - z_0) \quad \dots (7.2)$$

Figure 7.1 (b)

Now, for an aperture which couples the energy between two circular waveguide cavities along their longitudinal walls, the electric and magnetic polarization currents will be given by

$$\bar{P}_e = \varepsilon_0 \alpha_e E_z \hat{a}_z \quad \dots\dots (7.3)$$

$$\bar{P}_m = \alpha_m (H_y \hat{a}_y + H_x \hat{a}_x) \quad \dots\dots (7.4)$$

The electric and magnetic polarizability of the aperture are constants that depend on size and shape of the aperture and have been derived for a variety of simple shapes.[21]

For a round hole aperture,

$$\alpha_e = \frac{2r_0^3}{3} \quad \dots\dots (7.5)$$

$$\alpha_m = \frac{4r_0^3}{3} \quad \dots\dots (7.6)$$

From Cohn's theoretical model [Reference], we have

$$|s_{12}|^2 = \frac{64\pi^2 \alpha_m^2}{9R^4 \lambda_g^2} \quad \dots\dots (7.7)$$

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\lambda / 3.41r_0\right)^2}} \quad \dots\dots (7.8)$$

In our case, we want all the power to be transferred from the first cavity to the second cavity. Hence s_{12} should be maximum i.e. $|s_{12}| = 1$. Solving the equations 7.7 and 7.8 for the value of r_0 , we get the radius of the iris. The location of the iris is best at the center of height of the cavity i.e. 5mm from the top surface, so that it is farthest from any sharp corners.

7.2 Simulation Results:

The above theoretical deductions were then simulated to verify the workability of the concept. Shown below is the structure simulated in HFSS for a coupled re-entrant cavity.

Figure 7.2

Coupled Re-entrant Cavity Resonator

The two cavities are exactly the same in structure and if the coupling is adequate, they should resonate at the same frequency. The S_{11} characteristic of the simulation is shown in Figure 7.3. From the simulation we can see, that there is only one sharp

resonance, hence the two cavities resonate at the same frequency. The S_{12} characteristic is shown in green color.

Figure 7.3

Scattering parameters, S_{11} and S_{12} of a coupled re-entrant cavity system.

For practical applications, the filter has to be broadband and its typical characteristics are shown in Figure 7.4..

Figure 7.4

Typical Bandpass Filter Characteristics

In order to achieve such a broadband characteristic of the filter, we can make the two cavities resonate at slightly different frequencies from each other. This can be done by using a tuning screws in both of the cavity structures.[25] The screws can be used to tune the cavities as well as offset one of the cavity resonant frequencies to provide a band pass type characteristic. The simulation for such a system is shown on in Figures 7.5(a) and 7.5(b).

We can see that the S_{12} characteristics of the coupled re-entrant cavity filter are similar to the bandpass filter characteristics. The practical bandpass filter can be made of multiple such cavities for wideband characteristics.

Fig. 7.5(a)

s_{11} for the tunable coupled cavity resonator

Fig 7.5(b)

s_{12} for the tunable coupled cavity resonator

Chapter 8

Conclusion and Suggestions for Further Work

In this thesis, we have successfully proved that the re-entrant cavity structure can be used to reduce the bulky size of the cavity filter. We have also shown that with the use of a superconducting material, the filter characteristics can be highly improved and a filter with a very high selectivity can be achieved. We have then proposed a design for a wideband filter using a coupled re-entrant cavity structure.

We could not test the working of a wideband filter design, because of lack of availability of time and resources. This work will be further pursued by another graduate student who can probably come up with some additional changes in the design to make the filter more interesting from the view of practical usability.

The immediate practical usability of the device is limited by the availability of high T_c superconductors. Also, the cryogenic coolers required for the material to become superconducting, make the system quite bulky and costly. We hope that with future progress in superconductivity research, the device will find valuable commercial applications.

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Appendix A

Matlab program for theoretical calculation of frequency of resonance of a cylindrical cavity:

```
p = [2.4048 5.5200 8.6537 11.7951; 3.8317 7.0155 10.1743 0; 5.1356 8.4172 11.6198 0;  
6.3801 9.7610 0 0; 7.5883 11.0647 0 0; 8.7714 0 0 0; 9.9361 0 0 0; 11.0863 0 0 0];
```

```
p1 = [3.8317 7.0156 10.1735 13.3237; 1.8412 5.3314 8.5363 11.7060; 3.0542 6.7061  
9.9695 0; 4.2012 8.0152 11.3459 0; 5.3175 9.2824 0 0; 6.4156 10.5199 0 0; 7.5013  
11.7349 0 0; 8.5778 0 0 0; 9.6474 0 0 0; 10.7114 0 0 0; 11.7709 0 0 0];
```

```
ur = 1  
er = 1  
c = 3.0e8;  
a = 1.0e-2;  
d = 1.0e-2;
```

```
val1 = c/((2*pi)*sqrt(ur*er))
```

```
for l=0:6  
    for n=1:7  
        for m=1:4  
            val2(n,m) = sqrt((p(n,m)./a)^2 + (l*pi/d)^2);  
        end  
    end  
    l,f = val1*val2  
end
```

```
for l=0:6  
    for n=1:10  
        for m=1:4  
            val3(n,m) = sqrt((p1(n,m)./a)^2 + (l*pi/d)^2);  
        end  
    end  
    l,f1 = val1*val3  
end
```

Appendix B

Matlab program for calculation o Q-factor from experimental data:

```
load amplitude.txt -ASCII;

amplitude(:,4) = 20.*log10(sqrt(((amplitude(:,2)).^2) + ((amplitude(:,3)).^2)));

plot (amplitude(:,1),(amplitude(:,4)))

Dm = min(amplitude(:,4))

hold;

beta1 = (1 + 10^(Dm/20))./(1 - 10^(Dm/20))%Overdamped

beta2 = (1 - 10^(Dm/20))./(1 + 10^(Dm/20))%Underdamped - The center freq lies in
between in phase resp

Do = 20.*log10(sqrt((2-2.*beta2+(beta2)^2)./(2+2.*beta2+(beta2)^2)))

DL = 20.*log10(sqrt((1+(beta2)^2)./((1+beta2)^2)));

[m,n]=size(amplitude);

for p=1:1:m

    if amplitude(p,4)==Dm

        fc=amplitude(p,1)

    end

end

amplitude(:,5)=abs(amplitude(:,4)- Do);

mo = min(amplitude(:,5));

for p=1:1:m

    if amplitude(p,5)==mo
```



```

        fo=amplitude(p,1)
    end
end

deltafo = 2*abs(fc-fo)

amplitude(:,6)=abs(amplitude(:,4)- DL);
mL = min(amplitude(:,6));
for p=1:1:m
    if amplitude(p,6)==mL
        fL=amplitude(p,1)
    end
end

deltafL = 2*abs(fL-fo)

Qo=fc/deltafo

QL=fc/deltafL

```