Salahaddin Universit

Salahaddin University –Erbil

# Microwave Bandpass Filter Design Based on waveguide cavity Resonator

## The Graduated Research Project

is submitted to the department of Physics in partial fulfilment of the requirements for the degree of Bachelor of Science in physics

**By:**

Shawbo kazm

**Supervised by:**

Assistant Professor Dr. Rashad Hassan Mahmud

# Abstract

There are many theories presented in the literature to make a Bandpass Filter, one of which is designed by a waveguide cavity resonator. The waveguide is commonly referred as a piece of hollow pipe guiding electromagnetics energy. The objective of the project is to utilize waveguide cavity resonators to design Bandpass Filters operating at the X-band Frequencies. An example of Bandpass, which is based on the 3rd cavity resonators, is investigated in this graduated research project. The method used to obtain the external quality factor and coupling coefficient of cavity resonators is discussed.

# Chapter one

The term microwave refers to alternating current signal with frequencies between 300MHz and 300GHz (Pozar, 2011), with a corresponding electrical wavelength between $\lambda$=1m and $\lambda$=1mm. In today's world, microwave technologies are widely used in communication systems, radar systems, environmental remote sensing and medical systems. Microwave communication systems are developing quickly as they offer many advantages in comparison to conventional wireless device, i.e., light weight, compact, low cost (Oliner, 1984).

A microwave Bandpass Filter (BPF) is a transition device, or transducer, between a guided wave from point (a) to point (b). It is useful in many applications, i.e. high-speed aircraft (Kraus, 1988), high-performance radar and communication systems.

In this project, a 3rd order waveguide BPF is simulated, and designed. The BPF is a two-port network which can provide transition with the passband and attenuation in the stop band of the filter. The design of the BPF is based on the principles of Chebyshev filter design, allows a combination of the design process of a BPF based on three cavity resonators.

**Figure 1.1:** An Actual photo of a waveguide Bandpass Filter (Rohde and Schwarz, 2023).

The waveguide BPF can be used as a receiver in the communication system on satellites and base station. Currently, many of the receiving systems are designed with separate receiving BPF. The new concept of combining BPF with other microwave circuits may be able to update the current technology in space communication.

This report is structured as follows. In the next section, some electromagnetic theory (i.e. waveguide theory, definition of quality factor, coupling theory) will be reviewed and two measurement methods will be discussed. This is followed by an introduction to the measurement of quality factors and coupling coefficients of cavity resonators. Next a detailed description of a 3rd order Chebyshev filter design will be presented and the framework of a Chebyshev filter is reviewed.

Then an example of 3rd order waveguide BPF is given and its frequency response and its performance are discussed. This report concludes with the limitations of this design and suggestions for future development.

# Chapter Two

# Literature Review

The design of the waveguide BPF in this project is based on a Chebyshev response. In this chapter, some important background knowledge for Chebyshev filters and waveguides are introduced. Also, two microwave measurement methods are included as a preparation for the measurement methods used in the following chapters.

## 2.1 Waveguide and Transmission Line

Transmissions lines are the interconnection convey electromagnetic energy from one point to another (Kraus et, al, 1999) they may include coaxial, two-wire, strip, microstrip, and waveguide. In a broad sense, a wireless link can also be considered as a transmission line. Compared with other types of transmission system, waveguides will not transmit low frequency energy with extremely high transition from one condition to the other (Kraus et al, 1972). A rectangular waveguide shown in Figure 2.1 is a hollow rectangular conducting structure of width (*a*) and height (*b*), where *a*≥*b* (Pozar, 2011).

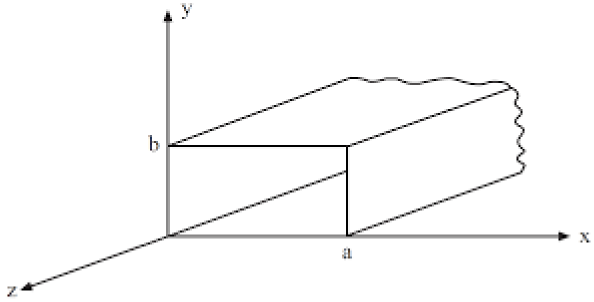


**Figure 2.1**: Coordinates for Hollow rectangular waveguide.

The critical frequency at which transmission is no longer possible is called the cut-off frequency (Kraus et al, 1999).The cut-off frequency can be developed in rectangular coordinates (figure 2.1) which is:

$$f_c = \frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad (1)$$

Where (*m*) is the number of half –cycle variations of field in X direction, (*n*) is the number of half-cycle variation of field in Y direction.

The cut-off frequency corresponds to the cut-off wavelength of a waveguide, given by:

$$\lambda_c = \frac{c}{f_c}\frac{2\pi}{\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2}} \qquad (2)$$

It is an important property of the waveguide that TE-mode wave will not be transmitted through the rectangular waveguide unless the wavelength is sufficiently short.

In this report, the waveguide is designed in the microwave region of X-band. The frequency region specified by IEEE is 8GHz to 12GHz. The standard waveguide used for the X-band is WR90, with dimensions *a*=22.86mm and *b*=10.16mm. Thus, the guide wavelength should be:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}} = 39.76 \text{ mm} \qquad (3)$$

Where $\lambda_0$ is the free-space wavelength of plane waves at the frequency of $f=\omega/2\pi$. In comparison to transmission lines and waveguides, whose function is to transmit electromagnetic energy efficiently, a resonator, on the other hand, aims at storing energy (Kraus, 1999). An effective way in analysing a cavity resonator is to use its equivalent circuit model, where a parallel or series connected capacitor and inductor can form a resonant system to simulate the conditions in cavity resonators. At low frequencies, the interconnection of resistors, capacitors and inductors result in a circuit, which are normally linear. At microwave frequencies, equivalent reactive and resistive elements may also be connected to form a microwave circuit. Many of the circuit analysis techniques and circuit properties that are valid at low frequencies are also valid for microwave circuits (Pozar, 2011). In this report, most of the analyses and calculations are based on their equivalent circuit model.

## 2.2 Quality factors (Q)

In physics, a quality factor (Q) generally characterizes the ratio of the centre frequency of a resonator to its bandwidth (or equivalent). It is defined as (Lancaster, 1997)

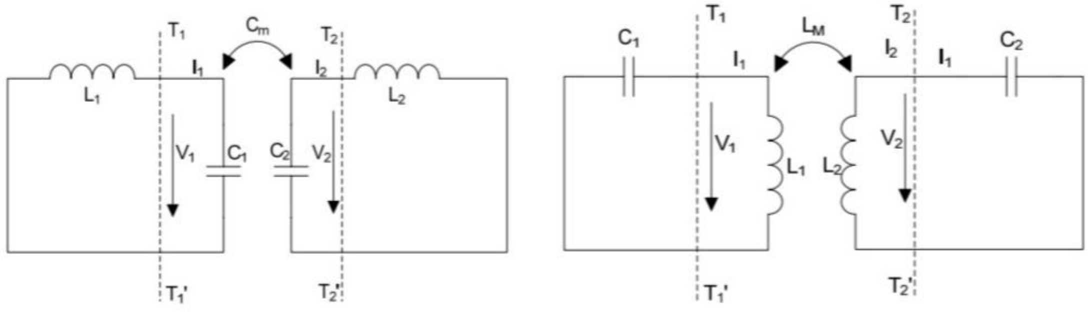
$$Q = \omega \frac{Energy\ stored\ in\ the\ cavity}{Average\ Power\ Loss} \qquad (4)$$

Quality factor of a resonator or filter is to extract information about how the cavity is constructed. Regardless of the cavity type, only the measurement of Q and resonant frequency is of interest (i.e. the unloaded quality factor $Q_0$). The power loss of a cavity may come from a lot of mechanisms, which may come from: a) conduction currents in walls $Q_c$; b) Dielectric loss due to the dielectric within the cavity $Q_d$; c) radiation when the cavity is not fully enclosed $Q_r$. The following equation represents the relations between these factors,

$$\frac{1}{Q_0} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} \qquad (5)$$

## 2.3 Coupling Coefficient ($M_{12}$)

In general, the coupling coefficient of microwave resonators can be defined on the basis of the ratio of coupled energy to stored energy (Hong et al, 2001). The result of the coupling will have either positive sign or negative sign. A positive sign shows that the coupling enhances the stored energy of the uncoupled resonators, whereas a negative sign indicates a reduced stored energy. In order to simplify the calculation, the coupling coefficient will discussed in lumped-element circuit; the conclusion can also be applied to microwave resonators. There are two kinds of couplings in lumped-element circuit, i.e., electric coupling and magnetic coupling (Hong et al, 2001).



a) *Electric Coupling* b) *Magnetic Coupling*

**Figure 2.2** Equivalent circuits of electric coupling and magnetic coupling (Pozar, 2010).

In the condition of both electric and magnetic coupling, assume the resonant frequencies of the uncoupled resonator are $\omega_{01}$ and $\omega_{02}$, respectively, then the universal formulation of the coupling coefficient in electric and magnetic coupling

$$M_{12} = \mp \frac{1}{2}\left(\frac{\omega_{02}}{\omega_{01}} + \frac{\omega_{01}}{\omega_{02}}\right)\sqrt{\left(\frac{\omega_2^2-\omega_1^2}{\omega_2^2+\omega_1^2}\right)^2 - \left(\frac{\omega_{02}^2-\omega_{01}^2}{\omega_{02}^2+\omega_{01}^2}\right)^2} \qquad (6)$$

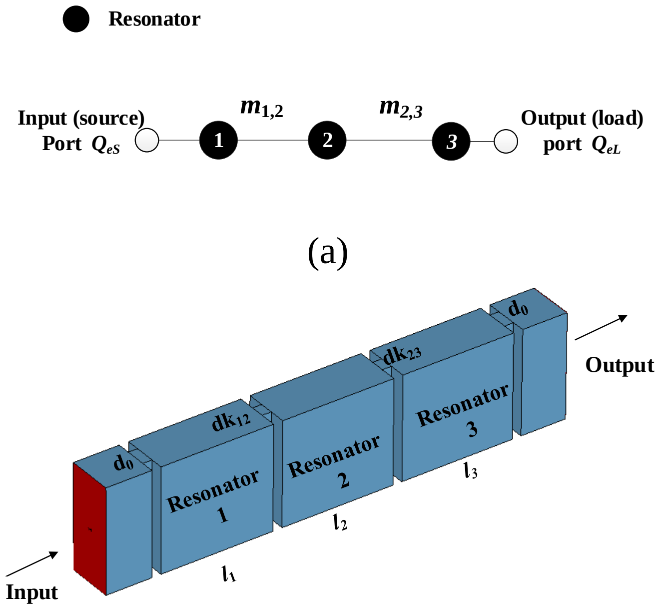
# Chapter Three

# Bandpass Filter Design

In this chapter, the design of the 3rd order BPF based on waveguide is presented. Some formulas used to extract the physical dimensions of the BPF are given. The simulated results of the 3rd order BPF is discussed and analysed.

## 3.1 Design of the 3rd order BPF

This section exhibits the topology and physical configuration of the proposed 3rd order BPF as shown in Fig. 3.1. It can be seen in the Fig. 3.1 (a), the topology consists of three resonators coupling with each other inline. The physical configuration of the proposed BPF is based on three rectangular waveguide cavity resonators which they are coupled with each other via capacitive irises. In the followings, the techniques used to extract the physical dimensions of the BPF are discussed.



(a)

(b)

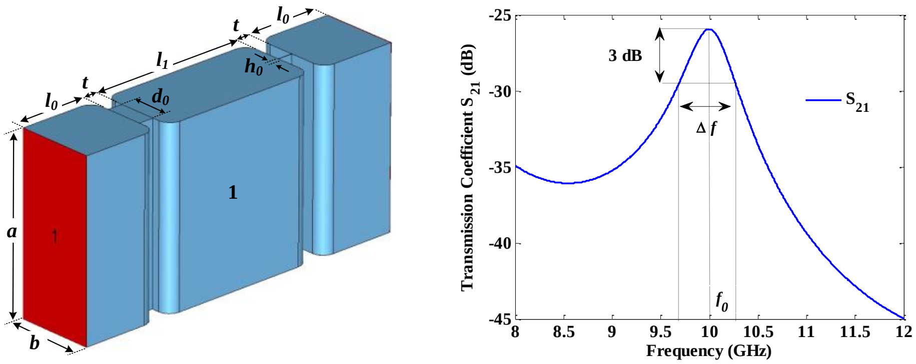
**Figure 3.1** The proposed BPF. **(a)** Topology. **(b)** Physical configuration.

### 3.1.1 $d_0$ Extraction

To extract the initial $d_0$ value of the BPF, a rectangular cavity modeled in CST and shown in Fig. 3.2 (a) is utilized. It is coupled to the input port from one side via an iris with dimension $d_0$, and the other side is weekly coupled to the output port via the iris ($h_0$=0.04 mm). The simulated transmission coefficient ($S_{21}$) response of the cavity given in Fig. 3.2 (b) can be used to determine the quality factor $Q_{es}$ and then find $d_0$ value using the relation (Lancaster, 2004):

$$Q_{es}= \frac{f_0}{\Delta f_{3dB}} \tag{7}$$

Here $f_0$ is the resonant frequency. $\Delta f_{3dB}$ is the 3-dB *FBW*. It is found that when $d_0$ =2.95 mm, the $Q_{es}$ is equal to the calculated value (i.e. $Q_{es}$ =8.516). A parametric data base to determine the desired Qes which is equivalent to the d0 dimension is presented in Table 3.1. It can be noticed from the table, the larger $d_0$ value the smaller $Q_{es}$ is resulted. This is confirmed in Fig. 3.3.



(a) (b)

**Fig. 3.2**. (a) Single cavity modeled in CST to extract the initial $d_0$ value. (b) The simulated response.

**Table 3.1: relationship between the $Q_{es}$ and $d_0$ values.**

| $d_0$ (mm) | $f_0$ (GHz) | $l$ (mm) | $BW$ (GHz) | $Q$ |
|---|---|---|---|---|
| **1.8** | 10 | 21.73 | 1.172 | 8.532423208 |
| **2** | 10 | 21.86 | 1.1728 | 8.526603001 |
| **2.2** | 10 | 21.97 | 1.1732 | 8.523695875 |
| **2.4** | 10 | 22.09 | 1.17368 | 8.520209938 |
| **2.6** | 10 | 22.2 | 1.17392 | 8.518468039 |
| **2.8** | 10 | 22.3 | 1.174 | 8.517887564 |
| **2.95** | 10 | 22.355 | 1.17426 | 8.516001567 |
| **3** | 10 | 22.37 | 1.17427 | 8.515929045 |
| **3.2** | 10 | 22.46 | 1.174295 | 8.515747747 |
| **3.4** | 10 | 22.55 | 1.1743 | 8.515711488 |
| **3.6** | 10 | 22.64 | 1.17432 | 8.515566455 |
| **3.8** | 10 | 22.71 | 1.17439 | 8.515058882 |

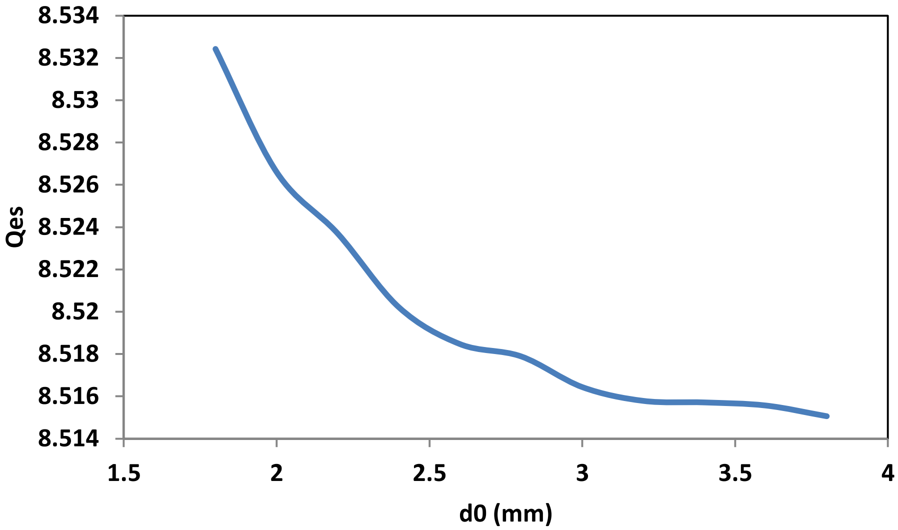


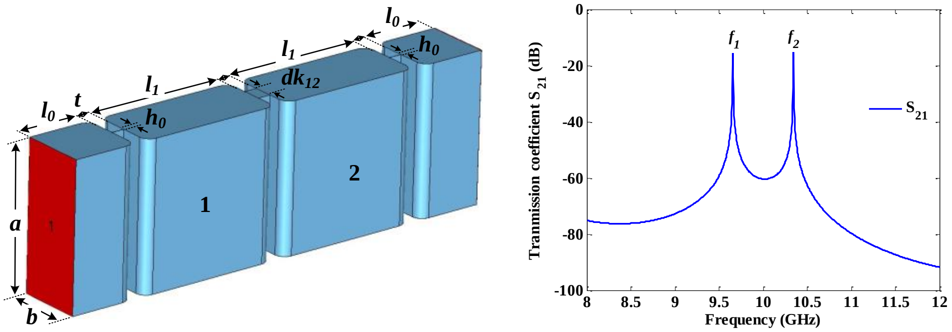
**Figure 3.3**: the relationship between the $d_0$ and $Q_{es}$.

### 3.1.2 $dk_{12}$ Extraction

To extract the initial $dk_{12}$ value, the structure shown in Fig. 3.4 (a) is utilized. It consists of two resonators coupled to each other via the capacitive iris with dimension $dk_{12}$. On the other sides, they are weekly coupled to the electrical ports. In the $S_{21}$ response of the structure given in Fig. 3.4 (b), two identifiable resonance frequencies ($f_1$, $f_2$) can be observed. They can be used to obtain the $M_{12}$, $M_{23}$, and then find the $dk_{12}$ value using the following relation (Lancaster, 2004):

$$M_{12} = \frac{{f_2}^2 - {f_1}^2}{{f_2}^2 + {f_1}^2} \tag{3}$$

It should be mentioned that the $dk_{12}$ dimension controls the frequency positions of $f_1$ and $f_2$. It is found that when $dk_{12}$ = 2.95 mm, the $M_{12}$ is equal to the calculated value (i.e. $M_{12}$=0.1031). In table 3.2, the relationship between the *dk*12 and $M_{12}$ is presented. A proportional relationship between $dk_{12}$ and $M_{12}$ is noticed. This is confirmed by Fig. 3.5.



(a) (b)

**Figure 3.4:** (a) Two cavities modeled in CST to extract the initial $dk_{12}$ value. (b) The simulated response.

**Table 3.2: relationship between the $d_{k12}$ and $M_{12}$ values.**

| d$k_{12}$ (mm) | *l* (mm) | $f_1$ (GHz) | $f_2$ (GHz) | $f_0$ (GHz) | $M_{12}$ |
|---|---|---|---|---|---|
| **1.8** | 23.05 | 9.65 | 10.35 | 10 | 0.069914 |
| **2** | 23.15 | 9.62 | 10.38 | 10 | 0.07589 |
| **2.2** | 23.25 | 9.6 | 10.4 | 10 | 0.079872 |
| **2.4** | 23.38 | 9.56 | 10.44 | 10 | 0.08783 |
| **2.6** | 23.52 | 9.53 | 10.47 | 10 | 0.093793 |
| **2.8** | 23.64 | 9.5 | 10.5 | 10 | 0.099751 |
| **2.95** | 23.735 | 9.4826 | 10.5174 | 10 | 0.10310 |
| **3** | 23.75 | 9.48 | 10.52 | 10 | 0.10372 |
| **3.2** | 23.85 | 9.45 | 10.55 | 10 | 0.109668 |
| **3.4** | 23.95 | 9.43 | 10.57 | 10 | 0.113631 |
| **3.6** | 24.04 | 9.41 | 10.59 | 10 | 0.117591 |
| **3.8** | 24.15 | 9.38 | 10.62 | 10 | 0.123525 |
| **4** | 24.25 | 9.37 | 10.63 | 10 | 0.125502 |

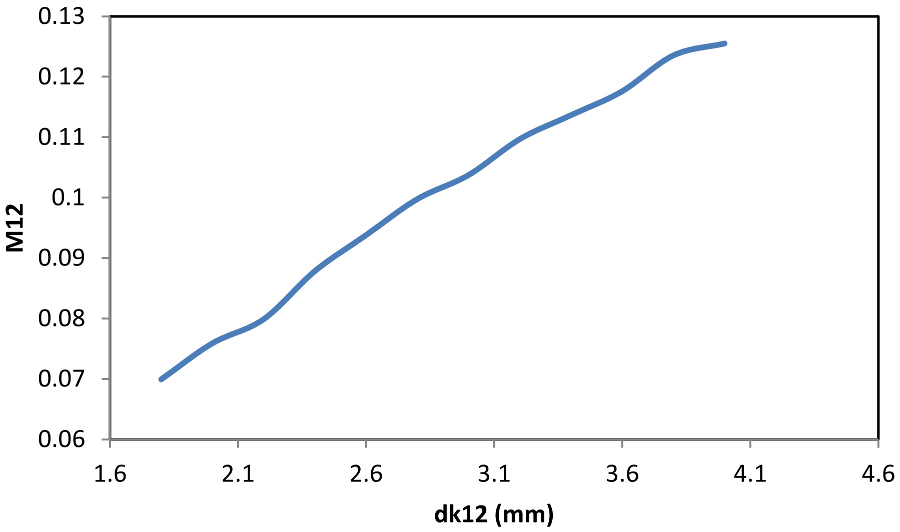


**Figure 3.5**: the relationship between the $M_{12}$ and $d_{k12}$.

## 3.2 Results

This section presents the simulated results of the proposed BPF shown in Fig. 3.1. The results are obtained using the commercial electromagnetic simulator (CST) studio. The physical dimensions of the BPF are obtained using the relations given in sections 3.1 and 3.2.

Fig. 3.6 shows the initial simulated results of the proposed BPF. It can be seen that there are three poles within the passband which goes back to the three cavities employed in the design. The BPF has extremely bandwidth which is useful for modern wireless communication system.

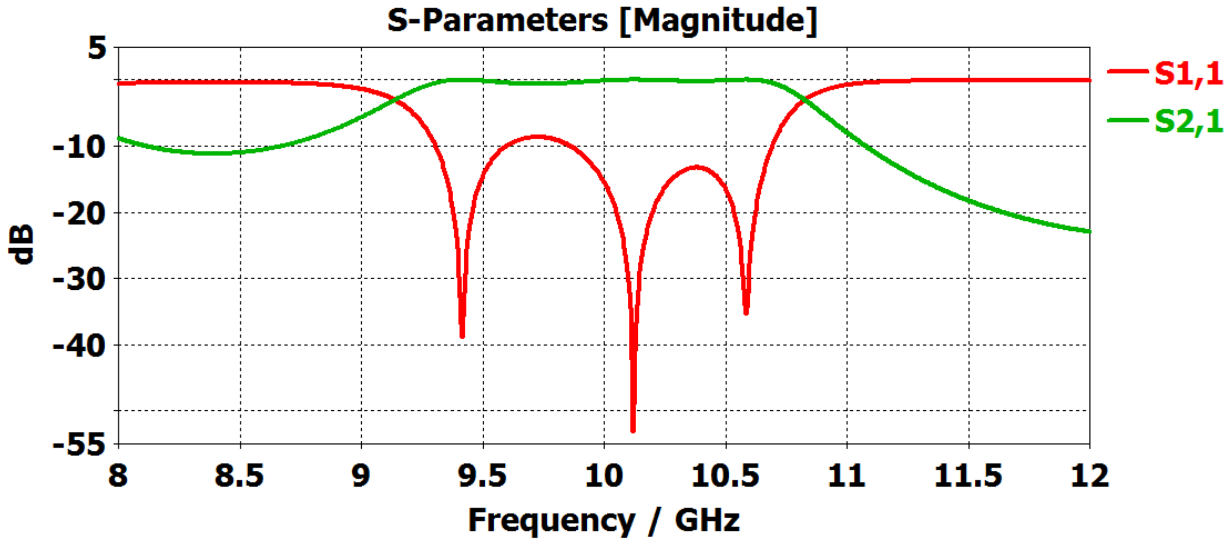


**Figure 3.6**: The $S_{11}$ and $S_{21}$ response of the proposed BPF.

# Chapter Four

# Conclusions and Future Works

## 4.1 Conclusions

In this graduated research project, it has been found that the development of microwave components is speeding up daily. This goes back to the demands of the uses to exchange information in a very short period of time. To meet this, the component of the system such as BPF is to provide the large bandwidth. In this project, a BPF based on rectangular cavity resonator is introduced. The results are promising.

## 4.2 Future Works

During this graduated research project, it has been found that only the enhancement of BPF bandwidth helps the system users to exchange information quickly, but also other components like antennas and amplifiers should have large bandwidths. Thus, in the future, the technique presented in this project can be used for other components like antennas and amplifiers.

## References

- Pozar, D.M., 2011. *Microwave engineering*. John wiley & sons.
- Oliner, A.A., 1984. Historical perspectives on microwave field theory. *IEEE Transactions on Microwave Theory and Techniques*, *32*(9), pp.1022-1045.
- Leschhorn, R. and Buchin, B., 2004, November. Military software defined radios-rohde and schwarz status and perspective. In *Proceedings of the SDR* (Vol. 4).
- Kraus, John. (1988) *Antenna (2nd edition)*. New York: McGraw-Hill, pp. 17-85, 624-660.
- Kraus, John., Carver, Keith. (1973) *Electromagnetic (2nd edition)*. New York: McGraw-Hill, pp. 482-600.
- Kraus, John., Fleisch, Daniel. (1999) *Electromagnetics: with applications (5th edition)*. Singapore: McGraw-Hill, pp. 119-166, 247-343, 447-500.
- Lancaster, Michael. (1997) *Passive microwave device applications of high-temperature superconductors*. Cambridge: Cambridge University Press, pp. 67-142.
- Hong, Jia-Sheng., Lancaster, Michael. (2001) *Microstrip filters for RF/microwave applications*. New York: John Wiley & Sons, pp. 235-272.