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Title:

Investigation of Multiband Microstrip Bandstop Filters with and without SMD Capacitors

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Abstract

This work presents the design of multiband bandstop filters (BSFs) based on defected ground structure (DGS) technique. The filters are loaded by surface-mount device (SMD) capacitors for dual and triple stopbands operated at 3.69/7.63 GHz and 3.2/5.56/7.28 GHz, respectively. An additional BSF structure without SMD capacitors operated at 3.77/7.16 GHz is as well designed and fabricated. Due to their satisfactory stopband performances, the proposed filters can be useful for various communication systems with dual and triple bands rejection for WiMAX/C bands.

Keywords: Bandstop filter (BSF), Multiband, Defected ground structure (DGS), Surface-mount device (SMD) capacitor, WiMAX/C bands.

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Thank you to all.

Ammar BOUKHALFA **Bilal MEKATI**

Dedication

This thesis is dedicated to:

My beloved parents Hocine and Fatima, my words are not enough to express my thanks to you, who continually provide their moral, spiritual emotional support and more.

To my brothers (especially Riadh),

my sisters (especially my littles Hana and Rania).

To my nieces and nephews,

My relatives (my cousin Fouad),

To all my dearest friends.

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To my partner in this work: Bilal

To all the people in my life who touch my heart.

May Allah protect you all.

And lastly, I thank Allah for the guidance, strength, power of mind, protection and skills and for giving me a healthy life.

And May Allah bless the Prophet Muhammad, his family and all his Companions.

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Dedication

First of all, I would like to thank « Allah » Almighty for his reconciliation in completing this graduation project. I would also like to thank my family and all those who love me for their support and help, especially my unique friend ^ Lounes ^ and my partner in this work ^ Ammar ^.

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List of Abbreviations

BSF	Band stop filter.
BW	Bandwidth.
BPF	Band pass filter.
HPF	High pass filer.
LPF	Low pass filter.
DGS	Defected ground structure.
DBBSF	Dual band band-stop filter.
TBBSF	Triple band band-stop filter.
EM	Electromagnetic.
IL	Insertion loss.
RL	Return loss.
MEMS	Micro electro mechanic system.
HTS	High temperature superconductor.
LTCC	Low-temperature co-fired ceramics.
CST	Computer simulation technology.
PCB	Printed circuit board.
VNA	Vector network analyzer.
FF	Filling factor.
GSM	Global system for mobile.
CDMA	Code Division Multiple Access
WLAN	Wireless local area network
LTE	Long term evolution.
WiMAX	Worldwide interoperability for microwave access.
GPS	Global positioning system.
TEM	Transverse electromagnetic.
VSWR	Voltage standing wave ration.
FBW	Fractional bandwidth.
IEEE	Institute of Electrical and Electronics Engineers.
RF	Radio frequency.
SIW	Substrate integrated waveguide.
EBG	Electromagnetic band gap.
PBG	Photonic band gap structure.
TF	Transfer function.
ITT	International telephone and telegram

List of Abbreviations

MMICs	Monolithic microwave integrated circuits.
LAN	Local Network Area.
Wi-Fi	Wireless fidelity.
SMD	Surface mount device.
SMT	Surface mount technology

List of symbols

W	Stripline Width.
t	Stripline thickness.
h	Substrate thickness.
ε_{eff}	Effective dielectric constant.
ε_r	Relative permittivity.
Z_0	Characteristic impedance.
Ω	Ohms.
λ_g	Guided wavelength.
λ_0	Free space wavelength.
f	Operation frequency.
β	Propagation constant.
π	Pi number.
v_p	Phase velocity.
c	Light velocity.
s	Seconds.
m	meters.
mm	millimeters.
l	Microstrip physical length.
θ	Electrical length.
C	Capacitance.
F	Farads.
μ	Micro (10^{-6}).
η	Nano (10^{-9}).
p	Pico (10^{-12}).
L	Inductance.
H	Henry.
L_{Wi}	Inductance per unit length.
S	Gap length
S_{ij}	S-parameter.
C_o	Odd-mode capacitance.
C_e	Even-mode capacitance.
C_p	Shunt capacitance.

List of symbols

Δ	Determinant.
Γ_S	Source reflection coefficient.
Γ_L	Load reflection coefficient.
w	Frequency variable.
Hz	Hertz.
F_{-3dB}	Frequency at 3dB attenuation point.
dB	Decibels.
P_{ref}	Reflected power.
P_{in}	Input power.
F_c	Center frequency.
Q	Quality factor.
f_{cutoff}	Cutoff frequency.
Y_0	Characteristic admittance of transmission line.
f_0	Mid-point frequency.
R	Resistance.

INTRODUCTION

Wireless communication has been rapidly developing in recent years. The evolution has started with Global System for Mobile Communications (GSM) and has proceeded to Wireless Local Area Network (WLAN), Worldwide Interoperability for Microwave Access (WiMAX), Code Division Multiple Access (CDMA), and the latest, Long Term Evolution (LTE) and Fifth Generation (5G).

A single device has the ability to work in multiple frequencies and support various wireless communications such as GSM, WLAN, WiMAX and LTE which is one of the requirements for global devices [1]. Today one can access data and voice anywhere at any time because of the RF/Microwave technology [2]. For that the wireless technology revolutionized by Radio Frequency (RF) and microwaves. In many RF/Microwave applications, Filters play irreplaceable roles. They are used to separate or combine different frequencies. The electromagnetic (EM) spectrum is limited and has to be shared, filters are used to select or confine the RF/Microwave signals within assigned spectral limits. Emerging applications such as wireless communications continue to challenge RF/Microwave filters with ever more stringent requirements, high performance, small size, light weight, easy to fabricate and low cost. Depending on the requirements and specifications, RF/Microwave filters may be designed as lumped element or distributed element circuits, they may be realized in various transmission line structures, such as waveguide, coaxial line and microstrip [3-8]. Bandstop filters have an important role in microwave and millimeter-wave systems, which are applied to discriminate the desired and unwanted signals.

The main purpose of this work is to design, analyze and implement compact microstrip BSFs for varied communication systems with dual and triple bands rejection for WiMAX/C bands. The used substrate material has a relative dielectric constant of 4.3, a thickness of 1.62 mm, a copper thickness 0.035 mm and a loss tangent of 0.017. The design and simulation are carried out using CST software (Appendix A).

The report is organized as follows:

A literature review of RF theory is presented in Chapter 1.

Chapter 2 introduces a brief theory of filter and common design methods. Moreover, defected ground structure (DGS) technique is also presented in this Chapter.

Chapter 3 investigates the design, implementation and measurement of simple microstrip BSFs with various bands based on DGS technique. The designed filters with using SMD capacitors are operated at 3.69/7.63 GHz and 3.2/5.56/7.28 GHz for dual and triple bands, respectively. The BSF structure without employing SMD capacitors operated at 3.77/7.16 GHz is as well designed. This chapter includes also the fabrication and measurement of some proposed filters. The process of implementation is carried out using an MITS Electronics PCB Prototyping machine while the measurement part is performed using a Rohde and Schwarz vector network analyzer (VNA).

Finally, a conclusion and some suggestions for future scope are presented.

Chapter 1

General RF theory

1.1 Introduction

A wide range of systems and applications incorporate RF, microwave and wireless devices and signals which are designed to operate at frequencies between 3 KHz and 300 GHz. They are used in the field of communication, such as GSM, WLAN, LTE, Bluetooth, WiMAX, satellite communication, space navigation and radar systems, require the frequency to be high.

This chapter mainly describes the general overview of this project. It explains basic concepts and design equations for microstrip line, S parameters and advantages and drawbacks of microstrip technology.

1.2 Microwave frequency bands

The descriptive term microwaves is used to describe electromagnetic wave with wavelengths ranging from 100 cm to 1 mm. The corresponding frequency range is 300 MHz to 300 GHz. Millimeter waves, which derive their name from the dimensions of the wavelengths (from 10 mm to 1 mm), can be classified as microwave since millimeter wave technology is quite similar to microwave technology. For convenience, microwave and millimeter wave are further divided into many frequency bands. Figure 1.1 [14] shows all microwaves bands and Table 1.1 shows the commonly used microwave bands.

Table 1. 1 Frequency bands and their usage [10].

Designation	Frequency Range	Wavelength Range	Typical Uses
L band	1 to 2 GHz	15 cm to 30 cm	Military telemetry, GPS, mobile phones (GSM), amateur radio
S band	2 to 4 GHz	7.5 cm to 15 cm	Weather radar, surface ship radar, and some communications satellites (microwave communications, radio astronomy, mobile phones, wireless LAN)
C band	4 to 8 GHz	3.75 cm to 7.5 cm	Long-distance radio telecommunications
X band	8 to 12 GHz	25 mm to 37.5 mm	Satellite communications, radar, terrestrial broadband, space communications

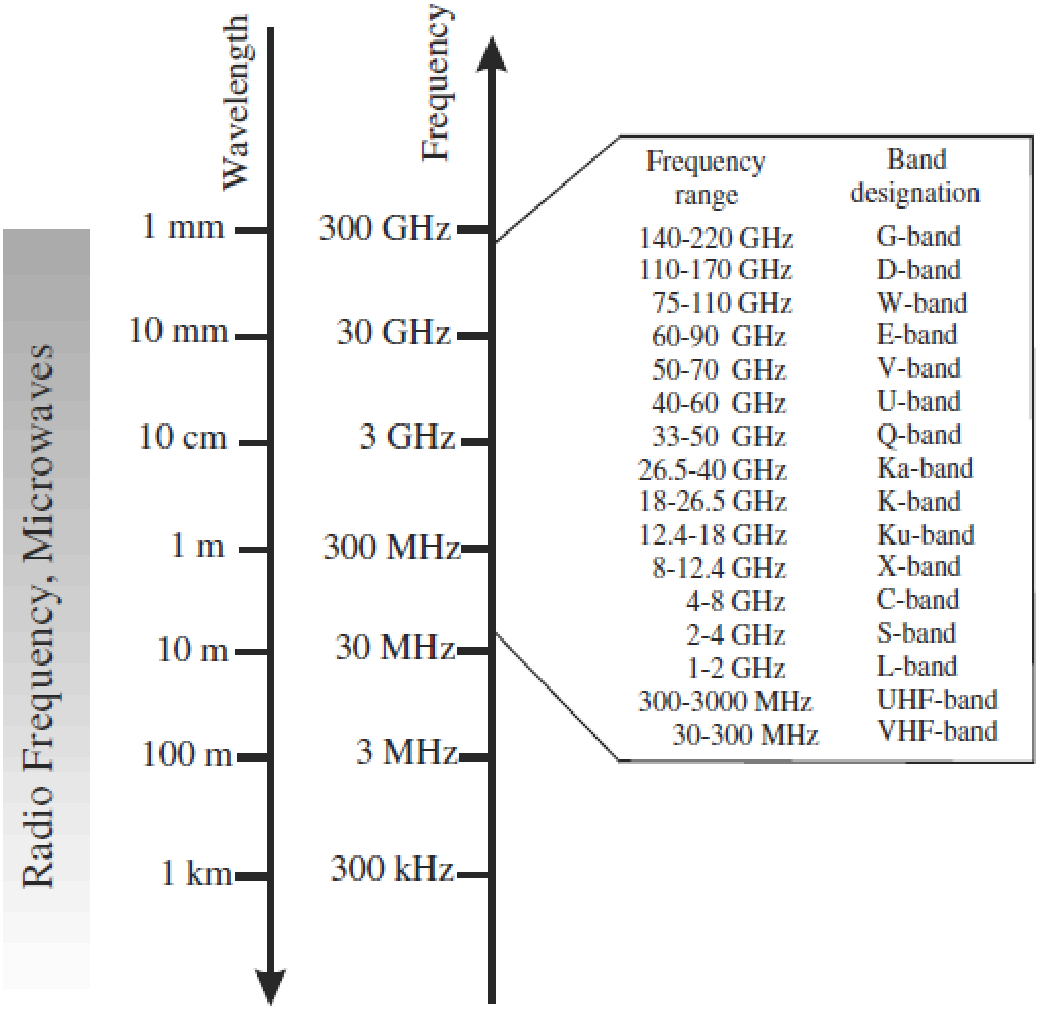

Figure 1. 1 RF/microwave spectrum

1.3 Transmission Lines

The connecting link between a source and a load is referred to as a transmission line. It is also defined as the path carrying alternating electrical energy from source to load. This connecting link consists mostly of two conductors (some have more, e.g., a three-phase power line) with the different types being coaxial lines, two-wire lines, waveguides, optical fibers, striplines, and microstrip lines. Each of these media has its own advantages and disadvantages [12] [13] [14]. Table 1.2 represents a comparison between some common transmission lines.

Table 1. 2 A comparison between some common transmission lines.

Characteristic	Coax	Waveguide	Stripline	Microstrip
Preferred mode	TEM	TE10	TEM	Quasi-TEM
Other modes	TE, TM	TE, TM	TE, TM	TE, TM
Dispersion	None	Medium	None	Low
Bandwidth	High	Low	High	High
Loss	Medium	Low	High	High
Power Capacity	Medium	High	Low	Low
Physical size	Large	Real large	Medium	Small
Fabrication ease	Medium	Medium	Easy	Real easy
Component integration	Hard	Hard	Fair	Easy

1.4. Microstrip line transmission

1.4.1 History of microstrip

Microstrip is a planar transmission line, similar to stripline and coplanar waveguide. Microstrip was developed by ITT Federal Telecommunications Laboratories in Nutley New Jersey, as a competitor to stripline (first published by Grieg and Engelmann in the December 1952 IRE proceedings). According to Pozar [15], early microstrip used thick substrates, which does not allowed TEM waves to propagate which makes results unpredictable. In the 1960s the thin version of microstrip became common.

1.4.2 Overview of microstrip

The general structure of a microstrip is illustrated in Figure 1.2. A conducting strip(microstrip line) with a width *W* and a thickness *t* is on the top of a dielectric substrate that has a relative dielectric constant ε_r and a thickness *h*, and the bottom of the substrate is a ground (conducting) plane.

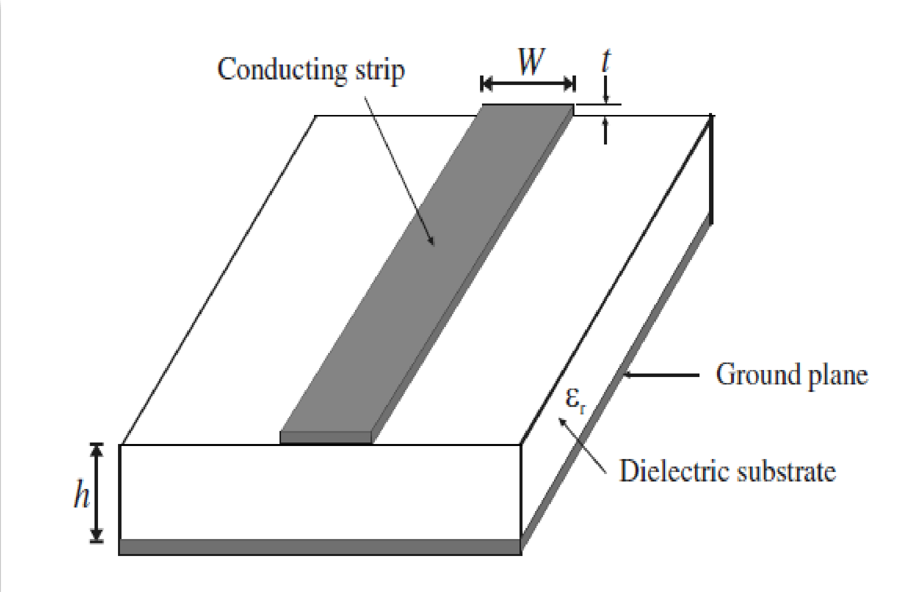

Figure 1. 2 Microstrip transmission line [14]

Microstrip does not support a TEM mode, because of its filling factor (Filling factor or FF is a measure of the percentage of the electrical fields in a transmission line that cross through the substrate [16]). For coupled lines, the even and odd modes will not have the same phase velocity. This property is what causes the asymmetric frequency of microstrip bandpass filters.

1.5 Analysis formulas

1.5.1 Effective dielectric constant

Because part of the fields from the microstrip conductor exists in air, the effective dielectric constant is somewhat less than the substrate's dielectric constant.

The effective dielectric constant, ε_{eff}, and the characteristic impedance, Z_0, of microstrip are respectively calculated by [17]:

- When (W/h) < 1

$$\varepsilon_{eff} = \frac{\varepsilon_r - 1}{2}\left[\left(1 + \frac{12h}{W}\right)^{-1/2} + 0.04\left(1 - \frac{W}{h}\right)^2\right] \tag{1.1}$$

and

$$Z_0(\Omega) = 60\left(\varepsilon_{eff}\right)^{-1/2} \ln\left(\frac{8h}{W} + \frac{W}{4h}\right) \tag{1.2}$$

- When (W/h) > 1

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1 + \frac{12h}{w}\right)^{-1/2} \quad (1.3)$$

$$Z_0(\Omega) = \frac{\left[120\pi(\varepsilon_{eff})\right]^{-1/2}}{\left(\frac{w}{h}\right)+1.393+0.667ln\left(1.444+\left(\frac{w}{h}\right)\right)} \quad (1.4)$$

1.5.2 Guided wavelength

Once the effective dielectric constant of a microstrip is determined, the guided wavelength of the quasi-TEM mode of microstrip is given by (for non-magnetic material) [13]:

$$\lambda_g(m) = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \quad (1.5)$$

where λ_0 is the free space wavelength at operation frequency *f*.

More conveniently, where the frequency is given in gigahertz (GHz), the guided wavelength can be evaluated directly in millimeters as follows [18]:

$$\lambda_g(mm) = \frac{300}{f\sqrt{\varepsilon_{eff}}} \quad (1.6)$$

1.5.3 Propagation constant

Propagation constant $\boldsymbol{\beta}$ is given by [15]:

$$\beta = \frac{2\pi}{\lambda_g} \quad (1.7)$$

1.5.4 Phase velocity

Phase velocity $\boldsymbol{v_p}$ is given by [15]:

$$v_p(m/s) = \frac{W}{\beta} = \frac{c}{\sqrt{\varepsilon_{eff}}} \quad (1.8)$$

where “c” is the light velocity in free space (c=3*10^8 m/s)

1.5.5 Electrical length

For a given physical length of a microstrip *l*, the electrical length is [5]:

$$\theta = \beta l \quad (1.9)$$

Therefore, $\theta = \pi/2$ when $l = \lambda_g/4$, and $\theta = \pi$ when $l = \lambda_g/2$. These so-called quarter-wavelength and half-wavelength microstrip lines are important for design of microstrip filters.

1.6 Microstrip discontinuities

All practical microstrip circuits contain discontinuities. These discontinuities are commonly encountered in the layout of practical filters, and they include: steps, open-ends, Bends, gap and T- junctions. Although such discontinuities give rise to only very small capacitances and inductances (often < 0.1 pF and 0.1 ηH) the reactances of these become particularly significant at the high microwave and millimeter wave frequencies [19].

1.6.1 Main discontinuities

There exist many types of discontinuities, among which we state:

a. Steps in width

For a symmetrical step, the capacitance and inductances of the equivalent circuit indicated in Figure1.2 may be approximated by the equation [3]:

$$C(pF) = 0.00137h\frac{\sqrt{\varepsilon_{eff1}}}{Z_{01}}\left(1-\frac{W_2}{W_1}\right)\left(\frac{\varepsilon_{eff1}+0.3}{\varepsilon_{eff1}-0.258}\right)\left(\frac{\frac{W_1}{h}+0.264}{\frac{W_1}{h}+0.8}\right) \quad (1.10)$$

$$L_1 = \frac{L_{W1}}{L_{W1}+L_{W2}}L \quad (1.11)$$

and

$$L_2 = \frac{L_{W2}}{L_{W1}+L_{W2}}L \quad (1.12)$$

$$L_{Wi} = \frac{Z_{0i}\sqrt{\varepsilon_{effi}}}{c} \quad (1.13)$$

where

$$L(\eta H) = 0.000987h\left(1-\frac{Z_{01}}{Z_{02}}\sqrt{\frac{\varepsilon_{eff1}}{\varepsilon_{eff2}}}\right)^2 \quad (1.14)$$

and ε_{eff1}, ε_{eff2} are obtained from equation (1.3) for W_1, W_2 respectively .

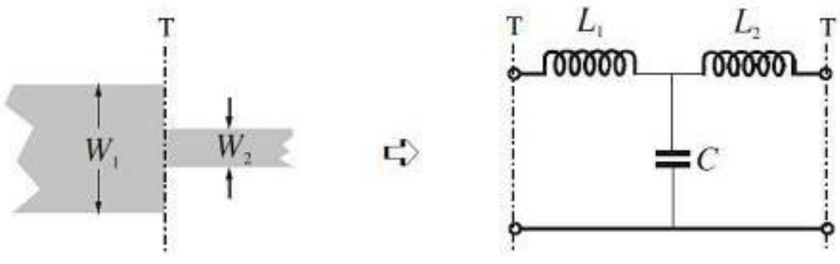

Figure 1. 3 Microstrip steps in width and its equivalent circuit [5]

b. Open ends

At the open end of a microstrip line with a width of W, the fields do not stop abruptly but extend slightly further due to the effect of the fringing field. This effect can be modelled either with an equivalent shunt capacitance Cp or with an equivalent length of transmission line Δl, as shown in Figure 1.3. This equivalent length is usually more convenient for filter design [6].

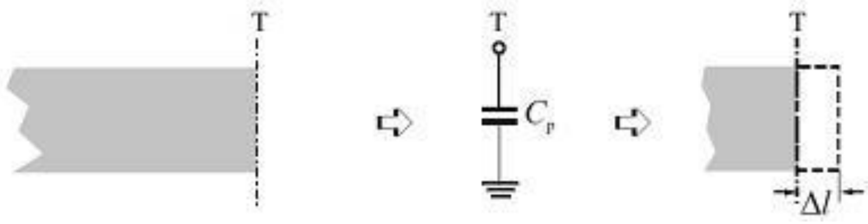

Figure 1. 3Microstrip discontinuities open- end and its equivalent circuit [5]

The relation between the two equivalent parameters may be found by [5]:

$$\Delta l = \frac{c Z_0 C_p}{\sqrt{\varepsilon_{eff}}} \tag{1.15}$$

and the closed-form expression is given as:

$$\frac{\Delta l}{h} = \frac{\xi_1 \xi_3 \xi_5}{\xi_4} \tag{1.16}$$

where

$$\xi_1 = 0.434907 \frac{\varepsilon_{eff}^{0.81} + 0.26\left(\frac{W}{h}\right)^{0.8544} + 0.236}{\varepsilon_{eff}^{0.81} - 0.189\left(\frac{W}{h}\right)^{0.8544} + 0.87} \tag{1.17}$$

$$\xi_2 = 1 + \frac{\left(\frac{W}{h}\right)^{0.371}}{2.35\varepsilon_{eff} + 1} \tag{1.18}$$

$$\xi_3 = 1 + \frac{0.5274 \tan^{-1}\left[0.084\left(\frac{W}{h}\right)^{\frac{1.9413}{\xi_2}}\right]}{\varepsilon_{eff}^{0.9236}} \tag{1.19}$$

$$\xi_4 = 1 + 0.0377 \tan^{-1}\left[0.067\left(\frac{W}{h}\right)^{1.456}\right]\{6 - 5exp[0.036(1 - \varepsilon_{eff})]\} \tag{1.20}$$

$$\xi_5 = 1 - 0.218exp\left(-7.5\frac{W}{h}\right) \tag{1.21}$$

The accuracy is less than 0.2% for the range of $0.01 \le (W/h) \le 100$ and $\varepsilon_{eff} \le 128$.

c. Gaps

A semi analytical full-wave formulation is used to analyze a narrow gap in a microstrip line. The analysis assumes that the length of the gap S is small compared to the strip width [6].

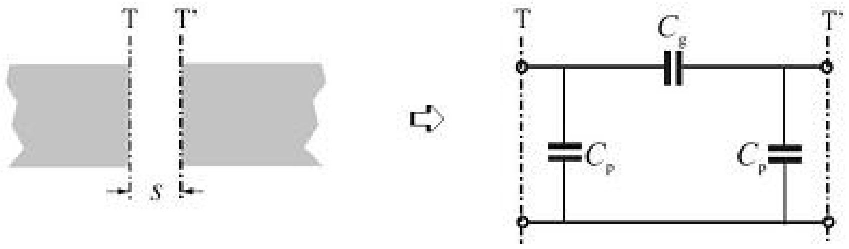

Figure 1. 4 Microstrip discontinuities gaps and its equivalent circuit [5]

where

$$C_p(pF) = 0.5C_e \tag{1.22}$$

$$C_g(pF) = 0.5C_o - 0.25C_e \tag{1.23}$$

$$\frac{C_o}{W}(pF/m) = \left(\frac{\varepsilon_{eff}}{9.6}\right)^{0.8}\left(\frac{S}{W}\right)^{m_o} exp(K_0) \tag{1.24}$$

$$\frac{C_e}{W}(pF/m) = 12\left(\frac{\varepsilon_{eff}}{9.6}\right)^{0.9}\left(\frac{S}{W}\right)^{m_e} exp(K_0) \tag{1.25}$$

- For $0.1 \leq \frac{S}{W} \leq 1.0$

$$K_o = 4.26 - 1.453\log\left(\frac{W}{h}\right) \tag{1.26}$$

$$m_e = 0.8675$$

- For $0.3 \leq \frac{S}{W} \leq 1.0$

$$K_e = 1.97 - \frac{0.03h}{W} \tag{1.27}$$

The accuracy is within 7% for $0.5 \leq (W/h) \leq 2$ and $2.5 \leq \varepsilon_{eff} \leq 15$.

d. Bends

Right-angle bends of microstrips may be modelled by an equivalent T-network, as shown in Figure 1.5. (Kupta and al., 1996) have given closed-form expressions for evaluation of capacitance and inductance [5].

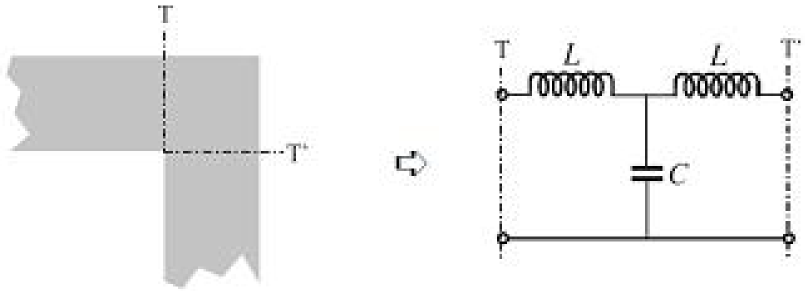

Figure 1. 5 Microstrip discontinuities bends and its equivalent circuit [20]

where

$$\frac{C}{W}(pF/m) = \begin{cases} \frac{(14\varepsilon_{eff}+12.5)\frac{W}{h}-(1.83\varepsilon_{eff}-2.25)}{\sqrt{\frac{W}{h}}} + \frac{0.02\varepsilon_{eff}}{\frac{W}{h}} & for\ \frac{W}{h} < 1 \\ (9.5\varepsilon_{eff}+1.25)\frac{W}{h} + 5.2\varepsilon_{eff} + 7.0 & for\ \frac{W}{h} > 1 \end{cases} \quad (1.29a)$$

$$\frac{L}{h}(\eta H/m) = 100\left(\sqrt{\frac{W}{h}} - 4.21\right) \quad (1.29b)$$

The accuracy on the capacitance is quoted as within 5% over the range of $2.5 \leq \varepsilon_{eff} \leq 15$ and $0.1 \leq W/h \leq 5$.

The accuracy on the inductance is about 3% for $0.5 \leq (W/h) \leq 2$.

1.7 Scattering parameters

The scattering parameters (known as S-parameters) is the more used to describe an electrical network since it is difficult to obtain voltages and currents at high frequencies. For Z and Y parameters it is necessary to use open and short circuit which at microwave frequencies may cause instability when active elements are involved.

In order to simplify the analysis of an RF circuit, the system can be defined as a two port network as shown in Figure

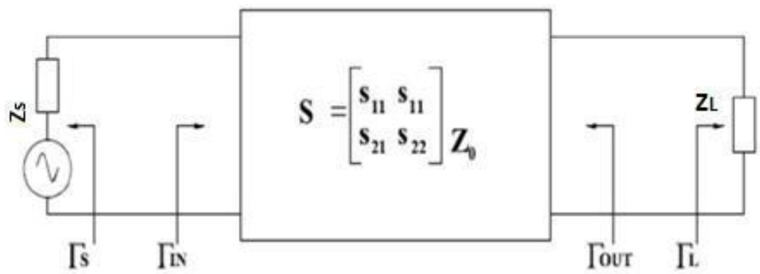

Figure 1. 6 General Two port network s-parameter [21]

The input and output reflection coefficients are expressed, respectively, by [14]:

$$\Gamma_{in} = \frac{S_{11}-\Delta\Gamma_L}{1-S_{22}\Gamma_L} \quad (1.33) \qquad \Gamma_{out} = \frac{S_{22}-\Delta\Gamma_S}{1-S_{11}\Gamma_S} \quad (1.34)$$

Whereas the source and load reflection coefficients are expressed, respectively, as follows [26]:

$$\Gamma_S = \frac{Z_S-Z_0}{Z_s+Z_0} \quad (1.35) \qquad \Gamma_L = \frac{Z_L-Z_0}{Z_L+Z_O} \quad (1.36)$$

and

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (1.37)$$

Where:

- **Δ** is called the determinant of the S-parameter matrix
- **S_{11}** is the input reflection coefficient where $\Gamma_L = 0$
- **S_{12}** is the reverse transmission (insertion) gain
- **S_{21}** describes the forward transmission coefficient (insertion) gain
- **S_{22}** is the output reflection coefficient of the device where $\Gamma_S = 0$

For some components and circuits, the scattering parameters can be calculated using network analysis techniques. Otherwise, it can be measured directly with a vector network analyser (VNA) for one or two-port network.

1.8 Advantages and drawbacks of microstrip technology

Microstrip technology has advantages such as less expensive, lighter, more compact and easy to integrate active devices than other technologies. Moreover, it presents high selectivity and is widely used in variety of microwave systems to transmit energy in one or more stop-bands. Like any technology, it has some drawbacks for example when high isolation is required such as in a filter or switch, some external shielding may have to be considered [3-7].

Given the chance, microstrip circuits can radiate, causing unintended circuit response. A minor issue with microstrip is that it is dispersive, meaning that signals of different frequencies travel at slightly different speeds. Microstrip does not support a TEM mode, because of its filling factor. For coupled lines, the even and odd modes will not have the same phase velocity. This property is what causes the asymmetric frequency of microstrip bandpass filters [15-14][17].

Chapter 2

Theory of Filter and Defected Ground Structure Technique

2.1 Introduction

In today's advanced world, we are totally dependent on electronic gadgets such as mobile phone for communication applications. Filters play an important role in these applications. They were developed and practiced by many researchers such as Richards, Darlington, and Sykes etc [22]. In order to have the Electromagnetic (EM) spectrum shared between the bands used without any interference, different applications of RF microwave necessitate the use of filters. The frequencies are to be separated or combined depending on the desired result. Filters with high performance, high selectivity, low loss, small size and low cost characteristics are required. Therefore, designers put noticeable efforts in realizing filters with the pre-mentioned characteristics.

Within this chapter; basic concepts, the different types of filters and introducing briefly the DGS and its characteristics.

2.2 RF/Microwave filter types

Filters in general can be defined as a two port network with energy storage elements like inductors, capacitors and transmission lines. These are used to obtain frequency dependent characteristics i.e. transmitting required signals in the pass band and rejecting or attenuating in the stop band. These kinds of characteristics can be obtained using different combinations of capacitors and inductors. A capacitor blocks DC and lower frequencies while allowing higher frequencies to pass through it, on the other hand inductor plays quite opposite to capacitor by blocking higher frequencies and allowing low frequencies to pass through it.

With these reciprocal elements one can achieve different configurations, basically four different kinds of filters:

a) **Low Pass Filter (LPF):** This filter allows all the frequencies below cutoff frequency f_c to pass through and blocks or attenuates all other frequencies.

b) **High Pass Filter (HPF):** This filter allows all the frequencies above cutoff frequency f_c to pass through while blocking others.

c) **Band Stop Filter (BSF):** This kind of filter is also called as notch filter. It blocks a band of frequencies which is determined by upper and lower cutoff frequencies and allows all other frequencies. Hence the name band stop filter.

d) **Band Pass Filter (BPF):** This filter works quite opposite to BSF, allowing a band of frequencies determined by the upper and lower cutoff frequencies and rejecting all other frequencies.

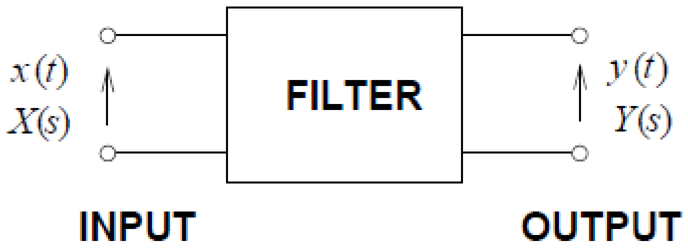

Figure 2. 1 Basic Filter [23]

The figure above shows a basic filter and its transfer function is given by:

$$T(s) = Y(s) / X(s) \quad (2.1)$$

The main objective of these filters is to block or reject the noise entering into the circuitry and keeping the signals confined to determined band of frequencies. The figure below shows the ideal and practical responses of all basic kind of filters.

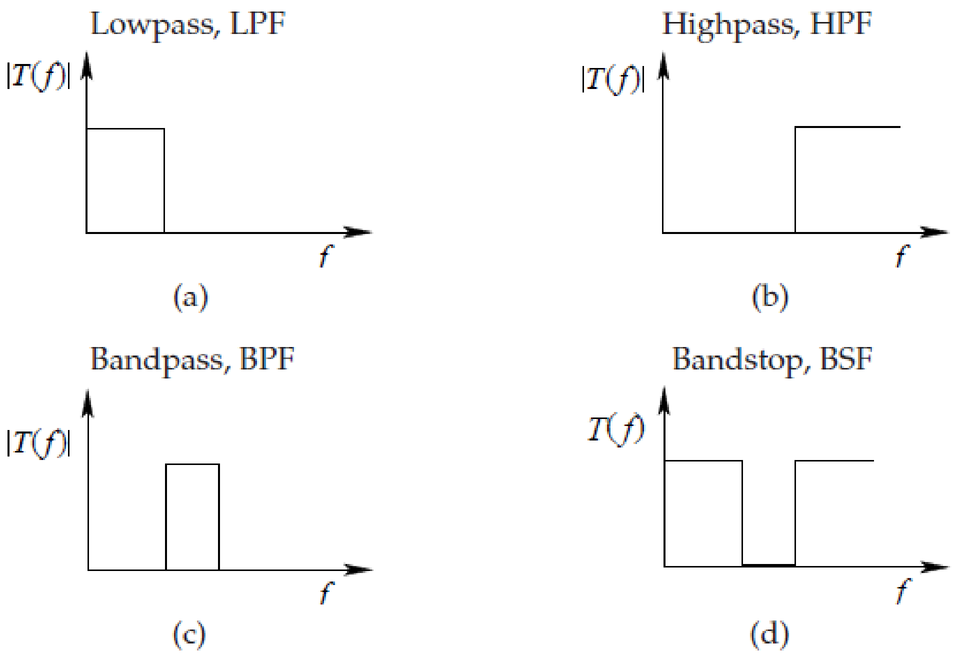

Figure 2. 2 Ideal filter responses [23]

The figure 2.2 shows ideal filter responses. It is not possible in real life to achieve such an ideal filter response. A design is said to be best when its frequency response is close to ideal frequency response. Practical filter frequency response is shown in figure 2.3.

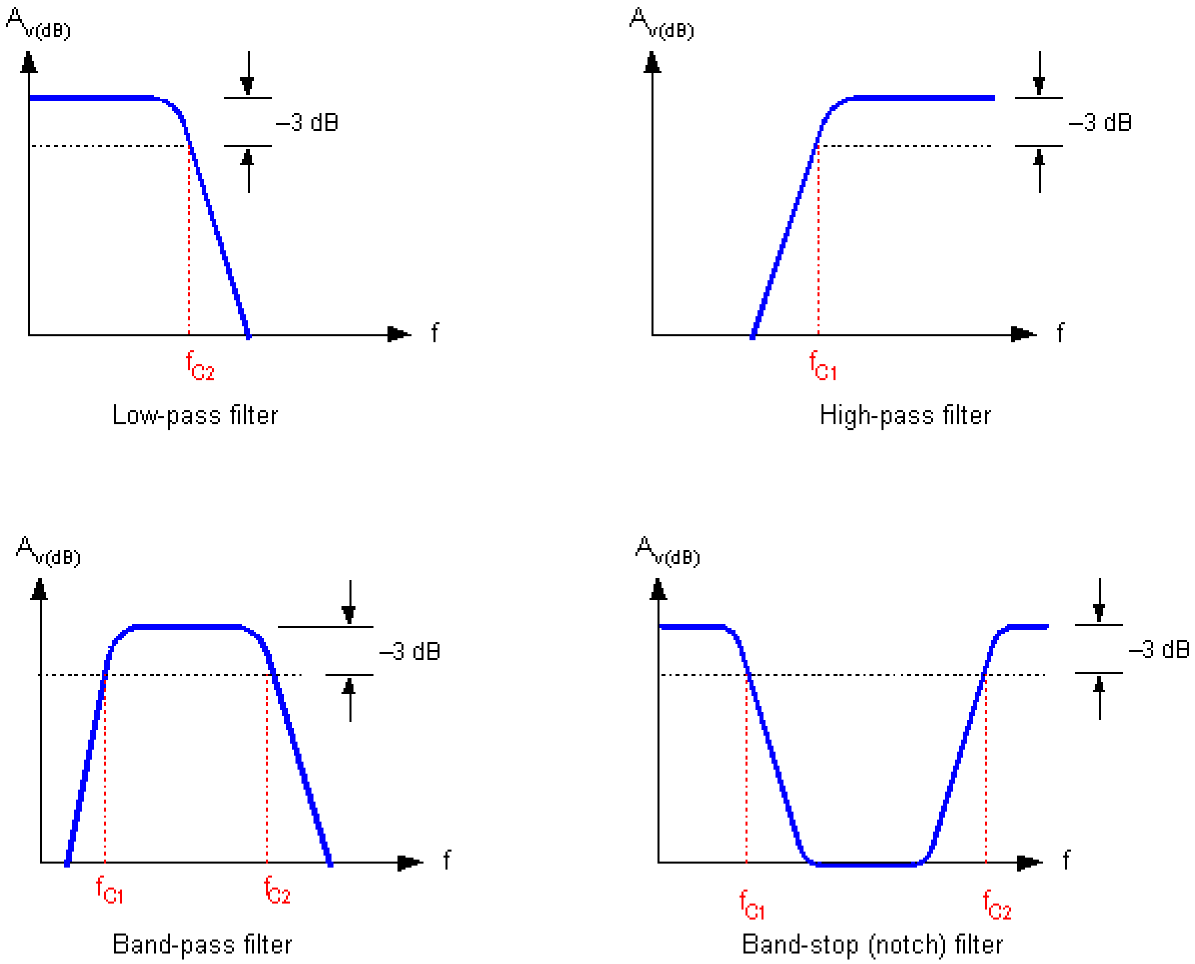

Figure 2. 3 Practically realizable version of the different types of filters [38]

Filters are widely used in wireless communications, satellite communications, radar systems, telecommunications and many other military and commercial applications. With all these applications filters have many stringent requirements to meet as to fulfill requirements. Frequency selectivity, size, weight, reliability and performance at various environments are some of the key factors for the filters.

With the recent advancements, filters can be designed as lumped element or distributed element circuits based on the requirements. They can also be made tunable with the novel materials and fabrication technologies which adds more flexibility. These include Microelectromechanical system (MEMS), Ferroelectrics, High-Temperature super conductors (HTS), Low-Temperature co-fired ceramics (LTCC), Liquid Crystal Polymers (LCP), Monolithic microwave integrated circuits (MMIC) and Defected Grounded Structures (DGS) etc[24].

2.3 Important definition used in filters

In the field of filter design, many parameters and terms are taken into consideration, the most important ones are:

2.3.1 Transfer function

Transfer function is an essential feature used in analyzing electronic systems, such as signal processing, communication systems.

In a two-port filter network, the network response characteristics are described by the transfer function different mathematical laws called filtering function, where the most ones used are: Butterworth and Chebyshev laws [25].

In RF/microwave systems, the transfer function defined by using scattering parameter S_{21}, but in general, the square of S_{21} magnitude is used instead of its magnitude only, so for a lossless passive filter network the TF is defined as [3]:

$$|S_{21}(Jw)|^2 = \frac{1}{1+\varepsilon^2 F_n^2(w)} \quad (2.2)$$

Where *w* represents a frequency variable, ε is the ripple constant and $F_n(w)$ is the characteristic function.

2.3.2 Bandwidth

The IEEE definition of the bandwidth is: "The range of frequencies within which the performance of the network complies with the specified limits [26]. The Pass-band bandwidth (BW) of the filter is simply the difference between the upper and lower cutoff frequencies relative to 3 dB attenuation point usually expressed in Herts (Hz).

$$BW(\text{Hz}) = F_{-3dB_{upper}} - F_{-3dB_{lower}} \quad (2.3)$$

2.3.3 Insertion loss

The insertion loss of a filter is the additional loss between the source and the load caused by the insertion of the filter compared to its absence. Insertion loss is equal to the sum of dielectric losses, copper losses and reflected losses which caused by power dissipated in dielectric materials, the power dissipated by the conductor and by the voltage standing wave ratios (VSWR) [6]. It is usually expressed in Decibel (dB).

$$IL(dB) = -20log_{10}|S_{21}| \quad (2.4)$$

2.3.4 Return loss

Return loss (RL) is the loss rate of the power reflected back from the load to the power transmitted into the line, in other words is the measure of the effectiveness of the power delivery from a transmission line to a load, expressed in Decibel (dB).

$$RL(\text{dB}) = 10log_{10}\left(\frac{P_{in}}{P_{ref}}\right) \tag{2.5}$$

Where P_{ref} is the reflected power and P_{in} is the input power.

In RF/microwave applications, return loss expressed using scattering parameter S_{11} [15]:

$$RL(dB) = -20log_{10}|S_{11}| \tag{2.6}$$

In addition, it can be expressed by voltage-standing-wave-ratio (VSWR) [15]:

$$RL(dB) = +20log_{10}\left|\frac{VSWR+1}{VSWR-1}\right| \tag{2.7}$$

2.3.5 Center frequency

The center frequency (F_c) of a filter is a measure of a central frequency between the upper and lower 3 dB frequencies [27]. F_c may not necessarily be the peak transmission point of the load of the band pass filter. Usually is defined as arithmetic mean or geometric mean of the lower and the upper cutoff frequencies.

$$Arithmitic\ mean = F_c = \frac{F_{-3dB_{upper}} + F_{-3dB_{lower}}}{2} \tag{2.8}$$

$$Geometric\ mean = F_c = \sqrt{\left(F_{-3dB_{upper}}\right) X \left(F_{-3dB_{lower}}\right)} \tag{2.9}$$

2.3.6 Fractional bandwidth

Fractional bandwidth is the bandwidth of a device divided by its center frequency defined by:

$$FBW = \frac{BW}{F_C} \tag{2.10}$$

2.3.7 Quality Factor

The quality factor (Q) of a filter is the ration of the center frequency to bandwidth. In other words, the inverse of FBW.

$$Q = \frac{F_c}{BW} \quad (2.11)$$

2.3.8 Cut-off frequency

The cutoff frequency (f_{cutoff}) is the frequency at which the filter **IL** is equal to 3 dB, or where the output power becomes only half of the input power magnitude. At this point, the attenuation amount due to the filter starts to increase rapidly.

2.3.9 Stop band

The IEEE definition of the stop band is: “The range of frequencies within which the attenuation of a filter or network is higher than at frequencies outside the range” [26]; stop band is a range of frequencies, between specified limits, at which the filter insertion loss is greater than a specified Value [28].

2.4 Design techniques

2.4.1 Defected ground structure (DGS) technique

In recent years, there have been several new concepts applied to distributed microwave circuits. One such technique is defected ground structure or DGS, where the ground plane metal of a microstrip (or stripline, or coplanar waveguide) circuit is intentionally modified to enhance performance. The name for this technique simply means that a “defect” has been placed in the ground plane, which is typically considered to be an approximation of an infinite, perfectly-conducting current sink. Of course, a ground plane at microwave frequencies is far removed from the idealized behavior of perfect ground. Although the additional perturbations of DGS alter the uniformity of the ground plane, they do not render it defective [30].

First DGS was proposed in 1999, later, many researchers have proposed alternate designs that has boosted the applicability’s of DGS. The main advantage of DGS over PBG is the circuit area, for DGS the circuit area is relatively very small when compared to PBG as few DGS elements can achieve similar parameters as periodic PBG and can show slow-wave effect [29] - [31]. As mentioned the DGS has a defect that is etched on the uniform ground plane which alters the uniformity of the ground plane, thus called Defected Ground Structure. This etched defect in the ground plane disturbs the shielding current distribution, which alters and rise the inductance and capacitance of the line [32]. The shielding current distribution depends on the shape and dimensions of the defect and the band gap property relies on many design parameters such as lattice shape, lattice spacing, and number of lattice [31].

Another advantage of DGS is by cascading the unit cell we can achieve deeper and steeper stop band depending on the number of cells. The cascading can be in both horizontal and vertical direction but with the conventional planar transmission line, vertical cascading is not possible. Cascading has to be done along the transmission line direction [32].

The etched section of DGS increases the series inductance which in turn increases the reactance of the microstrip with increase in frequency. This gives a start for the rejection of certain frequency range. The attenuation pole location is provided by the series inductance in parallel with the capacitance. This acts like a parallel LC resonator. The unwanted surface waves, leakage and spurious signals can be suppressed with stopband characteristics of DGS. The reactance of capacitance is decreased with the increase in frequency.

DGS can provide sharp selectivity at cutoff frequency and excellent performance in terms of spurious signals in stop band and ripples in pass band [32]. Using DGS we can suppress harmonics too. Many researchers have combined DGS with new materials to achieve special characteristics like tunability and more. In [33] a filter is designed using DGS and LTCC and moreover Substrate integrated waveguide (SIW) was adopted and combined with DGS in [34].

The LC equivalent components of DGS causes slow wave effect which is one of the most important advantages of DGS. The transmission line with DGS when compared to conventional lines has higher impedance and slow wave factor [32]. With these properties the circuit sizes can be reduced. DGS can be applied to microwave oscillators, microwave couplers (to increase the coupling), microwave filters, microwave amplifiers etc. DGS is also used in microstrip antenna design for different applications such as antenna size reduction, cross polarization reduction and harmonic suppressions.

✓ Defected Ground Structure characteristics

The basic element of DGS is a resonant gap or slot in the ground metal, placed directly under a transmission line and aligned for efficient coupling to the line. Figure 2.4 shows several resonant structures that may be used. Each one differs in occupied area, equivalent L-C ratio, coupling coefficient, higher-order responses, and other electrical parameters. A user will select the structure that works best for the particular application. The equivalent circuit for a DGS is a parallel-tuned circuit in series with the transmission line to which it is coupled as shown in Figure 2.5.

The input and output impedances are that of the line section, while the equivalent values of L, C and R are determined by the dimensions of the DGS structure and its position relative to the transmission line. The range of structures, of which Figure 2.4 is only a sample, arises from different requirements for bandwidth (BW) and center frequency, as well as practical concerns such as a size/shape that does not overlap other portions of the circuit, or a structure that can be easily trimmed to the desired center frequency.

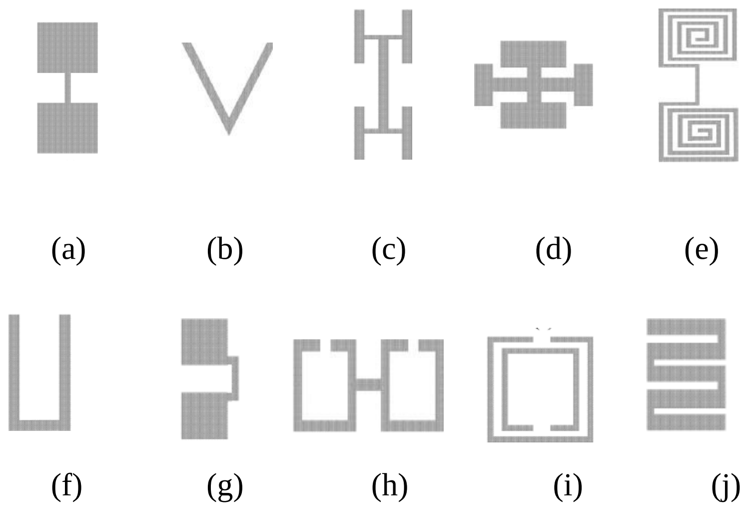

Figure 2. 4 different DGS geometry: (a) dumbbell-shaped (b) V-shaped (c) H-shaped (d) Cross-shaped (e) Spiral-shaped (f) U-shaped (g) square heads connected with U slots (h) open loop dumbbell (i) split-ring resonators (j) meander line [39].

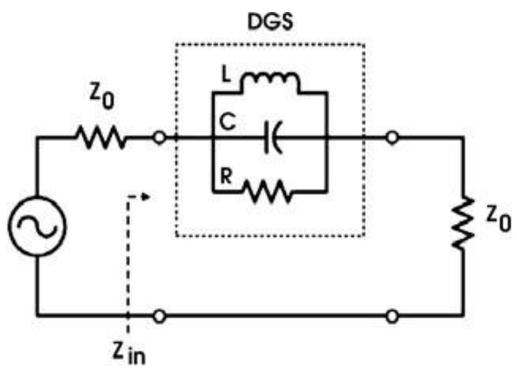

Figure 2. 5 Equivalent circuit of the unit DGS [40].

The values of L, C and R are determined by the dimensions and location relative to the "through" transmission line.

The values of the capacitor, the inductor and the resistance can be obtained as follow [40]:

$$C = \frac{w_c}{2Z_0(w_0^2 - w_c^2)} \tag{2.13}$$

$$L = \frac{1}{4\pi^2 f_0^2 C} \tag{2.14}$$

$$R = \frac{2Z_0}{\sqrt{\frac{1}{|S_{11}(w_0)|^2} - \left(2Z_0\left(w_0 C - \frac{1}{W_0 L}\right)\right)^2 - 1}} \tag{2.15}$$

✓ Applications, advantages, and disadvantages

Application, advantages, and disadvantages of different shapes of DGS are summarized in Table 2.2

Table 2. 1 Applications, advantages, and disadvantages of different type of DGS [41]

S.number	Shape	Reference	Advantage	Disadvantage	Applications
1	Dumbbell	[47]	Simple structure, easy to design and analyse	Single stop band	Band-stop filter
2	HPDGS	[42]	size reduction	Larger size than VPDGS, dispersion problem	Matching network of amplifier
3	VPDGS	[42]	size reduction	Dispersion problem	Matching network of amplifier
4	U-slot	[43]	Improved - factor	Single stop band	Band-stop filter
5	V-slot	[43]	Improved – factor	Single stop band	Band-stop filter

6	Cross DGS	[44]	Sharp rejection, ultra-wide stop band	—	Low pass filter
7	Fractal DGS	[45]	Wide stop band	No sharp cut-off frequency	Band-stop filter
8	Spiral DGS	[46]	Multistop band	Complex analysis	Band-stop filter

2.4.2 Photonic Band Gap (PBG) technique

Photonic Band Gap (PBG) structures are periodic structures etched on the ground plane and have the ability to control the propagation of electromagnetic waves. Periodic structures effect the current distribution of the structure. The periodic structures can influence on the propagation of electromagnetic waves and radiation characteristics. The PBG have the periodic defects, which can be treated as a resonant cavity and affect the propagation of the electromagnetic waves. PBG forms free mode inside the forbidden band gap and provides a stopband at certain frequency. PBG has been reported for improving the directivity of antennas, surface wave's suppression, and harmonics suppression [35].

2.4.3 Electromagnetic Band Gap (EBG) technique

The EBG technique is based on the PBG phenomena and also realized by periodical structures. In [36], EBG has been introduced as high-impedance surface or PBG surface. These structures are compact and result in high gain, low profile and high efficiency antennas. EBG has been created an interest in the field of antenna. EBG structures suppress the surface wave current hence increase the antenna efficiency. The surface waves decrease the antenna efficiency. Surface wave suppression using EBG technique improves the antenna performance by increasing the antenna efficiency and antenna gain [37].

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2.4.4 The comparison between PBG, EBG, and DGS

The comparison between PBG, EBG, and DGS is depicted in Table 2.1[38]

Table 2. 2 The comparison between PBG, EBG, and DGS

	EBG	EBG	DGS
Definition	Photonic Band Gap (PBG) structures are periodic structures etched on the ground plane and have the ability to control the propagation of electromagnetic waves	The EBG technique is based on the PBG phenomena and also realized by periodical structures but compact in size	Single or few compact geometrical slots embedded on the ground plane of microwave circuits are referred to as Defected Ground Structure (DGS)
Geometry	Periodic etched structure	Periodic etched structure	One or few etched structures
Parameter extraction	Very difficult	Very difficult	Relatively simple
Size	Large	Smaller than PBG and larger than DGS	Much more compact than PBG and EBG
Fabrication	Difficult	Difficult	Easy

2.5 Band stop filter

Several compact and high performance components have been reported by using the generic structure called DGS for the microstrip line. In [47], Dumbbell DGS is the first proposed structure that rejects unwanted frequency around 3.5 GHz with 28 dB IL. In [51], an arrowhead DGS slot is used to achieved a BSF, the attenuation pole frequency for an arrowhead is at 3.7 GHz. In [52], a H-shaped DGS is proposed with 26.3% compact lengthwise than other reported structures. The simulated frequency that achieved using this DGS was around 4.1 GHz. In [53], a novel W defected ground structure (WDGS) was presented. The effects of the WDGS geometric parameters on frequency and width were analyzed in detail. A band-stop filter was built by three cascaded WDGS. The bandwidth of the filter was increased effectively and the attenuation to signals was improved. The results show that the filter rejects signals from -25dB to - 37dB in 2.6GHz-3.4GHz.

Chapter 3

Design of Multiband Bandstop Filters

3.1 Introduction

The purpose of this work is to design simple structures of multiband BSFs that reject 5.46 GHz, 3.69/7.63 GHz, and 3.2/5.56/7.28 GHz bands. The substrate used is FR4 with thickness 1.62 mm, relative dielectric constant of 4.3 and dielectric loss tangent of 0.017. The design and simulation are carried out using computer simulation technology CST software (Appendix A) where fabrication and measurement are made using MITS Electronics and ROHDE & SCHWARZ vector network analyzer (VNA), respectively, at the signals and systems laboratory of IGEE.

3.2 Design procedure

The first step of this work is to introduce the FR4 substrate parameters. The width of the 50 Ω conductive strip is obtained using analytical line impedance calculator as shown in Figure 3.1.

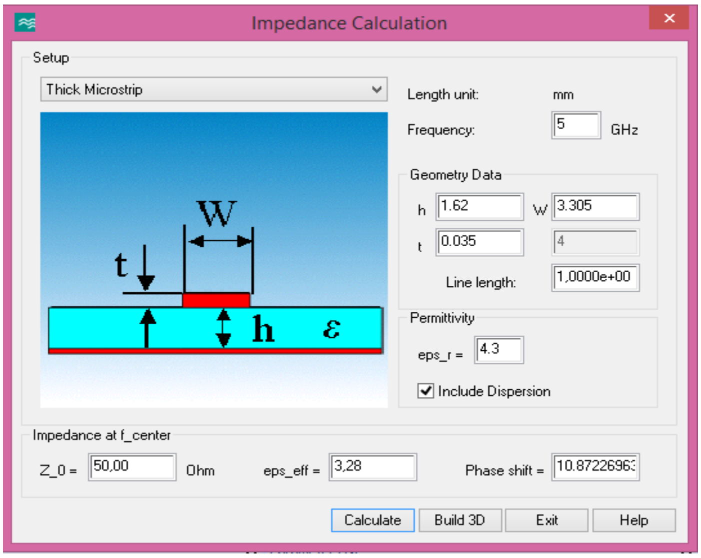
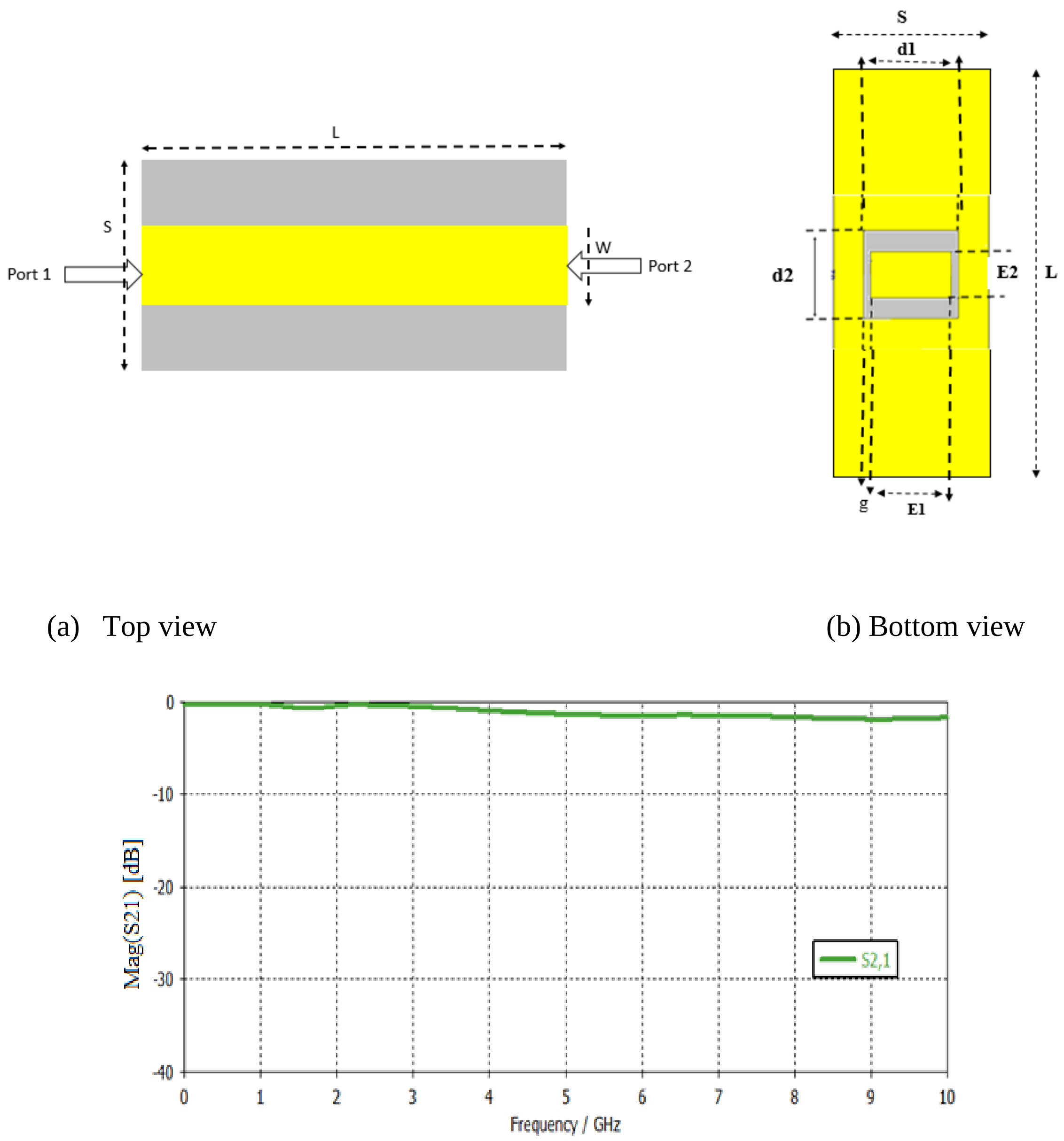


Figure 3. 1 impedance calculation in CST software

The next step is to use a simple structure of a DGS unit as shown in Figure 3.2(a-b). The initial structure dimensions d1, d2, E1, E2, L, S, h, W and g are listed in Table 3.1. The simulated S21-parameter are shown in Figure 3.2(c).

Table 3. 1 Initial dimensions of the purposed structure.

Parameter	**S**	**L**	**h**	**E1**	**E2**	**d1**	**d2**	**W**	**g**
Dimension (mm)	10.2	28.4	1.62	5.3	3.5	6.2	6.6	3.305	0.45

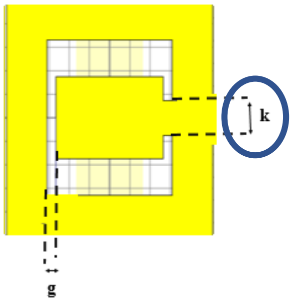


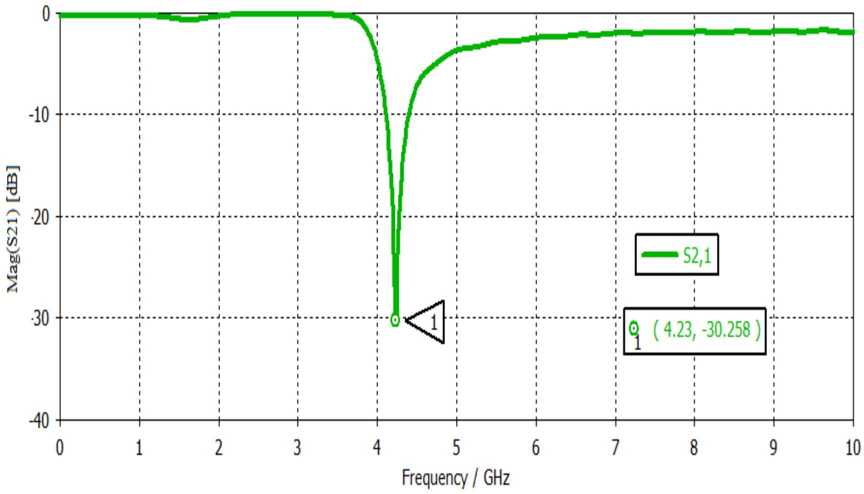
(a) Top view (b) Bottom view

(c)

Figure 3. 2*(a)* Side view of the substrate (b) Bottom view of the substrate (c) The magnitude of S_{21}

From Figure 3.2(c), it is clearly that the achieved result is unacceptable for the suitable requirements. For that, the DGS unit is opened (open-loop) in the middle as shown in Figure 3.3(a). The structure is simulated as illustrated in Figure 3.3(b). The proposed filter exhibits a good bandstop performance at around 4.23 GHz.





(a) Bottom view (b)

Figure 3. 3(a) The DGS unit with a gap (b) The magnitude of S_{21}

The influences of gap variation of the DGS unit on pole (zero transmission) and cutoff frequencies are investigated as shown in Figure 3.4. One can observe that when k increases, the pole frequency is shifted to higher frequencies whereas the cutoff frequency is shifted to lower frequencies.

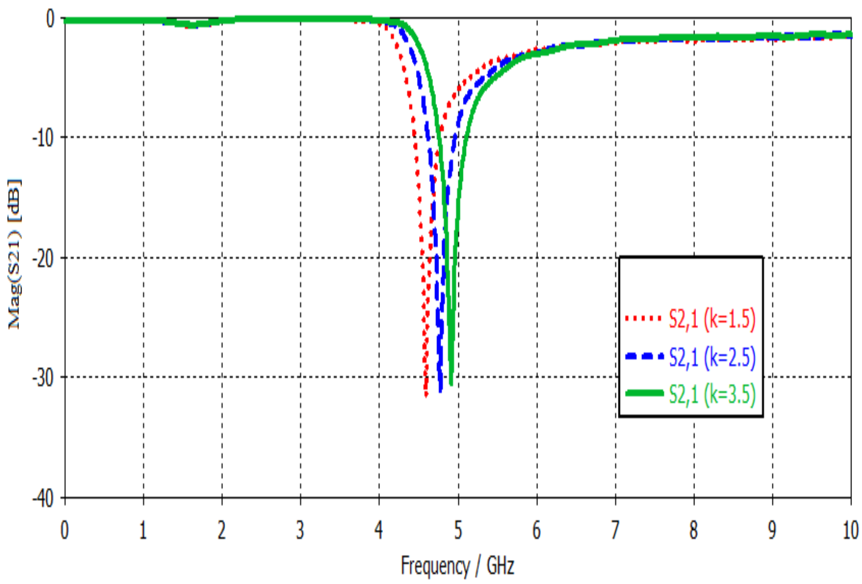


Figure 3. 4(a) Magnitude of S_{21} for different values of k

The effect of varying the parameter g while the others are kept constants is shown in Figure 3.5. When g increases, the bandstop frequency is shifted to higher values.

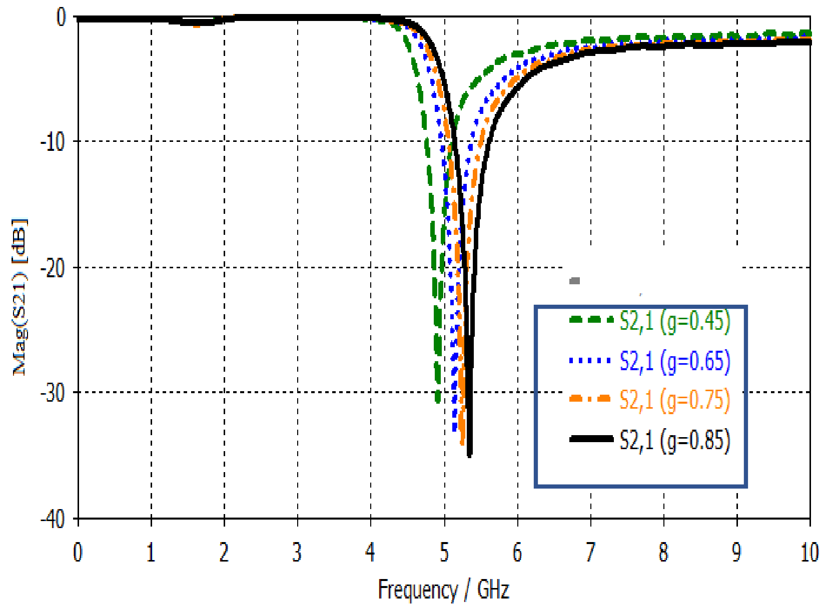


Figure 3. 5 Magnitude of S_{21} for different values of g

3.3.1 Single-band BSF

The modified structure that gives the most effective result is simulated and S-parameters are represented in Figure 3.6. The rejected (bandstop) frequency is around 5.46 GHz which is used for WiMAX application (5.25-5.85 GHz) with high insertion (IL) loss and low return loss (RL). The final dimensions of the designed filter are d1, d2, E1, E2, k and g are considered respectively 6.2 mm, 6.6 mm, 5.3 mm, 3.5 mm, 3.15 mm and 0.85 mm.

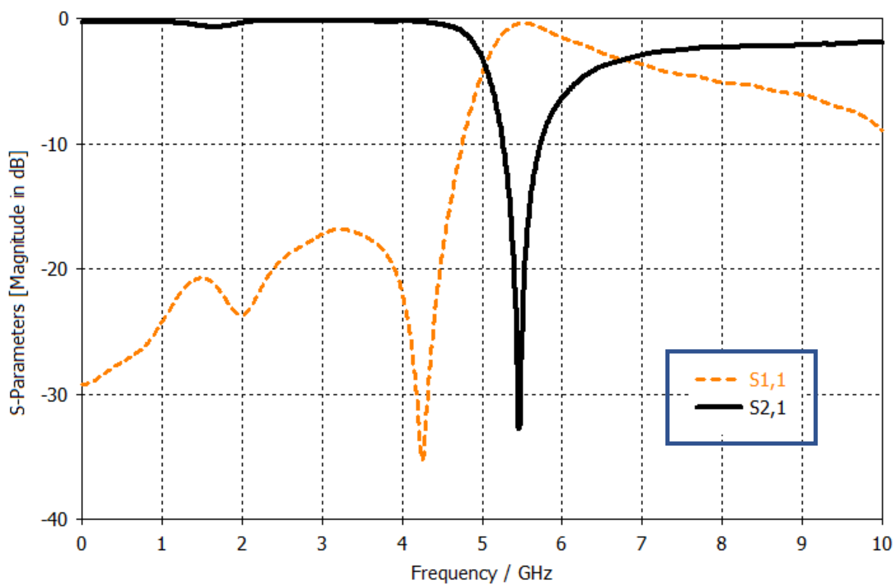


Figure 3. 6 Magnitudes of S parameters for single BSF

Figure 3.7 shows the current distribution of the single-band-BSF at the rejection band frequency 5.4 GHz. From Figure 3.7, it is noticed that the current flows are more dominant around the DGS-unit/right-side-feeding-line and the transmission zero response of the filter at 5.46 GHz is affected from them.

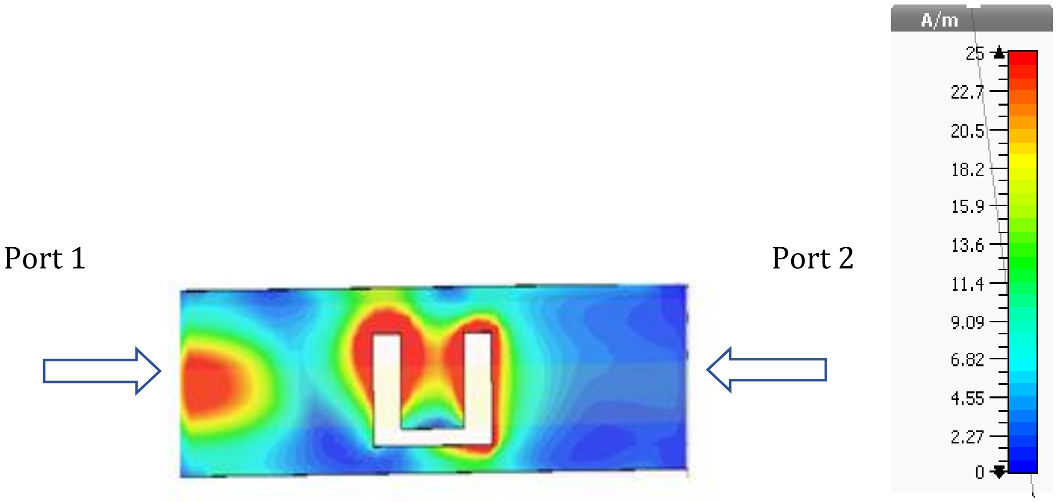
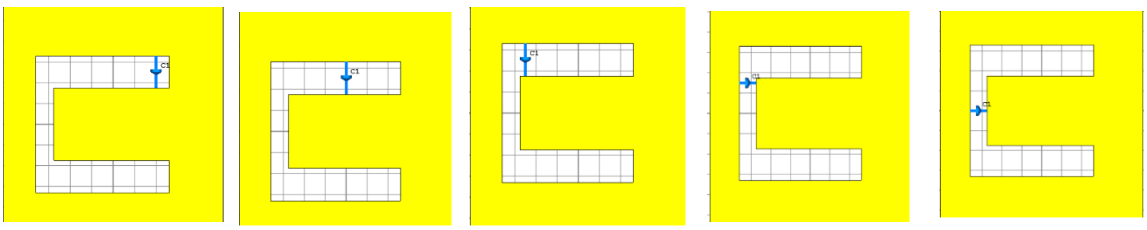


Figure 3. 7 Simulated surface current distribution at 5.46 GHz

3.2.2 Dual-band BSFs

3.2.2.1 Dual-band BSF based on using surface-mount device (SMD) capacitors

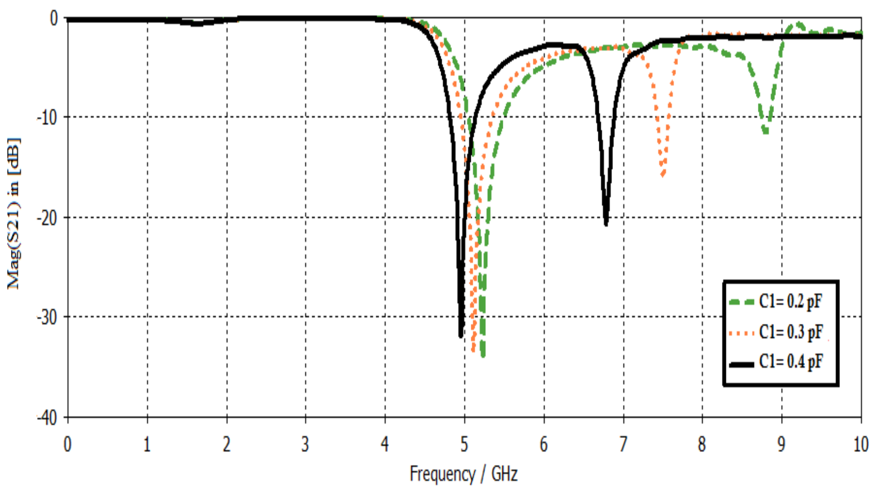
In order to obtain a filter with dual-band (DBBSF), the structure is loaded with a surface-mount device (SMD) capacitor, often referred to as surface mount technology (SMT), at different positions as shown in Figure 3.8(a-e).



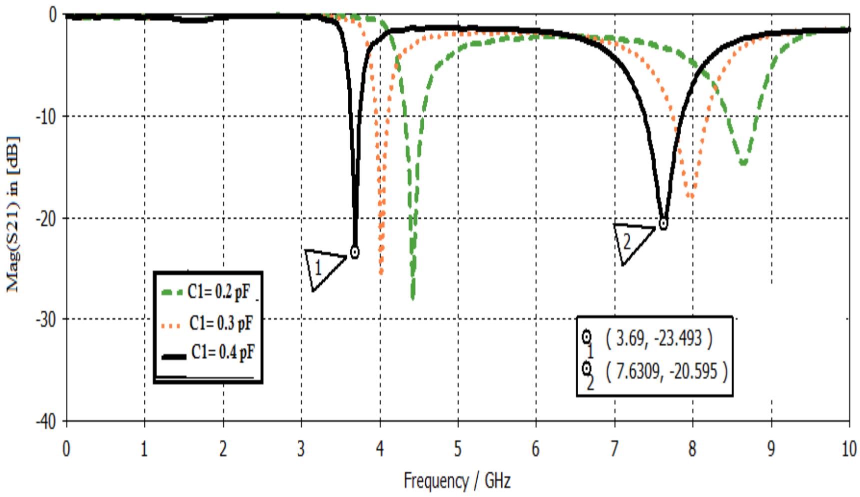
(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5

Figure 3. 8 Placement of surface-mount capacitor in the DGS unit (a) 1st position, (b) 2nd position, (c) 3rd position, (c) 4th position and, (e) 5th position

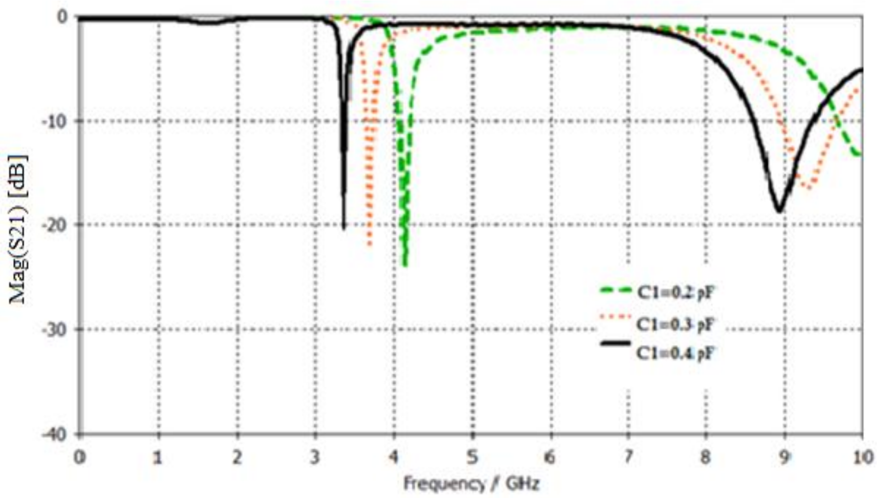
The magnitudes of S_{21}-parameters for three distinct values of capacitors, that give good performance, and for the five cases are depicted in Figure 3.9 (a-e).



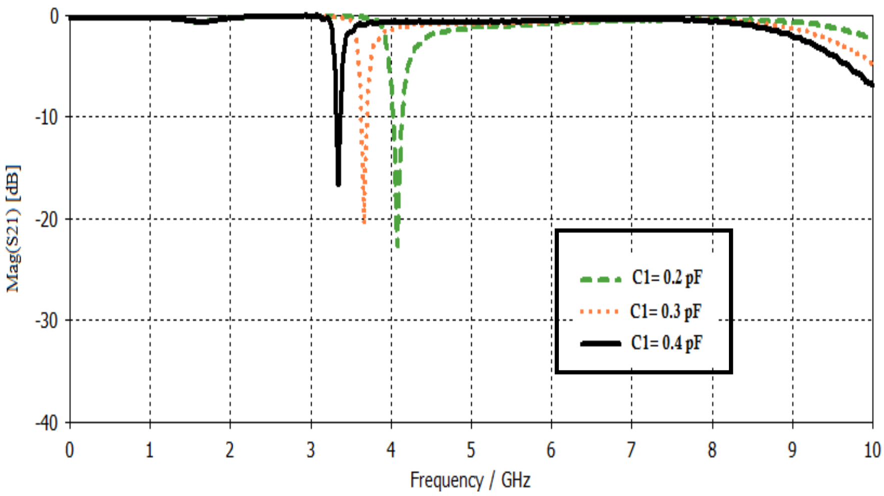
(a) Magnitudes of S_{21}-parameter for Case 1



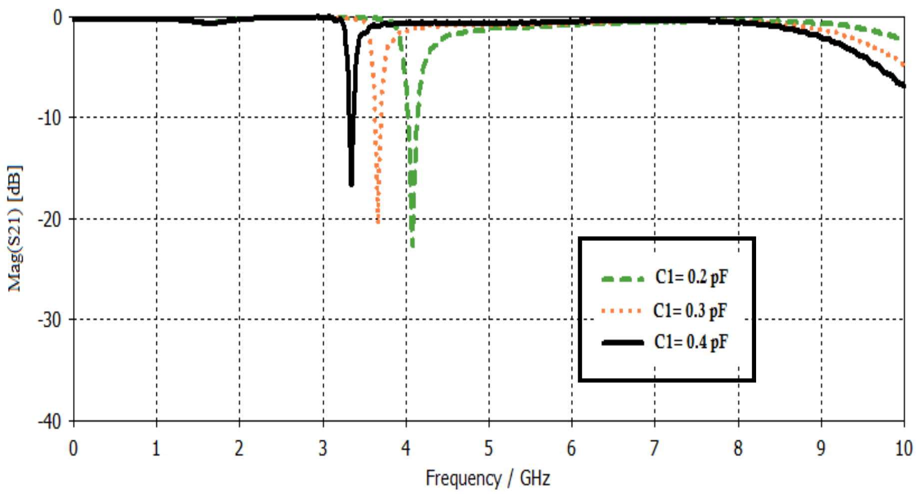
(b) Magnitudes of S_{21}-parameter for Case 2



(c) Magnitudes of S_{21}-parameter for Case 3



(d) Magnitudes of S_{21}-parameter for Case 4



(e) Magnitudes of S_{21}-parameter for Case 5

Figure 3. 9 Magnitudes of S_{21}-parameter for different cases

Tables 3.2, 3.3 and 3.4 summarize the results of the five cases.

Table 3. 2 Dual-band stop filter response for C=0.4 pF

Characteristics	Case 1	Case 2	Case 3	Case 4	Case 5
1st /2nd stop-band (GHz)	5.02/6.70	3.69/7.63	3.41/8.95	3.3	3.3
Insertion loss (dB)	30.02/19.52	23.49/20.68	20.13/18.92	18.1	18.1

Table 3. 3 Dual-band stop filter response for C=0.3 pF

Characteristics	Case 1	Case 2	Case 3	Case 4	Case 5
1st /2nd stop-band (GHz)	5.21/7.52	4.08 /8.06	3.67/9.32	3.62	3.62
Insertion loss (dB)	31.1/16.9	25/18.8	21.8/17.1	20.05	20.05

Table 3. 4 Dual-band stop filter response for C=0.2 pF

Characteristics	Case 1	Case 2	Case 3	Case 4	Case 5
1st /2nd stop-band GHz)	5.36/8.81	5.47 /8.71	4.13/10	4.08	4.08
Insertion loss (dB)	31.5/12.5	27/14.89	24.5/13.7	23	23

From Tables 3.1, 3.2 and 3.3, it is noticed that when the value of the capacitor increases, the stopband frequencies are shifted down to lower values. Moreover, the capacitor C=0.4 pF introduced in case 2, presents good results in terms of dual stopband characteristics that allows to reject WiMAX operated at 3.69 GHz and C-band operated at 7.63 GHz.

Figure 3.10 shows the current distribution of the dual-band-BSF at the rejection band frequencies 3.69 GHz and 7.63 GHz. From Figure 3.10, it is observed that the current flows are more dominant around the DGS-unit/right-side-feeding-line and the transmission zeros responses of the filter at 3.69/7.63 GHz are affected from them.

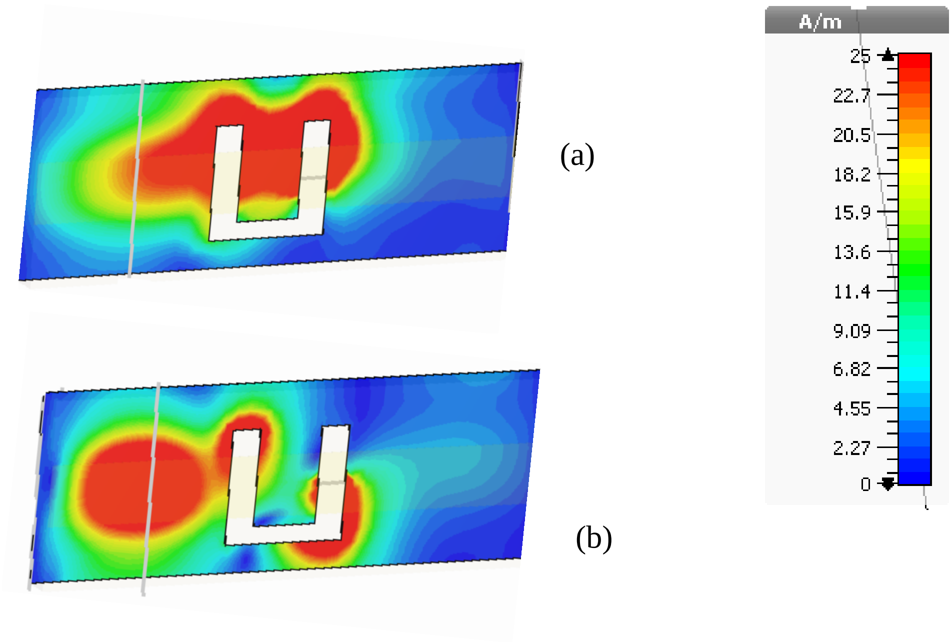
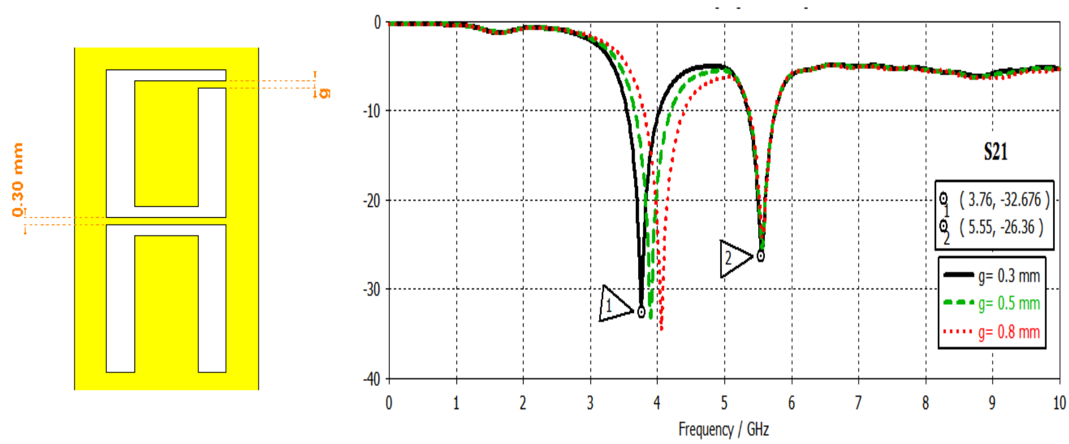


Figure 3. 10 Current distributions at (a) 3.69 GHz and, (b) 7.63 GHz

3.2.2.2 Dual-band BSF without using SMD capacitors

A. The proposed design:

The structure shown in Figure 3.2 is modified so that to achieve a dual stopband operation without using SMD capacitors as shown in Figure 3.11(a). The influences of a gap (g) on pole frequencies (zero transmissions) and cutoff frequency are investigated as shown in Figure 3.11(b). From Figure 3.11(b), two poles frequencies at 3.76 GHz and 5.55 GHz are achieved.

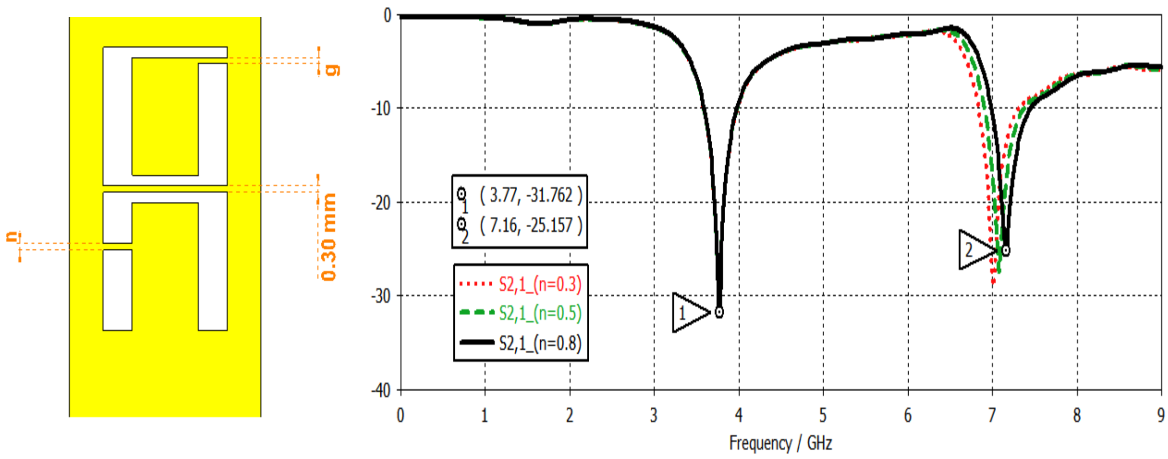


(a) (b)

Figure 3.11 The modified structure based on two cascaded DGS units along with two gaps (a) its geometry (Bottom view) and, (b) Its Magnitude of S_{21}

B. The modified proposed design

The structure shown in Figure 3.11(a) is modified so that to achieve the frequencies those have been obtained by using SMD capacitors. For that, a further gap (noted n) is performed as shown in Figure 3.12(a). The simulated results, shown in Figure 3.11(b), present the desirable rejected frequencies 3.77 GHz and 7.16 GHz.



(a) (b)

Figure 3. 122 The modified structure based on two cascaded DGS units along with three gaps (a) its geometry (bottom view), (b) Its Magnitude of S_{21}

Figure 3.13 shows the current distribution of the dual-band-BSF at rejection band frequencies 3.77 GHz and 7.16 GHz. From Figure 3.13, it is observed that the current flows are more dominant around the DGS-unit/right-side-feeding-line and the transmission zeros responses of the filter at 3.77/7.16 GHz are affected from them.

(a)

(**b**)

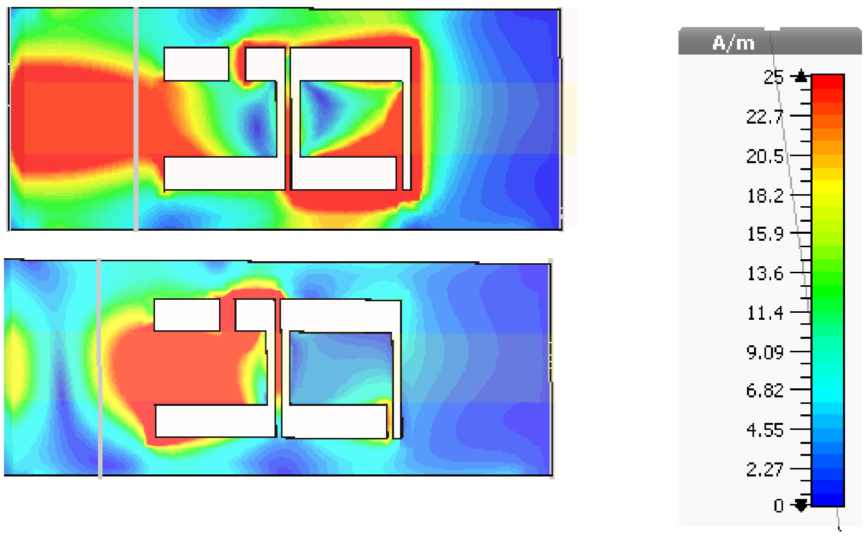
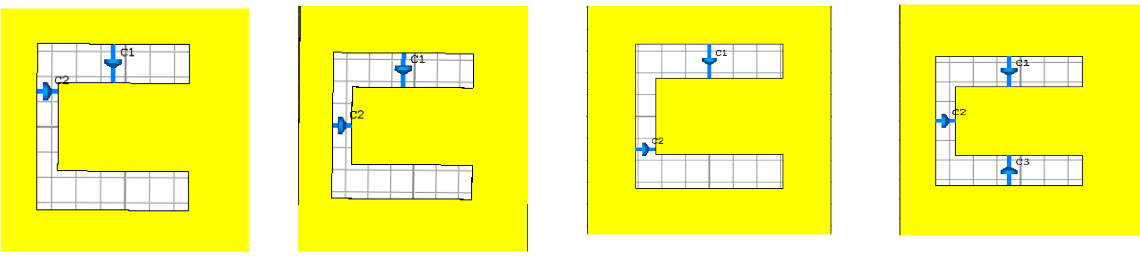


Figure 3. 13 Current distributions at (a) 3.77 GHz and, (b) 7.16 GHz

3.2.3 Triple-band BSFs

3.2.3.1 Triple -band BSF based on using SMD capacitors

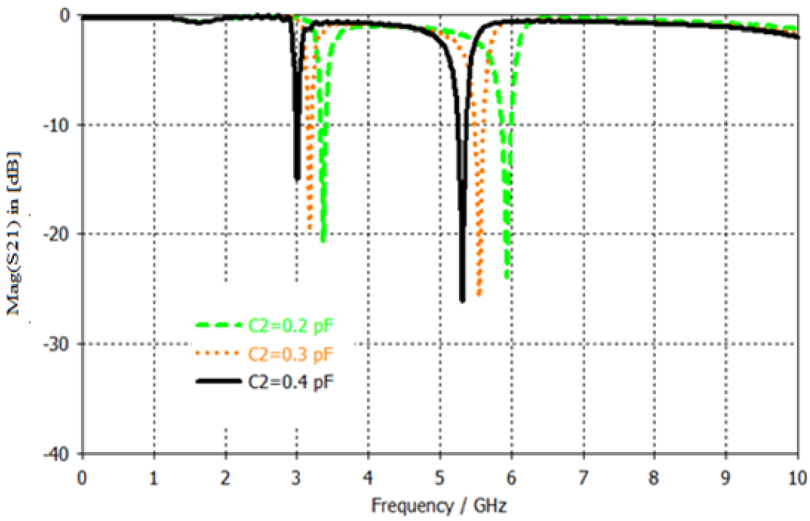
In order to obtain a filter with triple-band (TBBSF), the structure is loaded with a surface-mount devices (SMD) capacitors at different positions as shown in Figure 3.8(a-d). the capacitor C1 is fixed from the previous part that was in case 2 while C2 and C3 are loaded to the structure to get the desired filter.



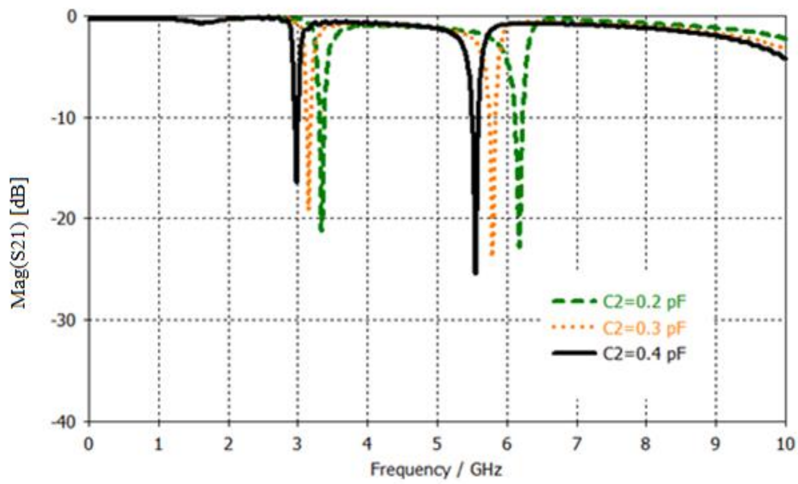
(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4

Figure 3. 14 Placement of surface-mount capacitors in the DGS unit (a) 1st position, (b) 2nd position, (c) 3rd position and, (d) 4th position

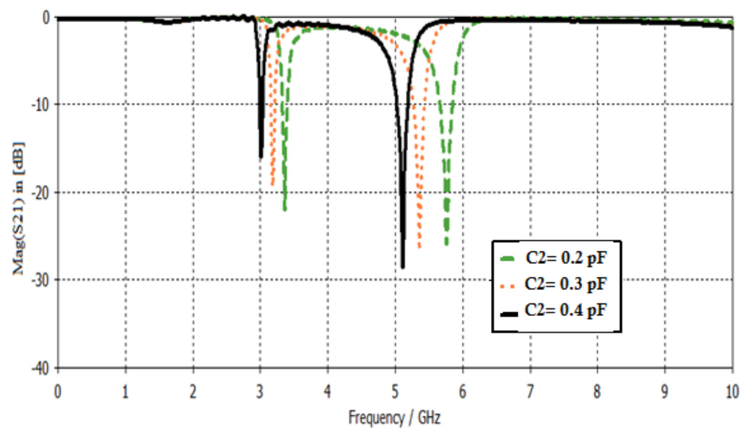
The magnitudes of S_{21}-parameters for three distinct values of capacitors, that give good performance, and for the four cases are depicted in Figure 3.9 (a-d).



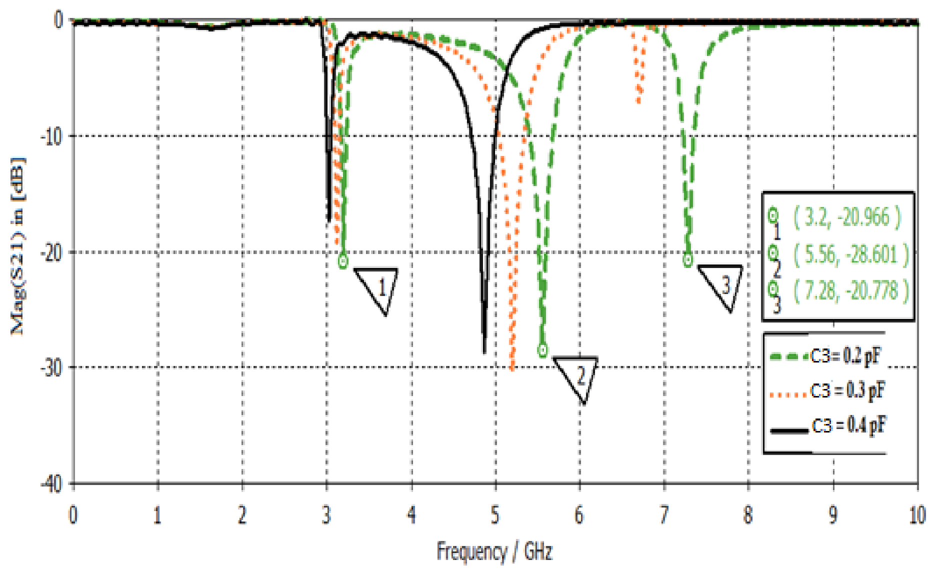
(a) Magnitudes of S_{21}-parameter for Case 1



(b) Magnitudes of S_{21}-parameter for Case 2



(c) Magnitudes of S_{21}-parameter for Case 3



(d) Magnitudes of S_{21}-parameter for Case 4

Figure 3. 15 Magnitudes of S_{21}-parameter for different cases

The Table 3.4 summarizes the results that are obtained from the five cases.

Table 3. 5 Triple-band BSF characteristics for different cases

Characteristics	Case 1	Case 2	Case 3	Case 4
Band (GHz)	3.35/5.97	3.28/6.12	3.35/5.88	3.23/5.55/7.26
Insertion loss (dB)	20.8/24	21/24	22/26	20.17/26.67/21.10

In the cases 1, 2 and 3, the designs still give a dual stopband response, however, in case 4 where C3 (0.2 pF) is added, a third frequency is generated. Therefore, the three rejected frequencies are 3.26 GHz, 5.55 GHz and 7.26 GHz for capacitors C1, C2 and C3 of 0.4 pF, 0.2 pF and 0.2 pF, respectively. Figure 4.16 shows the final result.

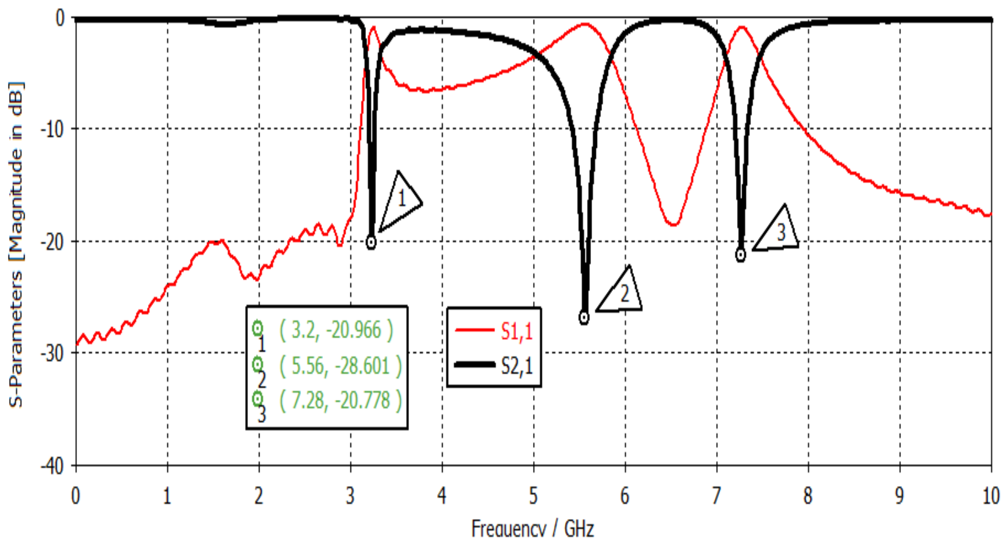


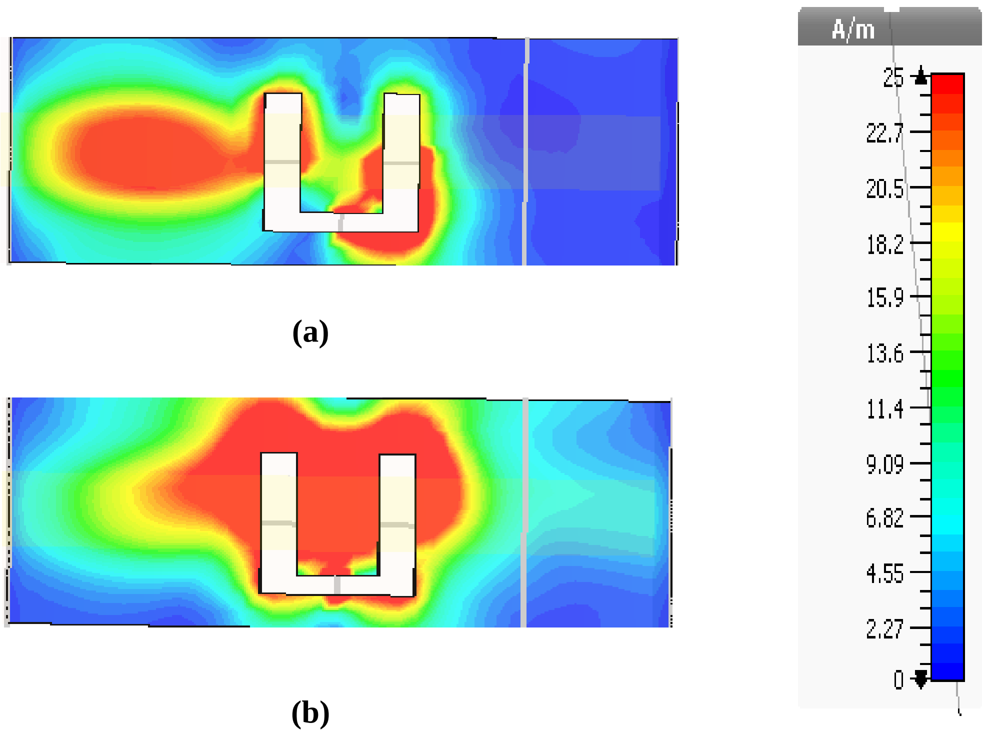
Figure 3. 16 S-parameter for triple-bands BSF

The achieved results of the triple-band BSF are listed in Table 3.5.

Table 3.5 Triple-band bandstop filter result

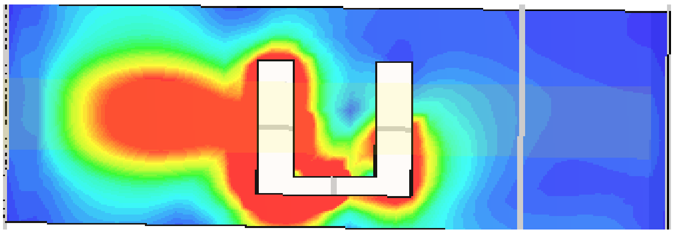
Characteristics	Band 1	Band 2	Band 3
Operating frequency (GHz)	3.2	5.56	7.28
-3dB bandwidth (GHz)	0.177	0.9	0.5
Fractional BW (%)	5.5	16.2	6.9
Insertion loss (dB)	20.96	28.6	20.77

Figure 3.17 shows the current distributions of the proposed triple-band-BSF at the rejection band frequencies 3.2 GHz, 5.56 GHz and 7.28 GHz. From Figure 3.17, it is observed that the current flows are more dominant around the DGS-unit/right-side-feeding-line and the transmission zeros responses of the filter at 3.2/5.56/7.28 GHz are affected from them.



(a)

(b)



(c)

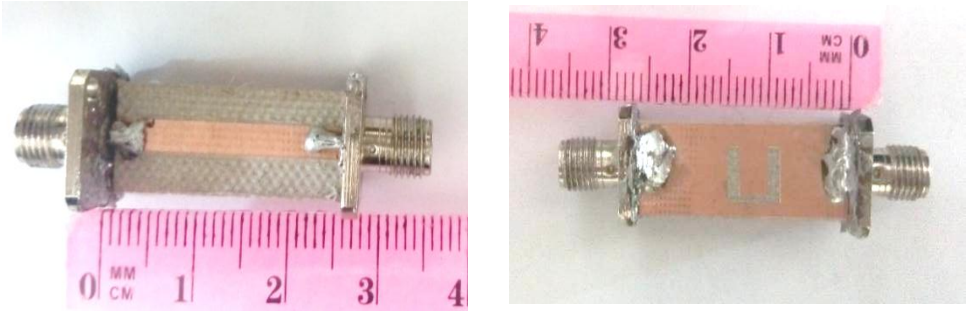
Figure 3.17 Current distributions at (a) 3.2 GHz (b) 5.56 GHz and, (c) 7.28 GHz

3.3 Implementation and Experimental Results

3.3.1 Implementation

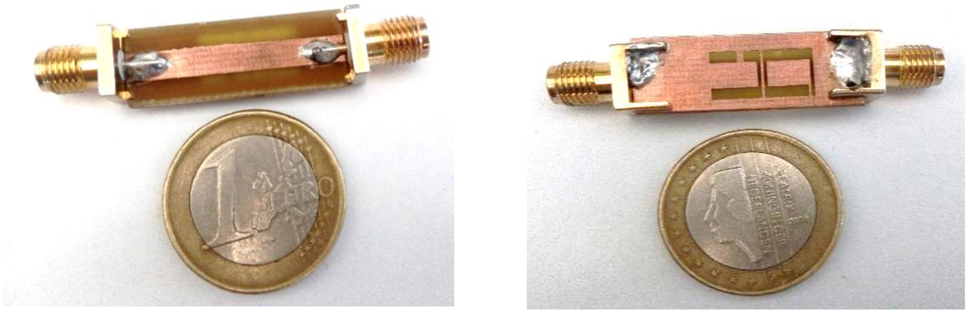
The circuit fabrication was done using an MITS Electronics machine shown in Figure 3.18 whereas the photographies of the fabricated filters are shown in Figures 3.19, 3.20.

Figure 3. 18 PCB prototyping machine.



(a) (b)

Figure 3. 19 Photography of the fabricated single-band BSF (a) Top view and, (b) Bottom view



(a) (b)

Figure 3. 20 Photography of the fabricated dual-band BSF (a) Top view and, (b) Bottom view

3.3.2. Experimental Results

After the fabrication process, the filters performances are measured by using a Rohde & Schwarz VNA as shown in Figure 3.21. Figure 3.22 and Figure 3.23 show the measured/simulated results of the proposed single-band BSF and dual-band BSF, respectively.

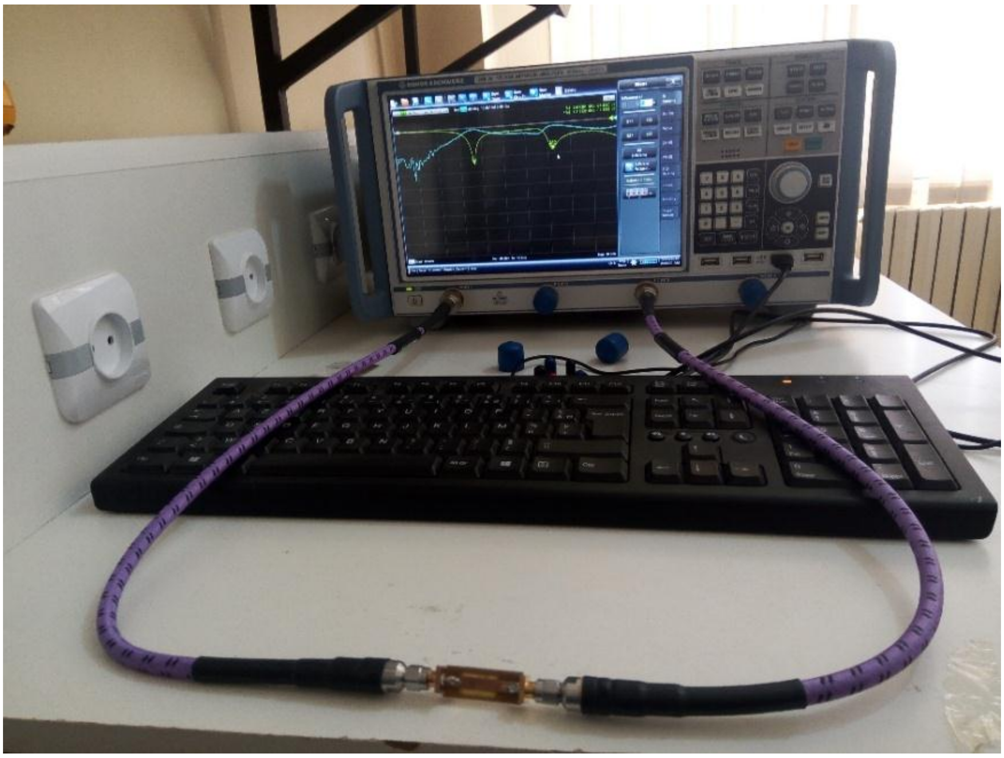


Figure 3. 21 Rohde & Schwarz VNA

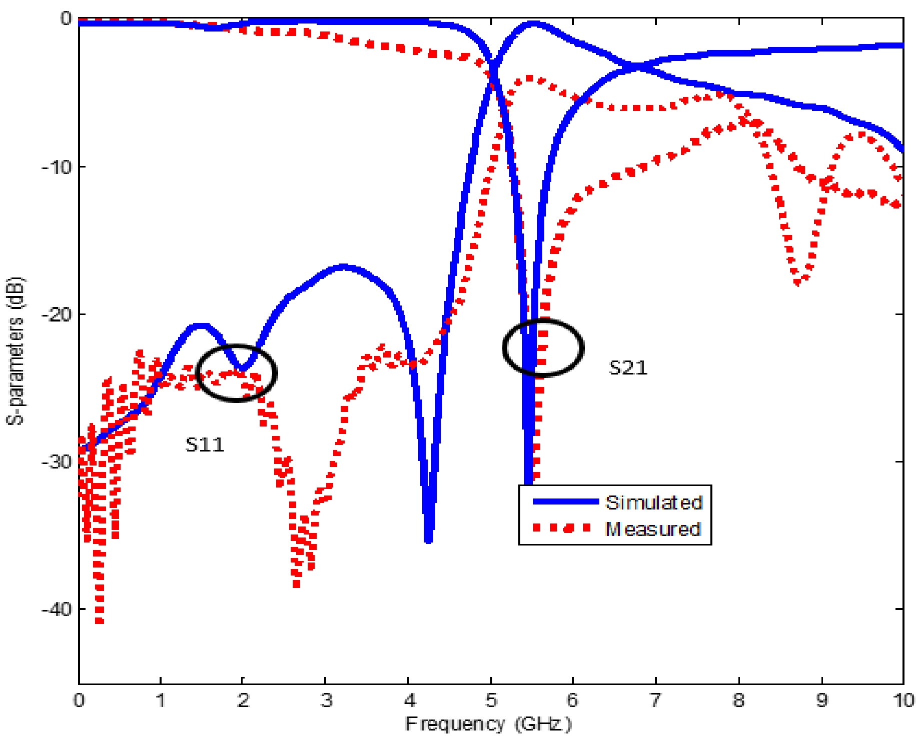


Figure 3. 22 Measured and simulated S-parameters of the proposed single-band BSF

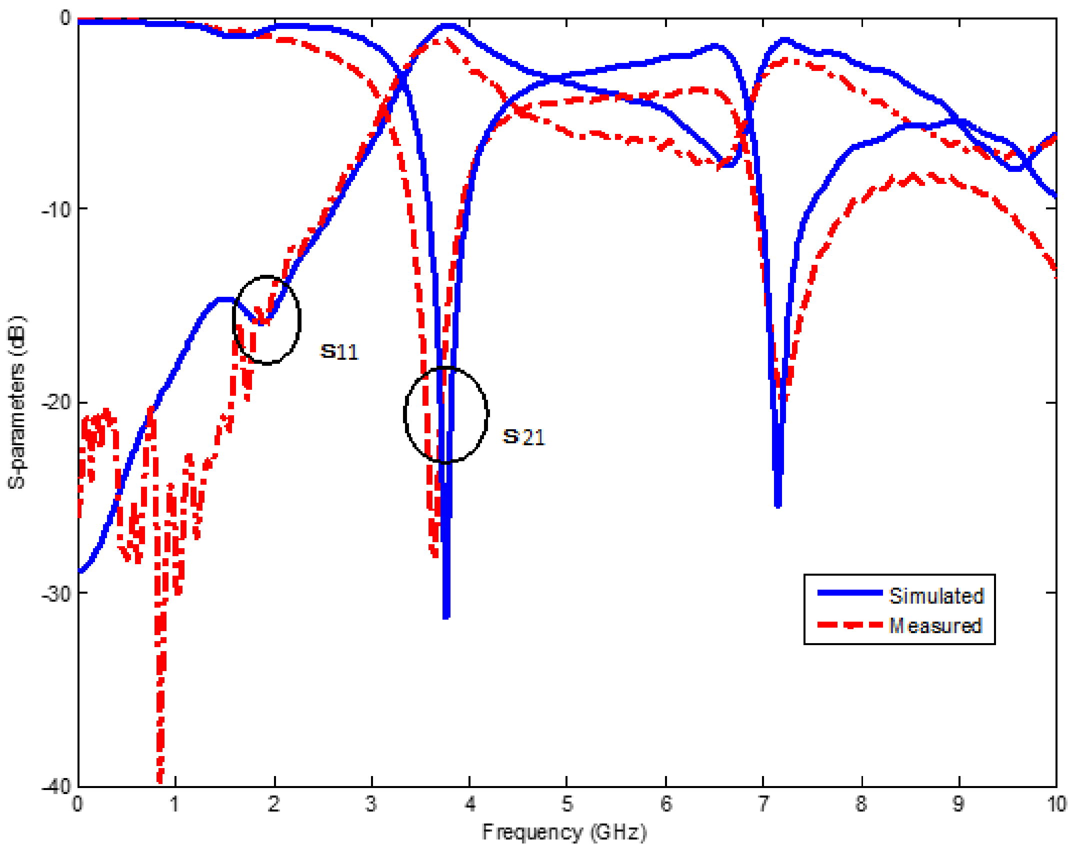


Figure 3. 23 Measured and simulated S-parameters of the proposed dual-band BSF

The results exhibit an acceptable agreement between the measurement and simulation results. The important degradation happens at more than 5 GHz due to the available substrate material which is not suitable for more than C-band applications. Moreover, this degradation is most probably attributed to the tolerance in fabrication process, diversity of material parameters and additional insertion loss of SMA connectors. Despite this small fluctuation, the filters still present satisfactory performance and meet the requirements.

Comparison of the proposed single, dual and triple-bands BSF with other designs is shown in Table 3.5. It is claimed that our proposed structure is good candidate for microwave application compared to [48], [49] and [50]. This filter also has a compact size and good WiMAX signals rejection.

Table 3. 6 Performance Comparison with other BSFs with proposed filter

Ref.	Number of bands	ε_r/h (mm)	Frequency bands (GHz)	Size (mm^2)
[48]	Triple	4.6 /0.8	0.9 /1.59/2.15	15.2×82.4
[49]	Triple	2.55/1.5	2.37/ 3.54/5.01	41.6 ×8.4
[50]	Triple	2.2/1.575	2.36/ 3.48/ 5.16	21.1 × 9.1
Proposed filters	Single	4.3/1.62	5.46	28.4×10.2
	Dual		3.73/7.72	
	Triple		2.26/5.56/7.23	

3.4 Conclusion

In this chapter, simple multiband BSF structures based on DGS technique have been proposed. The presented BSFs are loaded by SMD capacitors for dual and triple stopbands operated at 3.69/7.63 GHz and 3.2/5.56/7.28 GHz, respectively. An additional dual-band BSF structure without using SMD capacitors operated at 3.69/7.63 GHz has been as well designed. Due to their satisfactory stopband performances, the proposed filters can be useful for wide applications with dual and triple bands rejection for WiMAX/C bands.

Conclusion and Suggestions for Further Scope

In this work, multiband BSFs based on DGS technique have been proposed. The design, implementation and measurement have been accomplished respectively using the CST software, an MITS Electronics PCB Prototyping machine and a Rohde and Schwarz VNA.

The first BSF structure has given a single rejected frequency at around 5.46 GHz with an insertion loss of 33 dB which is acceptable for communication systems with a single band rejection for WiMAX band.

The second one based on the first structure has been loaded by an SMD capacitor to achieve the dual band BSF characteristics. The rejected frequencies that have been achieved are 3.69 GHz and 7.63 GHz with insertion losses of 23.5 dB and 20.6 dB, respectively. The same structure has been modified to achieve the 3.77/7.16 GHz dual band BSF without using SMD capacitors. For triple-band BSFs, another SMD capacitor is added to the design which has given three rejection frequencies that are 3.2 GHz, 5.56 GHz and 7.28 GHz. This filter type can be utilized for rejecting WiMAX/C bands.

The single band and dual band BSFs without using SMD capacitors have been fabricated and measured. The results have shown an acceptable agreement between the measurement and simulations. Small degradation in the performance was most probably attributed to the tolerance in fabrication process, diversity of material parameters and additional insertion loss of SMA connectors. Despite this small fluctuation, it has been shown that the proposed filters present satisfactory performance in terms of high insertion loss, good stopband selectivity and small size.

Finally, some suggestions for further work are briefly outlined as follows:

- An integrated digital capacitor (IDC) may be introduced in the filters design;
- The second goal would be the circuit modeling of the proposed single/dual/triple bands BSFs

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Computer Simulation Technology CST

CST offers accurate, efficient computational solutions for electromagnetic design and analysis. The 3D EM simulation software is user-friendly and enables you to choose the most appropriate method for the design and optimization of devices operating in a wide range of frequencies.

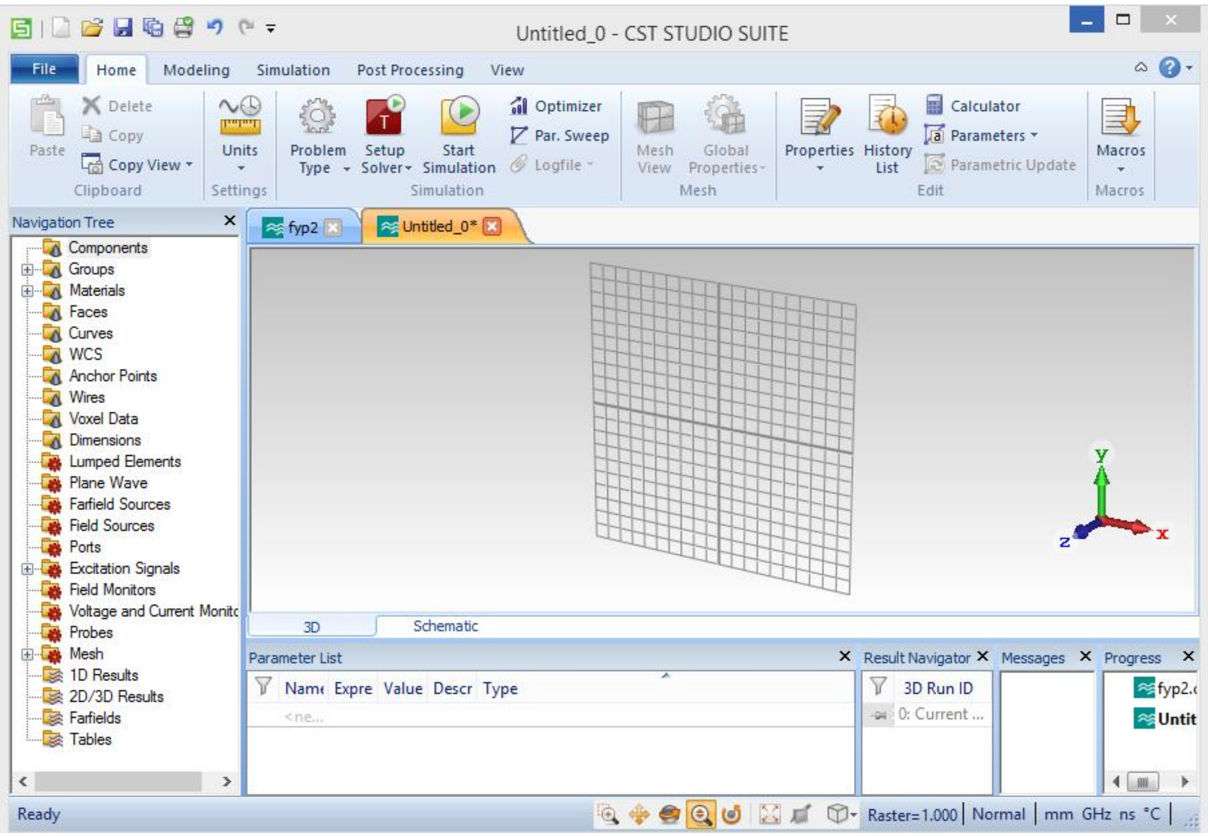


Figure 1 The graphical interface of the CST.

CST enables the fast and accurate analysis of high frequency (HF) devices such as antennas, filters, couplers, planar and multi-layer structures and SI and EMC effects. Exceptionally user friendly, CST quickly gives you an insight into the EM behavior of your high frequency designs.

CST promotes Complete Technology for 3D EM. Users of software are given great flexibility in tackling a wide application range through the variety of available solver technologies. Besides the flagship module, the broadly applicable Time Domain solver and the Frequency Domain solver, CST offers further solver modules for specific applications. Filters for the import of specific CAD files and the extraction of SPICE parameters enhance design possibilities and save time. In addition, CST can be embedded in various industry standard workflows through the CST STUDIO SUITE® user interface.

APPENDIX B

MATLAB Script

The MATLAB script used in the comparison between the simulated and measured results is:

```
% Representation of the data
clear all
close all
clc
% ******load the meausurments Data*****************
load SINGLE_BSF_MEAS.txt;
Data=SINGLE_FNL_MEAS;
fm=Data(:,1);
s11m=10.*log(sqrt(Data(:,2).^2+Data(:,3).^2)); % measures S11
magnetude vector
s21m=10.*log(sqrt(Data(:,4).^2+Data(:,5).^2)); % measures S21
magnetude vector
% **load the simulation Data******************
load BPF_FNL_SIMU.txt;
Datas=SINGLE_BSF_SIMU;
fs=Datas(:,1).*10^9;
s11s=Datas(:,2); % Simulated S11
s21s=Datas(:,3); % simulated S21
% ******Plot************************************
%plot(fs,s11s,fs,s21s)
plot(fs,s11s,'.-blue',fm,s11m,'.-red',fs,s21s,'.-blue',fm,
s21m,'.-red')
legend('Simulated','Measured')
xlabel('Frequency (GHz)');
ylabel('S-parameters (dB)')
```

APPENDIX C

SMD Ceramic Capacitors

Description:

MLCC consists of a conducting material and electrodes. To manufacture a chip-type SMT and achieve miniaturization, high density and high efficiency, ceramic condensers are used. WTC's MLCC is made by NP0, X7R and X5R dielectric material and which provides product with high electrical precision, stability and reliability.

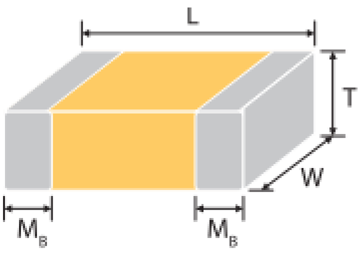
Features:

- A wide selection of sizes is available (0402 to 1210)
- High capacitance in given case size
- Capacitor with lead-free termination (pure Tin)

Applications:

- For general digital circuit
- For power supply bypass capacitors
- For consumer electronics
- For telecommunication

External dimension



Size Inch (mm)	L (mm)	W (mm)	T (mm)/Symbol		Remark	MB (mm)
0402 (1005)	1 ±0.05	0.5 ±0.05	0.5 ±0.05	N	#	0.25 +0.05/-0.1
0603 (1608)	1.6 ±0.1	0.8 ±0.1	0.8 ±0.07	S	-	0.4 ±0.15
	1.6 +0.15/-0.1	0.8 +0.15/-0.1	0.8 +0.15/-0.1	X	-	
0805 (2012)	2 ±0.15	1.25 ±0.1	0.6 ±0.1	A	-	0.5 ±0.2
			0.8 ±0.1	B	-	
			1.25 ±0.1	D	#	
	2 ±0.2	1.25 ±0.2	1.25 ±0.2	I	#	
1206 (3216)	3.2 ±0.15	1.6 ±0.15	0.8 ±0.1	B	-	0.6 ±0.2
			0.95 ±0.1	C	-	
			1.15 ±0.15	J	#	
			1.25 ±0.1	D	#	
			1.6 ±0.2	G	#	
	3.2 +0.3/-0.1	1.6 +0.3/0.1	1.6 +0.3/-0.1	P	#	
1210 (3225)	3.2 ±0.3	2.5 ±0.2	0.95 ±0.1	C	#	0.75 ±0.25
			1.25 ±0.1	D	#	
	3.2 ±0.4	2.5 ±0.3	1.6 ±0.2	G	#	
			2 ±0.2	K	#	
			2.5 ±0.3	M	#	
1812 (4532)	4.5 ±0.4	3.2 ±0.3	1.25 ±0.1	D	#	0.75 ±0.25
			2 ±0.2	K	#	

APPENDIX C

The capacitors which are used in the proposed filter are available in Mulicomp company [54]

Capacitance Range (NP0 Dielectric)

Dielectric	NP0														
Size	0402					0603					0805				
Rated Voltage	10	16	25	50	100	10	16	25	50	100	10	16	25	50	100
0.1pF (0R1)	N	N	N	N											
0.2pF (0R2)	N	N	N	N											
0.3pF (0R3)	N	N	N	N											
0.4pF (0R4)	N	N	N	N											
0.5pF (0R5)	N	N	N	N	N	S	S	S	S	S	A	A	A	A	A
0.6pF (0R6)	N	N	N	N	N	S	S	S	S	S	A	A	A	A	A
0.7pF (0R7)	N	N	N	N	N	S	S	S	S	S	A	A	A	A	A
0.8pF (0R8)	N	N	N	N	N	S	S	S	S	S	A	A	A	A	A
0.9pF (0R9)	N	N	N	N	N	S	S	S	S	S	A	A	A	A	A
1.0pF (1R0)	N	N	N	N	N	S	S	S	S	S	A	A	A	A	A

Figure 2 datasheet of the SMD capacitors