Design of Ultra-Wide Bandpass Filters Using Electromagnetic Band Gap

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Abstract—In this study, a new technique for the design of ultrawide bandpass filters with spurious suppression over a very wide band is presented. The method consists on the combination of a well-known analytical design approach to achieve wide bandwidths with an electromagnetic bandgap structure, which is fundamental for spurious suppression. To illustrate the technique, a microstrip of ultra-wide bandpass filter centered at 3.4 GHz with a bandwidth covering 4.8 GHz is implemented in an FR-4 Epoxy glass substrate (permittivity ἐr= 4.4, thickness h= 1.6 mm). Measured filter characteristics are good with in-band insertion losses below 0.90 dB and return losses better than 10 dB. Out-of-band performance is also good with spurious passband attenuation higher than 30 dB up to at least 20 GHz**.**

Index Terms—Electromagnetic bandgap (EBG), microstrip filters, ultra-wideband (UWB) technology

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1. INTRODUCTION

The term microwaves may be used to describe electromagnetic (EM) waves with frequencies ranging from 300 MHz to 300 GHz, which correspond to wavelengths (in free space) from 1 m to 1 mm. The EM waves with frequencies above 30 GHz and up to 300 GHz are also called millimeter waves because their wavelengths are in the millimeter range (1–10 mm). Filters play important roles in many RF/microwave applications. They are used to separate or combine different frequencies. The electromagnetic spectrum is limited and has to be shared; filters are used to select or confine the RF/microwave signals within assigned spectral limits.

Over the last years, the design of wide and ultra-wide bandpass filters is generating a great interest due to the fast development of broadband wireless communication systems. Traditional methods to implement ultra-wide bandpass filters usually introduce spurious bands. These undesired bands become an important drawback for ultra-wide bandpass filters performance due to their proximity to the passband of interest. There are several techniques to suppress the higher unwanted harmonics in a Band-pass filter. In this study, a new technique for the design of ultra-wide bandpass filters with harmonic passband suppression is proposed [1] [2]. To this end, a standard ultra-wide bandpass filters design approach is combined with a Electromagnetic Bandgap structure i.e. EBG [3], which is able to inhibit signal propagation over a very wide band. As will be shown, this design methodology allows for the implementation of ultra-wide bandpass filters with wide stopbands.

The ultra-wide bandpass filters design methodology used in this study was first introduced by Levy as a new class of prototype filters with applications to mixed lumped/distributed component design. The conventional ultra-wide bandpass filter is designed using this concept to get multiple bands. Next to eliminate the spurious bands there are multiple options. One possibility is to cascade a low-pass filter at the output stage, but this procedure increases the overall size of the device. It is, therefore, more convenient to combine (mix) both the low-pass and the bandpass filter structures. So to reduce the size and to suppress the spurious bands the concept of Electromagnetic Bandgap structure is used [6].

Microstrip filters play an important role in rejecting higher harmonics and spurious response for microwave, millimeter wave, and THz applications. Now to further reduce the size of the propose filter spur lines are used to reject the higher harmonics and provide good out of band performance.

This chapter is organized as follows. The overview of filters with its types and responses is presented in section 1.2. Next in section 1.3 the basics of ultra-wide band technology is presented. Section 1.4 outlines the main motivations behind this thesis. The main objective of the study is highlighted in section 1.5. Section 1.6 gives the detailed explanation of the problem statement which is being carried out to rectify through this study. Finally section 1.7 presents the outline of this Master's thesis.

2.Ultra wideband technology

Any technology having a spectrum that occupies BW>1/4 fc or > 1.5 GHz (proposed FCC definition) can be termed as ULTRA Wideband Technology. History started with radar applications for military use recent advances in silicon process and switching speeds is moving it into the commercial domain.

Ultra wideband is a radio technology that can be used at very low energy levels for short-range high-bandwidth communications by using a large portion of the radio spectrum. UWB has traditional applications in non-cooperative radar imaging. Most recent applications target sensor data collection, precision locating and tracking applications.

UWB communications transmit in a way that doesn't interfere largely with other more traditional narrow band and continuous carrier wave uses in the same frequency band. However first studies show that the rise of noise level by a number of UWB transmitters puts a burden on existing communications services. This may be hard to bear for traditional systems designs and may affect the stability of such existing systems. The Federal Communications Commission (FCC) has mandated legal operation of UWB transmission in the range of 3.1 GHz to 10.6 GHz.

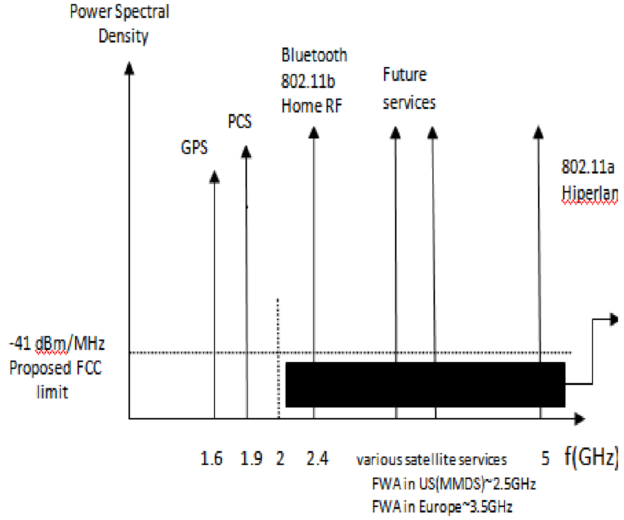


Figure 2.1 Ultra wideband Technology Spectrum

3.Objectives of the work

The basic equation for size reduction percentage is

$$Size\ reduction\ percentage = \frac{Area_{(conventional)} - Area_{(proposed)}}{Area_{(conventional)}} * 100$$

To reduce the size of the device we can either implement an Electromagnetic bandgap structure with proper electrical length and phase shift or by bending the terminating line, transmission line or the stubs and keeping intact with their characteristic impedance and the electrical length. Another thing to be realised is a good out of band performance by proper rejection outside the passband. This can be achieved through the spur lines implemented at the inputs and outputs of the proposed filter design with bend terminating lines.

3.1Ultrawide Bandpass Filter Implementation

In 1970, Levy proposed a new class of distributed filters consisting of a cascade of shunt stubs of equal electrical length Θ_c (at the frequency f_c) alternating with uniform transmission lines, each of twice the stub electrical length $(2\Theta_{c})$. Figure 3.1 shows the schematic of this filter structure [6], [23]. A very interesting characteristic of these filters is that by using *n* stubs, an insertion function of degree 2*n*-1 is implemented. If the stubs are short circuited, the proposed technique may be used to design bandpass filters with wide bandwidths. Besides a good control of the bandpass characteristics, these filters provide also nearly constant group delay over the passband.

Highpass filters can also be constructed from distributed elements such as commensurate (equal electrical length) transmission-line elements. Since any commensurate network exhibits periodic frequency response, the wide-band bandpass stub filters may be used as pseudo highpass filters as well, particularly for wide-band applications, but they may not be optimum ones. This is because the unit elements (connecting lines) in those filters are redundant, and their filtering properties are not fully utilized.

The type of filter to be discussed is shown in Figure 3.1, which consists of a cascade of shunt short-circuited stubs of electrical length Θ_c at some specified frequency f_c (usually the cutoff frequency of high pass), separated by connecting lines (unit elements) of electrical length $2\Theta_c$. Although the filter consists of only *n* stubs, it has an insertion function of degree 2*n*-1 in frequency so that its highpass response has 2*n*-1ripples. This compares with n ripples for an n-stub bandpass (pseudo highpass) filter.

Therefore, the stub filter of figure 3.1 will have a fast rate of cutoff, and may be argued to be optimum in this sense. Figure 3.2 illustrates the typical transmission characteristics of this type of filter, where f is the frequency variable and Θ is the electrical length, which is proportional to f, i.e.,

$$\Theta = \Theta_c \frac{f}{f_c} \qquad (3.1)$$

For highpass applications, the filter has a primary passband from Θ_c to $\pi - \Theta_c$ with a cutoff at Θ_c. The harmonic passbands occur periodically, centered at $\Theta = {}^{3\pi}/_2, {}^{5\pi}/_2, \ldots$. and separated by attenuation poles located at $\Theta = \pi, 2\pi$ ….The filtering characteristics of the network in Figure 3.1 can be described by a transfer (insertion) function $|s_{21}(\Theta)|^2 = {}^1/_{[1+\varepsilon^2 F_N^2(\Theta)]}$ (3.2)

where ε is the passband ripple constant, Θ is the electrical length as defined in 3.1 and F_N is the filtering function given by

$$F_N(\Theta) = \frac{\left(1+\sqrt{1-x_c^2}\right)T_{2n-1}\left(\frac{x}{x_c}\right) - \left(1-\sqrt{1-x_c^2}\right)T_{2n-3}\left(\frac{x}{x_c}\right)}{2\cos\left(\frac{\pi}{2}-\Theta\right)}$$

(3.3)

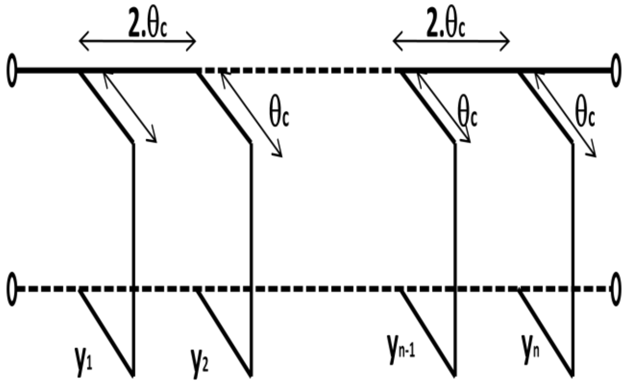


Figure 2.2 Schematic of the ultrawide bandpass filter

where n is the number of short-circuited stubs,

$$x = \sin\left(\frac{\pi}{2} - \Theta\right), \qquad x_c = \sin\left(\frac{\pi}{2} - \Theta_c\right) \qquad (3.4)$$

And $T_n(x) = \cos(n\cos^{-1}x)$ is the Chebyshev function of the first kind of degree n. Theoretically, this type of highpass filter can have an extremely wide primary passband as Θ_c becomes very small, however, this may require unreasonably high impedance levels for short-circuited stubs. Nevertheless, practical stub filter designs will meet many wide-band applications. Table 3.1 tabulates some typical element values of the network in Figure 3.1 for practical design of optimum highpass filters with two to six stubs and a passband ripple of 0.1 dB for Θ_c = 25°, 30°, and 35°. Note that the tabulated elements are the normalized characteristic admittances of transmission line elements, and for given terminating impedance Z_0 the associated characteristic line impedances are determined by

$$Z_t = {}^{Z_0}/_{y_t} \qquad (3.5)$$

$$Z_{t,t+1} = {}^{Z_0}/_{y_{t,t+1}}$$

$$\left(\frac{\pi}{\Theta_c} - 1\right)1.4 = 5.8 \qquad (3.6)$$

This gives Θc= 0.610 radians or Θc= 35°. Assume that the filter is designed with three shorted-circuited stubs. From table 3.1, for n = 3 and $\Theta c = 35^0$, the element value y_1 is calculated as follows:

$$y_1 = y_3 = 0.40104$$
$$y_{1,2} = y_{2,3} = 1.05378$$
$$y_2 = 0.48294$$

These interpolated element values are well within one percent of directly synthesized element values. The filter is supposed to be doubly terminated by Z_0= 50 ohms. Using (3.5), the characteristic impedances for the line elements are

$$\mathrm{Z}_1 = \mathrm{Z}_3 = \frac{\mathrm{Z}_0}{\mathrm{y}_1} = \frac{50}{0.40104} = 124.676 \qquad (3.7)$$

$$\mathrm{Z}_{1,2} = \mathrm{Z}_{2,3} = \frac{\mathrm{Z}_0}{\mathrm{y}_{1,2}} = \frac{50}{1.05378} = 47.448 \qquad (3.8)$$

$$\mathrm{Z}_2 = \frac{\mathrm{Z}_0}{\mathrm{y}_2} = \frac{50}{0.48294} = 103.53 \qquad (3.9)$$

Table 1.1 shows the circuit parameters for UWB band pass filter with three short-circuited stubs when ϴc= 35° (that implies a 4.8 GHz bandwidth) [4]. Figure 3.3 shows microstrip layout of a distributed UWB band pass filter using three short-circuited stubs.

Table 1.1 Circuit parameters for UWB bandpass filter with four short-circuited stubs with ϴc = 35°.

Stublineparameter Connecting line parameters		
Characteristic Characteristic impedance(Ω) impedance(Ω)	Width(mm) Width(mm)	Length(mm) Length(mm)
Z_1=Z_3=124.676	W_1=W_3=0.291	L_1=L_3=17.22
$Z_{1,2}$=$Z_{2,3}$=47.448	$W_{1,2}$=$W_{2,3}$=3.22	$L_{1,2}$=$L_{2,3}$=31.88
Z_2=103.53	W_2=0.568	L_2= 16.96

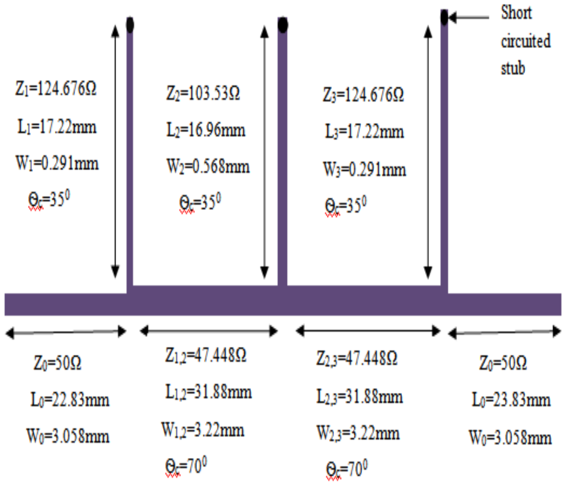


Figure 3.1Layout of the conventional ultrawide bandpass filter

4.Electromagnetic Bandgap Design

There are multiple options to eliminate spurious bands in bandpass filters. One possibility is to cascade a low-pass filter at the output stage, but this procedure increases the overall size of the device. It is, therefore, more convenient to combine (mix) both the low-pass and the bandpass filter structures.

To this end, EBGs implemented by capacitive loaded transmission lines are useful [11], [12]. Namely, by substituting the inter-stub transmission lines by transmission lines periodic loaded with shunt connected capacitances, the undesired spurious bands can be efficiently suppressed. Obviously, to preserve the in-band characteristics, the EBG-based transmission lines placed between the shunt connected stubs must fit the impedance and phase shift ($2\Theta_c$ at f_c) requirements.

Harmonic passband suppression in bandpass filters by using sinusoidal patterned EBGs has been demonstrated previously [17], but capacitive loaded EBG transmission lines are also effective and they provide certain size reduction due to the slow wave effect associated to the presence of the shunt capacitors. This justifies the type of EBGs that has been used in this study. Moreover, the stopband of capacitive loaded transmission lines can be easily controlled, and it can be extended up to relatively high frequencies [20], [24]. This will be important to achieve a wide stopband in the new EBG-based ultra-wide bandpass filters. The equivalent-circuit model of the capacitive loaded EBG transmission line is depicted in Figure 3.4, and the physical layout of the structure that will be integrated with the ultra-wide bandpass filters is shown in Figure 3.5. By assuming that the transmission lines between adjacent patch capacitors can be described by the per-section inductance L and capacitance C, the structure exhibits a low-pass behaviour with a cutoff (or Bragg) frequency given by [5].

$$f_B = \frac{1}{\pi\sqrt{L(C+C_{ls})}} \qquad (3.10)$$

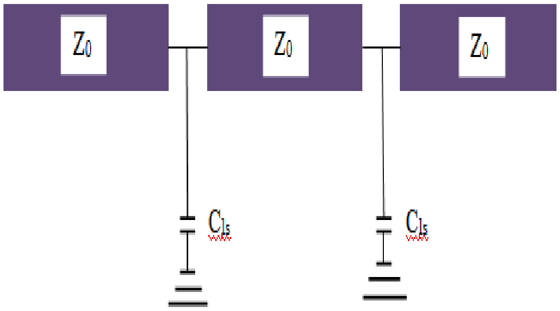


Figure 4.1 Equivalent-circuit model of the EBG capacitive loaded transmission lines.

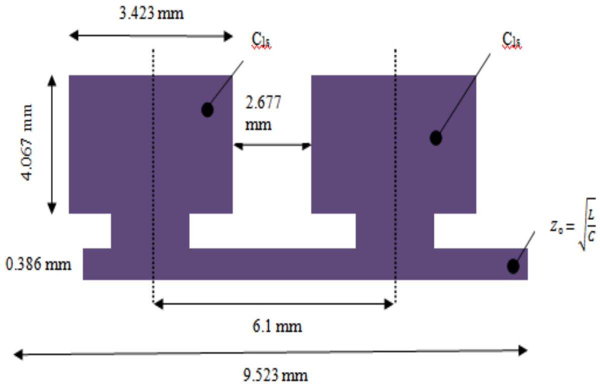


Figure 4.2 Layout of the structure in microstrip technology.

Here C_{ls} is the loading capacitance. The characteristic (or Bloch) impedance of the line Z_L and the impedance of the unloaded line Z_0 are given, respectivelyby $Z_L = \sqrt{\frac{L}{C+C_{ls}}}$ (3.11)

$$Z_0 = \sqrt{\frac{L}{C}} \qquad (3.12)$$

and the lower frequency limit of the first spurious is given by

$$f_s = \frac{1}{2\sqrt{LC}} \qquad (3.13)$$

Finally, the phase shift per cell can be obtained by a second order approximation of the well-known dispersion equation of a periodically loaded transmission line [4], [21]

$$\cos(\emptyset) = \cos\left(2\pi f\sqrt{LC}\right) - \frac{2\pi f C_{ls} Z_0}{2}\sin\left(2\pi f\sqrt{LC}\right) \quad (3.14)$$

obtaining the following expression:

$$\emptyset = 2\pi f\sqrt{L(C)(C_{ls})} \quad (3.15)$$

Equations (3.11) and (3.15) are valid sufficiently below the Bragg frequency of the capacitively loaded EBG. As frequency approximates to f_B, dispersion becomes significant and the Bloch impedance becomes extreme. However, this behaviour is only significant in close proximity to the Bragg frequency. It has been considered that within the passband of interest, this approximation holds and, indeed, the results of the final fabricated device point out a good behaviour.

Obviously the number of equations exceeds the number of unknowns (L, C, and C_{ls}). To determine the parameters of the structure, we have set the Bloch impedance to

Z_L= 47 Ω and the phase shift $\emptyset = 35^0$ of the basic cell to at f_c = 1.4 GHz in order to achieve the required 70 with a two-stage structure. Additionally, to obtain a huge stopband in the final filter, the spurious frequency of the EBG structure has been set to f_s = 22 GHz. The electrical parameters have been determined from the following equations, which are directly obtained by inverting (3.11), (3.14), and (3.16):

$$Z_0 = \sqrt{\frac{L}{C}} = 123.5\ \Omega \quad (3.16)$$

$$L = \frac{Z_L \emptyset}{2\pi f_c} = 3.1\ \text{nH} \quad (3.17)$$

$$C = \frac{\pi f}{2 Z_L \emptyset f_s^2} = 0.17\ \text{pF} \quad (3.18)$$

$$C_{ls} = \frac{L}{Z_L^2} - C = 1.2\ \text{pF} \quad (3.19)$$

5.Design of the Conventional Ultrawide Bandpass Filter

Firstly, we simulate the transmission lines for proper impedance matching along with the terminating impedance line. The design is simulated on moments method software tool (IE3D Software Release – version14, developed by M/s Zeland Software Inc.). The design is implemented on glass/epoxy' FR-4 substrate with dielectric constant ε_r=4.4, substrate thickness h=1.6mm and loss tangent=0.016. The electrical length Θ_c of the transmission line is calculated as 70^0. The design and the simulated response are shown in Figure 4.1 and Figure 4.4 respectively.

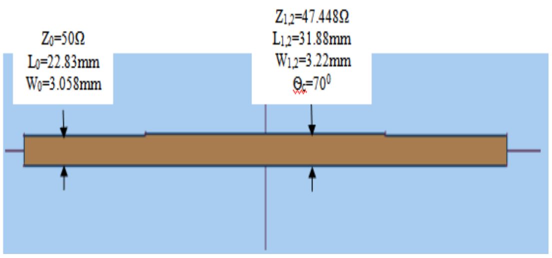


Figure 4.3 Simulated design of transmission lines

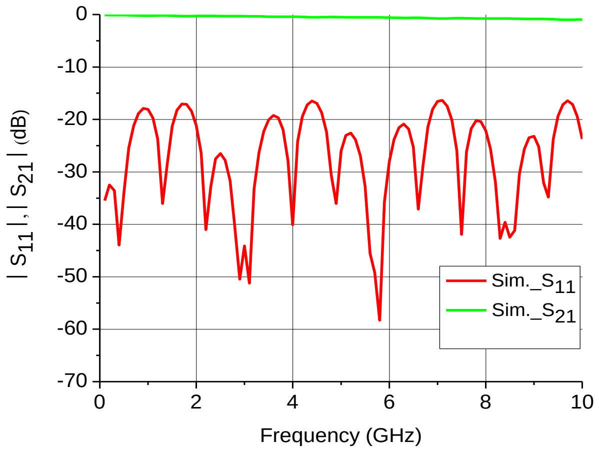


Figure 4.4 Simulated response of the transmission line

The simulated response exhibits an all pass filter response with no bands.

Next the Stubs are inserted between transmission line for impedance matching. These stubs are short circuited as shown in Figure 4.3. The design is simulated on on moments method software tool (IE3D Software Release – version14, developed by M/s Zeland Software Inc.) and the simulated response is shown in Figure 4.4. The design is implemented with:

Filter Specifications
Order of the filter (n) = 3
Center Frequency(f_c)=3.4 GHz
Electrical length ϴc=35^0(i.e. a 4.8 GHz bandwidth)
Substrate specifications
Permittivity (ε_r) = 2.4
Height of the substrate (h) = 0.675 mm
Loss tangent (δ) =0.016

5.1.Electromagnetic Bandgap Structure Design

Capacitive loaded EBG transmission lines are demonstrated in the Figure 4.5 and the design response is shown in Figure 4.6. The design is implemented on FR-4 substrate.

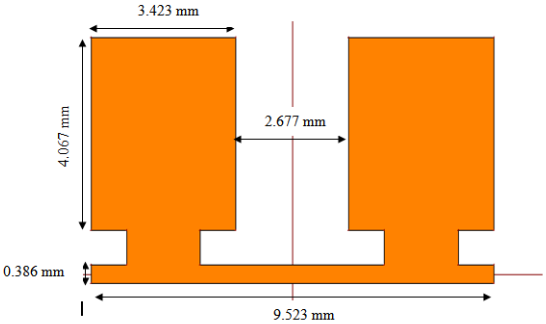


Figure 5.1. Electromagnetic bandgap structure layout.

The simulated response exhibits a lowpass response with huge stopband upto 10 GHz. The cutoff frequency of the lowpass response is 3.4 GHz.

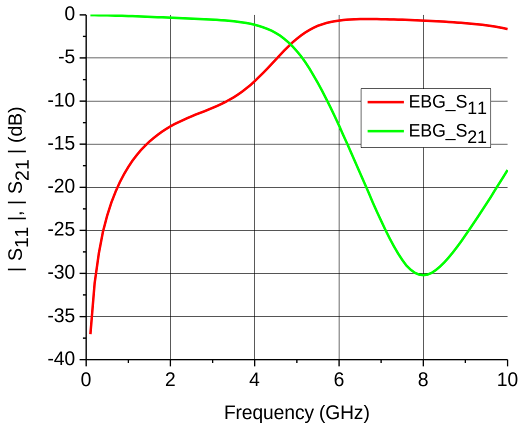
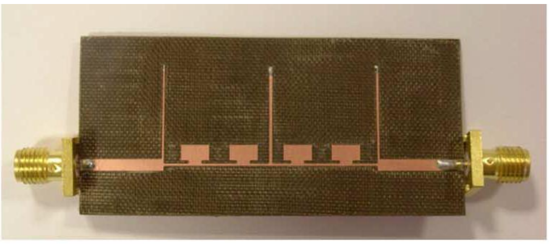


Figure Simulated response of the EBG structure



EBG-BASED ULTRA-WIDE BANDPASS FILTER

6.CONCLUSION

The underlying idea of this thesis is to investigate the out of band performance and size reduction of the traditionally implemented ultrawide bandpass filter for bandpass filters to be designed in future. The ultrawide bandpass system discussed in section 3.1.2 is considered as example case. The conventional and proposed filter has been designed and simulated using moments method software tool (IE3D Software Release – version14, developed by M/s Zeland Software Inc.) and the results obtained as been discussed. The bandpass filter is physically implemented on a FR-4 'Glass/Epoxy' substrate having dielectric constant ε_r=4.4, substrate thickness h=1.6 mm and loss tangent=0.016 using conventional fabrication process.

- Firstly, an extensive review of the literature about ultrawide bandpass filters was carried out. Drawing on the existing literature, Electromagnetic Bandgap based UWB filter design was investigated in Chapter 2. Different methods for size reduction, improve out of band performance and to mitigate interference is shown. These schemes include the Electromagnetic Bandgap structure and spurline techniques.

- This was followed by an ultrawide band pass filter implementation using Levi's method of distributed filters consisting of a cascade of shunt stubs of equal electrical length alternating with uniform transmission lines, each of twice the stub electrical length. This structure is designed and simulated on FR-4 substrate. The simulated responses ensured that a fractional bandwidth of 113% is obtained. Five reflection zeros can be observed in the transmission bands, such as one expects on account of the 2.n-1degree of the filter function (in our case, n=3).

Next to reduce the device size and to suppress the spurious bands EBGs implemented by capacitive loaded transmission lines are implemented. This

- structure is designed and simulated on FR-4 substrate. The simulated result shows a lowpass response with huge stopband.

- Further this EBG structure is employed on the conventional design for the reduction in size by 34%. The design is simulated and the simulated frequency response exhibits good in-band characteristics and spurious passband suppression above 15 dB up to at least10 GHz.

Again to reduce the size further the terminating impedance lines are bend such a way to get minimum coupling effect and next to get perfect notch characteristics spurline are implemented at the input and outputs of the propose design. Next the structure is simulated on a FR-4 substrate using IE3D software tool. The simulated and measured frequency response exhibits good out of band characteristics providing a passband of 3.8 GHz and passband suppression upto 10 GHz. The return loss is 15 dB at the centre frequency.

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