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Electromagnetic Bandgap Structures (EBGS): Implementation of Advanced Technology for Microwave Filter Designing

Navila Rahman Nadi, Sharmin Liaquat Urme

Abstract—Due to the realization of growing demand for larger bandwidth, high capacity Radio Frequency (RF) and microwave devices, new technologies of designing devices are being developed all over the world. On this consequence of latest technologies microwave filters and antennas with Planar Electromagnetic Bandgap Structures is considered as one of the bests. Electromagnetic Bandgap Structures (EBGS) is a new technology to improve the performances of existing RF active and passive devices. The technological design is which is just made upon a dielectric substrate with copper coating on both sides is very simple then any other devices. By etching these copper coating: Transmission line (T-line) on the upper side and EBGS on the ground plan are prepared which shows the performance like stopband, passband and Low Pass Filter (LPF). EBGSs, in recent years, have become most popular due to their low profile, ease of fabrication and integration with monolithic microwave integrated circuits (MMICs). Through out this whole thesis work some parametric studies and several new designs of EBGS are introduced and described. The thesis concerns the planar EBG structures in the forms of conventional circular, square and triangular forms and various patterned dumbbell shaped as well as some hybrid designs of EBGS. In addition, effect of same design area and a proposed method of Filling Factor (FF) calculation are also described in an intention to enlarge efficiency in the field of wireless technologies.

Keywords: Electromagnetic Bandgap Structures (EBGS) , Transmission line (T-line) , Low Pass Filter(LPF) , Radio Frequency (RF).

1 Introduction

EBGSs, in recent years, have become most popular due to their low profile, ease of fabrication and integration with monolithic microwave integrated circuits (MMICs). The goal of this thesis is to get familiariaed with advance microwave filter technology, microwave devices and to become proverbial with EBG assisted microstrip transmission lines as well as to observe the performance of various designs of it. The choice of the proper EBGS structure is a vital issue to achieve better performance of the designed components; hence, some parametric studies are done and several designs are tested and their results are described. Some investigations are focused on the improvement of the performances and it made a transformation into the pattern of the results.

The thesis concerns the planar EBG structures in the forms of conventional circular, square, triangular, hexagonal, rectangular and some hybrid designs. Moreover, it includes observation of Ripple free passband, wider stopband properties, low pass properties as well as multiple stopbands properties of filters. Effect of same etching area and a method of Filling Factor (FF) calculation are also been proposed through this paper. 2Structural Viewpoints:

EBG structures are periodic in nature, which may be realized by drilling, cutting and etching on the metal or substrates. They may be formed in the ground plane or over the substrate. The transmission line can also be modified to form EBG characteristics without having any perturbation in the ground plane. This new idea can be extended to filter, antenna and other microwave component and devices where the complexity of packaging is minimized. The EBG configuration is categorized as shown in figure 1. On the basis of dimension, EBG structures may be divided into 1-D, 2-D and 3-D EBGSs. Following are the descriptions of different EBG structures.

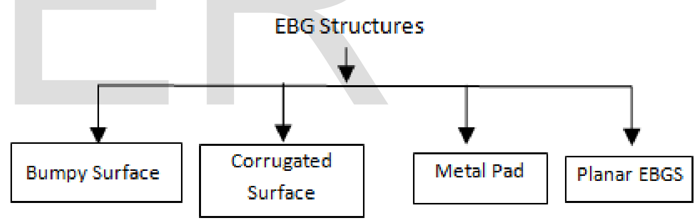

Fig. 1. Configuration of EBGS.

Due to the unique properties of EBG engineered structures, it can be found in many applications of microwave circuit components and devices. To realize microwave filters, mixers, antennas, power amplifiers, phased arrays etc. the stopband and passband has been created by the EBG structures to enhance performances of those devices.

2.1 Designing Factors

With the inclusion of PBGSs the dispersion characteristics of a transmission line change. At first a microstrip transmission line with unperturbed ground plane is designed that does not provide any stopband characteristics. Then the effect is observed on the dispersion characteristics in the form of scattering parameters matrices versus frequency by perturbing the ground plane with uniform circular PBGSs.

2.2 Designing equations

In the PBG engineering it is a conventional rule to use Bragg's condition [13] to calculate the central stopband frequency provided by PBGSs. Under this condition, inter-cell separation (known as period) is approximately equal to half wavelength of the stopband central frequency. From the inter-cell separation, the size of the PBG element is calculated on the basis of FF.

The center frequency of the stopband is calculated approximately with the following expression:

$$\beta a = \pi \qquad (1)$$

Where, a is the period of the PBG pattern, and π is the wave number in the dielectric slab and is defined by expression:

$$\beta = \frac{2\pi f_0}{c}\sqrt{\varepsilon_e} \qquad (2)$$

Where,
f_o = the center frequency of the stopband
ε_e = the effective relative permittivity of the dielectric slab
c = the speed of light in free space

2.3 Simple T-line and its performance:

T-line is just a line with a defined length and width on the upper surface of the substrate which is created by removing copper coating from the surface except the desired region. The figure is shown below where the blue region is a typical T-line whose length is 100 mm and width is 2.2642 mm (calculated by PCAAD for 50Ω microstrip T-line where dielectric constant of the substrate is 2.45 and thickness is 31 mils).

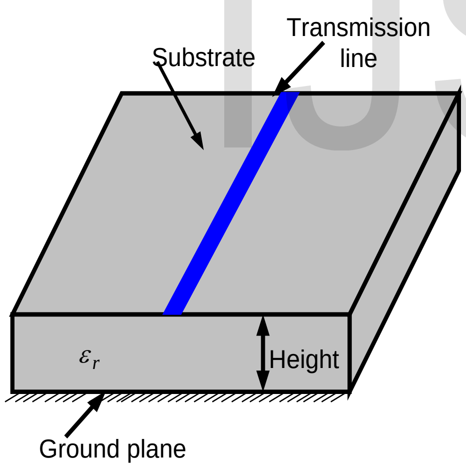

Fig. 2. Geometry of a standard 50-ohm microstrip transmission line on a substrate whose dielectric constant is 2.45 and thickness is 31 mils.

2.4 S-Parameter Performance of a microstrip T-line:

S-Parameter performances are inspected from the plotted curves of the simulation by Zeland ie3d where the curves of S11 (return loss) and S21 (insertion loss) are only shown here. Stopband and passband yield the frequency band width of insertion loss and return loss at -20 dB and -10 dB respectively. The following graph is plotted by Grapher software by taking simulated data from the Zeland ie3d.

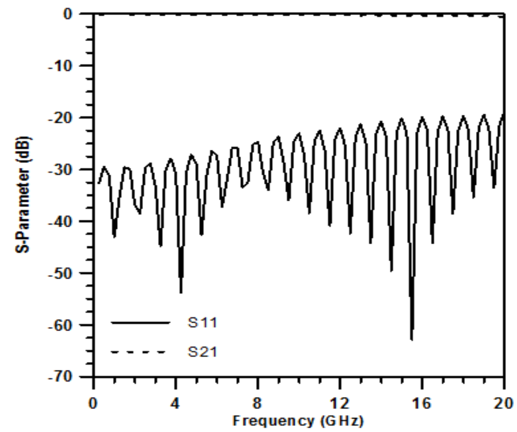

Fig. 3. S-parameter performance of 50 Ω T-line whose length is 100 mm and width is 2.2642 mm.

Within the range of 0-20GHz the signal has transmitted between two ports with negligible loss and there is no stopband formed. The return loss performance of the ideal microstrip line over the whole frequency range is also excellent and < - 10 dB. Since, there is no appreciable insertion loss observed at the s-parameter performance of the T-line, therefore it characterizes an ideal transmission line.

3 SIGNIFICANT TERMINOLOGIES

3.1 S Parameter

A T-line is said to be loaded when transmitter or receiver will be connected with it. There can be several ports on T-line; but for the ease of depiction a standard T-line of two ports will be considered.

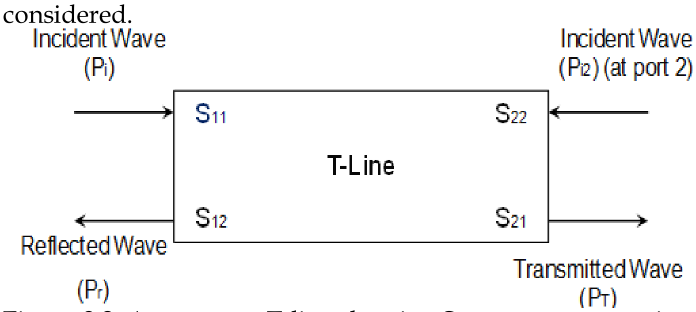

Figure 3.2: A two ports T-line showing S – parameter matrix.
Here, S11 = input port voltage reflection co-efficient.
S12 = reverse voltage gain.
S21 = forward voltage gain.
S22 = output port voltage reflection co-efficient.

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3.2 Return Loss

Calculation of reflection co-efficient in deci-bell (dB) unit is called Return loss. Therefore, return loss (RL) is defined as:
RL = -20 log | Γr | dB. (For voltage)
RL = -10 log | Γr | dB. (For power)

3.3 Insertion Loss (IL):

Calculation of transmission co-efficient in deci-bell (dB) unit is known as Insertion loss. Therefore, Insertion loss (IL) is defined as:
IL = -20 log | ΓT | dB (For voltage)

4 Performance Analysis of Different Shaped EBGS:

To observe the effects of s-parameter performances of different shapes of EBGS the following designs of uniform 1D EBGS are simulated on Zeland ie3d.All the designs are made on the substrate whose thickness is 25 mils and dielectric constant is 2.45 as well as at the beneath of 50Ω microstrip T-line. All of them are of same etching area and the area is calculated from the circular shaped EBGS whose FF is 0.25 and that is 21.36314 mm2.

4.1 Circular Designs

Circular EBGS of this design are made from the equation FF = r/a, here FF = 0.25, a = 10.4308 mm (inner element spacing) and r is the radius of the circular EBGS (= 2.6077 mm) for center frequency 10 GHz.

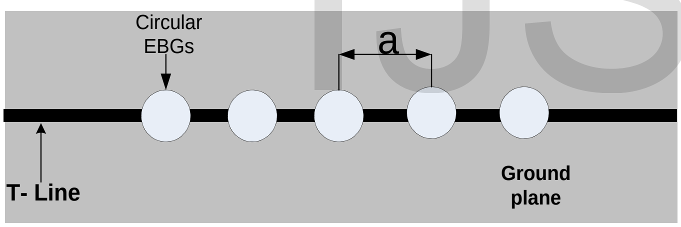

Fig. 3. Circular shaped EBGS designed on 50 Ω microstrip T-line on the substrate of dielectric constant 2.45 and thickness 25 mils.

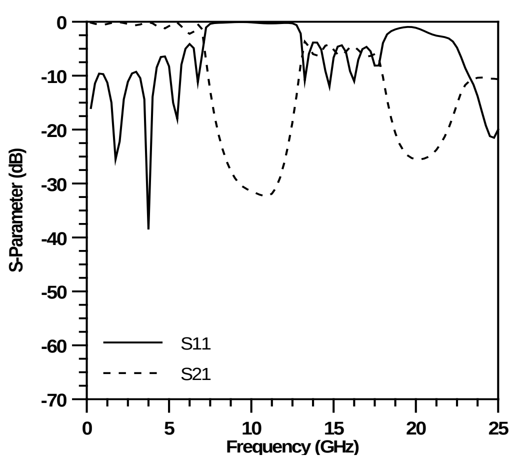

Fig.4. Simulated S-parameters performances of conventional circular shape EBGS.

From the above S-parameter performance we inspect 20dB Insertion Loss band width is 4.472 GHz and Stop Band width at 10dB is 6.81 GHz. The center frequency is found at 10 GHz.

4.2 Square Desings

The area of the square shaped EBGS is calculated by b2=21.36314 mm2. Here b is the arm of the square.

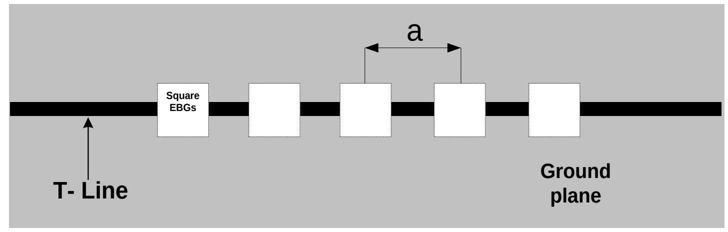

Fig. 5. Square shaped EBGS designed on 50 Ω microstrip T-line on the substrate of dielectric constant 2.45 and thickness 25 mils.

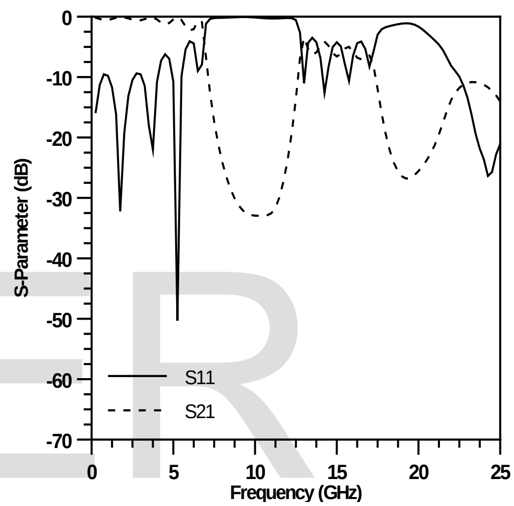

Fig. 6. Simulated S-parameters performances of square shape EBGS.

In this figure, center frequency of Stopband is also occurred at 10 GHz. 10 dB Return Loss Bandwidth is 5.4990 GHz and 20 dB Insertion Loss Bandwidth is 4.52782 GHz. The result is said to be similar to the circular shape EBGS.

4.3 Triangular Desings

Equilateral Triangle is another shape of EBGS that is inspected to observe the performance whose arm (e = 7.024mm) is calculated from the equation,

$$\frac{\sqrt{3}}{4}e^2 = \pi r^2 = 21.36341\text{mm}^2$$

to keep the area as same as circular EBGS. Since, there is no defined option to draw triangle, hence the option of drawing circular shape entity is used by choosing "Number of segments for circle" as 3; however, for this we calculated the radius of the circle from

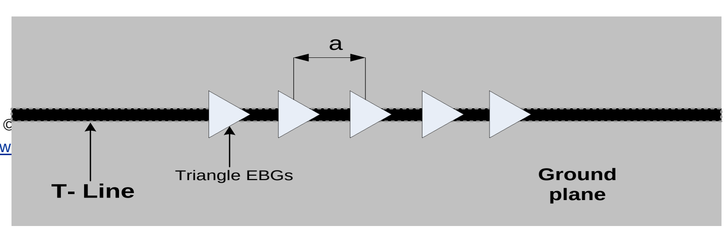

Fig. 7. Equilateral triangular shaped EBGS designed on 50 Ω microstrip T-line on the substrate of dielectric constant 2.45 and thickness 25 mils.

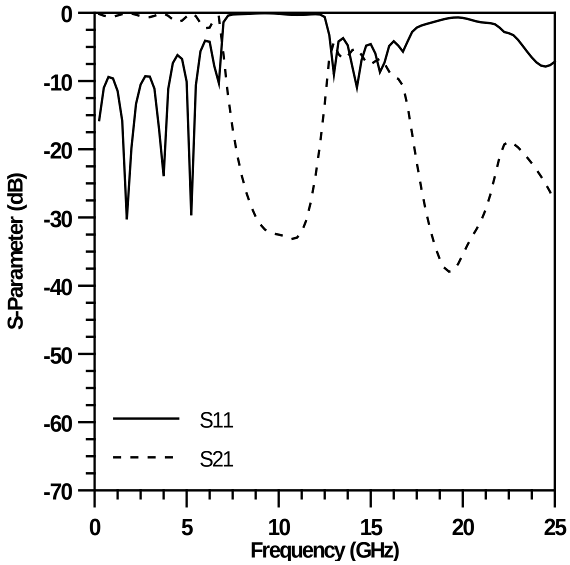

Fig.8. Simulated S-parameters performances of equilateral Triangular shaped EBGS.

Here almost the same results are also observed for the new shaped EBGS. The centre frequency is very much close to 10 GHz and the Return Loss and Insertion Loss are 6.7583 and 4.7682 respectively on first band; but second band is a bit different, however it is not a fact of concern here.

4.4 Data Table

The following table has accumulated all necessary data for observing the results closely.

TABLE 1: DATA TABLE OF S-PARAMETER PERFORMANCES OF DIFFERENT SHAPED OF EBGS.

Shape of Design	10 dB Return Loss Bandwidth - Pass band (GHz)	20 dB Insertion Loss Bandwidth - Stop band (GHz)	Depth of Stopband (at center frequency, 10 GHz)	Ripple Height (dB)	-3 dB Cut-off frequency (GHz)
Circular	6.81	4.472	-31.412	-2.22	7.0723
Square	5.4990	4.52782	-32.9488	-2.2543	6.8407
Triangular	6.7583	4.7682	-32.5175	-2.2306	6.8615
Hexagonal	6.8315	4.5675	-31.58	-2.2845	7.0540

The followed table is clearly showing that the performances of various type (or shaped) of EBGS, where Passand and Stopband width as well as depth of Stopband are very similar to each other. Therefore, it can be said that irrespective shapes and designs the performances are remain almost similar.

Now, for different shape (other than circular shape) what would be the equation of FF? Since there is no such definite formula instead the definition "volumetric ratio of EBGS to unit cell" then a generalized formula is proposed here with the modified definition "ratio of etching area of EBGS to area of Unit cell". As the thickness of the copper layer is very small and negligible to consider as 3-D; therefore, instead of volume, area is taken into account in the new definition.

Hence,

$$FF = \frac{\text{area of EBGS}}{\text{area of unit cell}} \quad (3)$$

Here, assuming the unit cell as a square.
Thus the Equations of FF become for various shapes:
For circular EBGS:

$$FF = \frac{\pi r^2}{a^2} \quad (4)$$

For square shaped EGBs:

$$FF = \frac{b^2}{a^2} \quad (5)$$

For Equilateral Triangular shaped EGBs:

$$FF = \frac{\sqrt{3}e^2}{4\,a^2} \quad (6)$$

For Hexagonal EBGS:

$$FF = \frac{3\sqrt{3}t^2}{2\,a^2} \quad (7)$$

5. OPTIMUM FILLING FACTOR (FF) ANALYSIS:

Filling Factor (FF) is a fractional quantity that is used to determine the size of the conventional EBG structures for a particular unit cell to keep the center frequency at particular point. As depiction, if unit cell length is 10.4308 mm which is denoted as a when center frequency is assumed as 10 GHz then the radius of the circular shaped EBG is determine from FF = r/a.
Now from the above equation the radius of a circular EBG is calculated r = 2.6077 mm where FF = 0.25.

5.1 FF analysis for circular EBGS:

For finding the optimum value of FF for uniform circular patterned EBGS and verifying the statement of optimum value of

FF, which is 0.25 for circular EBGS [3]. Here S-parameter performances are observed for designs having nine EBGSs for FF of 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40 and 0.45 that produce the below results.

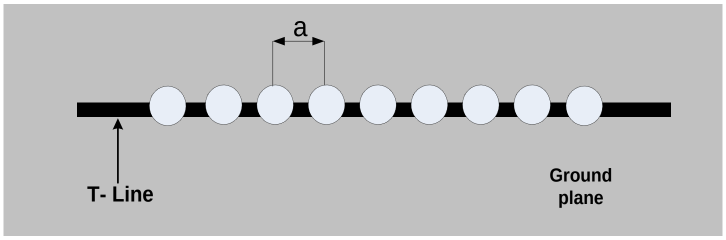

Fig. 9. Geometry of a standard 50-ohm transmission line with circular EBGS etched in the ground plane.

S-parameters of FF of 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40 and 0.45, where the substrate is Taconic having dielectric constant of 2.45, height of 31 mils and the inner-element spacing (period) a = 10.4308 mm. They show following performances as the table 4.1 describes.

TABLE 2: RETURN AND INSERTION LOSSES, DEPTH OF BANDS, RIPPLE HEIGHTS AND CUT OFF FREQUENCIES AT -3DB FOR FF VARIATION OF CIRCULAR EBGS

Filling Factor	10dB Return Loss Bandwidth - Pass band (GHz)	20 dB Insertion Loss Bandwidth - Stop band (GHz)	Depth of Stopband (at center frequency, 10 GHz)	Ripple Height (dB)	-3 dB Cut-off frequency (GHz)
0.10	9.0692	0	-2.9316	-9.9149	N/A
0.15	8.5641	0	-16.8701	-16.8457	N/A
0.20	7.3856	2.85196	-35.6975	-2.2371	8.0446
0.25	7.6706	4.43809	-71.5746	-4.5956	7.5424
0.30	6.0422	5.53013	-50.0074	-3.1114	6.8314
0.35	5.1942	6.22403	-45.4863	-4.3585	6.6009
0.40	5.1082	N/A	-43.0421	-5.5063	6.5451
0.45	5.3468	N/A	-40.5592	-6.6410	6.8163

Following two curves are formed by using the data from the table which is necessary to find out the optimum FF for getting better performances.

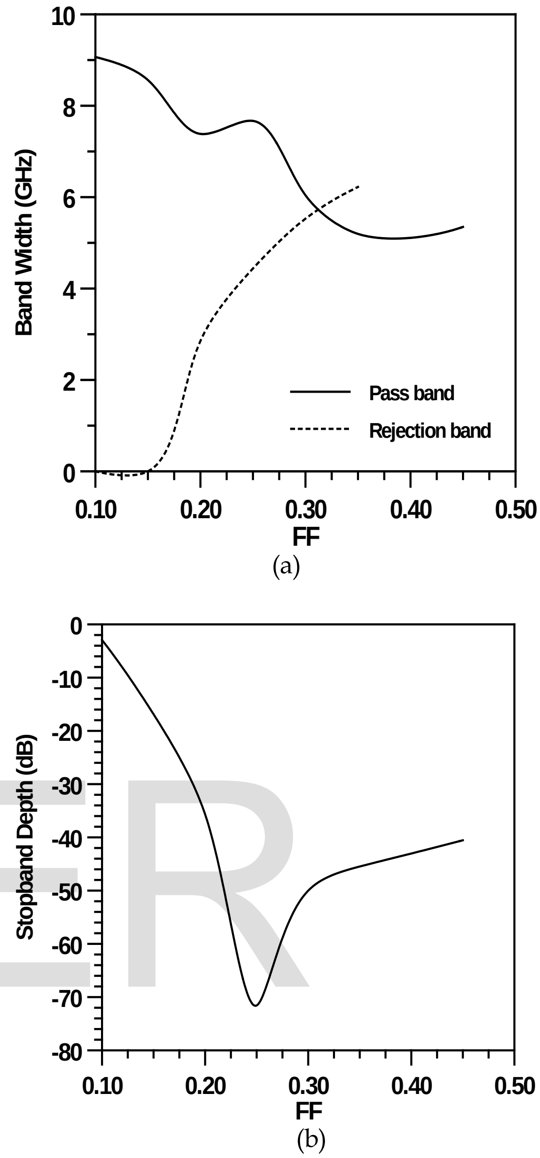

Fig. 10. (a) Filling factor Vs Insertion loss and Return loss curves
(b) Filling factor Vs stopband's depth ((at center frequency, 10 GHz)) curve for circular EBGS.

In graph (a) at FF = 0.325 Return Loss curve and Insertion Loss curve intersects each other i.e. both pass band width and stop band width becomes same; but on other hand, most significantly, the depth is highest at FF = 0.25, hence it is chosen as the optimum point of better performance by prof. T. Itoh [3] for circular shaped EBGS. Now, what happens for different shape of the EBGS? – described at the bellow section.

5.2 FF analysis for square shaped EBGS:

Square shapes are designed on the same substrate plate as it has been used earlier for circular EBGS and has been considered that the square shape's arm from the calculation of same area of circular shaped EBGS of corresponding FF. For example, if we consider FF = 0.25, from section 4.2, r = 2.6077. Then from b2 = πr2, b = 4.62203 mm, where b is the length of the arm.

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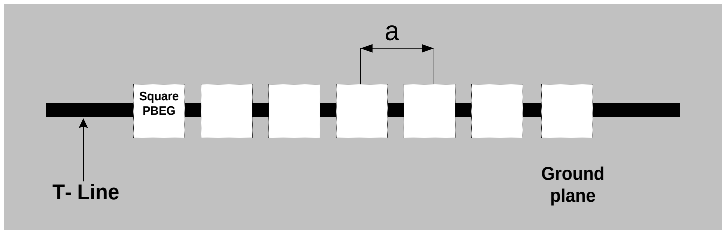

Fig. 11. Geometry of a 3D square patterned periodic structures under standard 50-ohm transmission line.

S-parameters of FF of 0.1, 0.15, 0.2, 0.25, 0.3 and 0.35 where the substrate is Taconic having dielectric constant of 2.45, height of 31 mils and the inner-element spacing (period) a = 10.4308 mm. These time numbers of EBGSs were nine too. By inspecting the S-parameter performances table 4.2 is made.

TABLE 3: S-PARAMETERS OBSERVATION FOR VARIATION OF FILLING FACTOR OF SQUARE SHAPED EBGS

Filling Factor	10 dB Return Loss Bandwidth - Pass band (GHz)	20 dB Insertion Loss Bandwidth - Stop band (GHz)	Depth of Stopband (at center frequency, 10 GHz)	Ripple Height (dB)	-3 dB Cut-off frequency (GHz)
0.10	9.0671	0	-2.6886	N/A	N/A
0.15	8.3587	0	-16.4602	N/A	N/A
0.20	7.1597	2.9228	-36.8916	-2.8792	7.8301
0.25	6.8507	4.4354	-75.4227	-2.0019	7.2791
0.30	5.8852	5.50504	-50.7088	-2.9526	6.5802
0.35	6.3377	6.18662	-45.4625	-4.1127	6.3396
0.40	5.6437	N/A	-44.8518	-3.6159	5.6551
0.45	4.8247	N/A	-43.5369	-4.5157	5.6318

Again for this data we got the following curves where FF Vs Return Loss is slightly diverged from that of circular EBGS; but FF Vs Insertion Loss curve followed the same path of that for circular EBGS, On the other hand FF Vs Stop-band depth curve shows exactly the similar characteristics of the circular shaped EBGS.

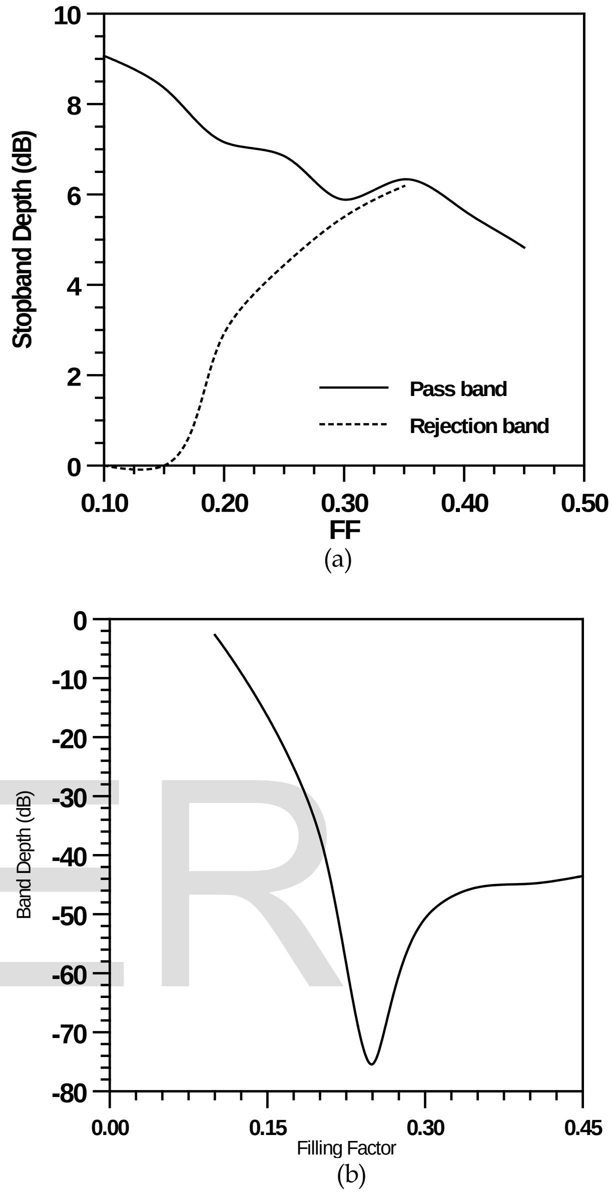

Fig. 12. (a) Filling Factor Vs Return loss and insertion loss curve,
(b) Filling Factor Vs Stopband Depth (at 10 GHz, center frequency) curve for square shaped EBGS where the area of square is same as corresponding circular EBGS.

5.3 Comparison

Below table shows the results of both circular and square EBGS.

TABLE 4: COMPARISON BETWEEN CIRCULAR AND SQUARE SHAPED

EBGS

Filling Factor	Circular EBGS		Square Shaped EBGS	
	10 dB Return Loss Bandwidth - Pass band (GHz)	20 dB Rejection Bandwidth -Stop band (GHz	10 dB Return Loss Band-width - Pass band (GHz)	20 dB Rejection Band-width - Stop band (GHz)
0.10	9.0692	0	9.0671	0
0.15	8.5641	0	8.3587	0
0.20	7.3856	2.85196	7.1597	2.9228
0.25	7.6706	4.43809	6.8507	4.4354
0.30	6.0422	5.53013	5.8852	5.50504
0.35	5.1942	6.22403	6.3377	6.18662
0.40	5.1082	N/A	5.6437	N/A
0.45	5.3468	N/A	4.8247	N/A

From the table it is seen that the performance parameters are showing almost similar results and in case of both type of EBGS FF = 0.25 is showing the best S-parameter performance. Since, areas of the both type of EBGS are same, so we can inspect the performances of same etching area; but for different shape of EBGS.

6. Conclusion

The work presented in this thesis has been concerned with EBG assisted filters. At present PBG engineering is an especial area in microwave engineering EBGSs are found to be very attractive in different microwave devices and components. The open literature has been surveyed very thoroughly to find their applications including their limitations. PBG theories have been reviewed to understand the passband and stopband phenomena of PBGSs. The depth and width of the stopband depends on few factors like FFs, number of elements, periods and substrate properties. Uniform circular, square and triangular patterned EBGSs have been investigated with variable number of EBG elements. The stopband-passband properties are reported by S-parameters performances. Different shapes of the EBG elements and different lattice structures have been shown. Three rows of various uniform patterned EBGSs under the standard 50-ohm transmission line have been simulated. Comparing with the result of one row circular uniform circular EBGSs it is found that three rows of uniform circular EBGSs and one row of uniform circular EBGSs yield very identical S-parameters performances; therefore, to clarify and understand the fact a typical design with very narrow blank space at the beneath of T-line is simulated and found reduction of stopband completely. So, only 1-D uniform EBGSs have been used onward. Effect of same etching area for different patterned of uniform conventional EBGS and some contradictory results to that effects are described.

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