

## Novel design of triple-band EBG

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### Abstract

This paper presents a novel design for a triple band electromagnetic band gap (EBG) structures that provides three band gaps, with operating frequency of below 10 GHz, while the ordinary mushroom like EBG structure gives only one band gap. Complexity reduction (reduce the number of unit cells and Vias) was achieved by replacing each four cells of the Mushroom like EBG by the one of double slotted type EBG (DSTEBG) or triple side slotted EBG (TSSEBG). The Mushroom like EBG was further modified by increasing its size and inserting the slots to gain more capacitance and inductance which resulted into triple band stop. The new designs were compared with bandwidths expressed by other EBGs and -20 dB cut-off frequencies. The size of EBG element and the gap between EBG elements, and slot width were investigated to analyse their effect on the transmission response. The structures were designed from 2.54 mm Rogers RT/Duroid 6010 substrate with relative permittivity of 10.2 and loss tangent of 0.0023. Among the investigated EBGs, the single band mushroom like EBG and the triple band of the TSSEBG demonstrated better bandwidth and lower resonance frequency performance, whereas the DSTEBG showed larger bandwidth for the first and third band. The proposed EBGs could be useful in the antenna design and other microwave circuits.

**Keywords:** electromagnetic band-gap EBG, mushroom-like EBG, transmission line technique, triple band EBG

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### 1. Introduction

The growth of a diverse and innovative technologies and services require an unremitting efforts to meet the stringent requirements of such technologies [1, 2]. In antennas the surface waves do not radiate in free space but propagate along the ground plane thus are undesirable in antenna design. They reduce the efficiency, gain and directivity of antenna, limit its bandwidth [3, 4]. When the permittivity of the substrate is above 1, this causes the surface waves to excite on microstrip antenna. In addition to end fire radiation, the coupling between different array elements is also caused by surface waves. These waves are fired into the substrate at an elevation angle  $\theta$  lying between  $\pi/2$  and  $\sin^{-1}(1/\sqrt{\epsilon_r})$  [5]. These waves are reflected from ground plane after being incident at the angle faces the dielectric-air interface and get reflected from there as well. These surface waves reach the boundary of the microstrip structure following this zig-zag path, as shown in Figure 1 (a), where the end-fire radiation is caused by their reflection and diffraction over the edges.

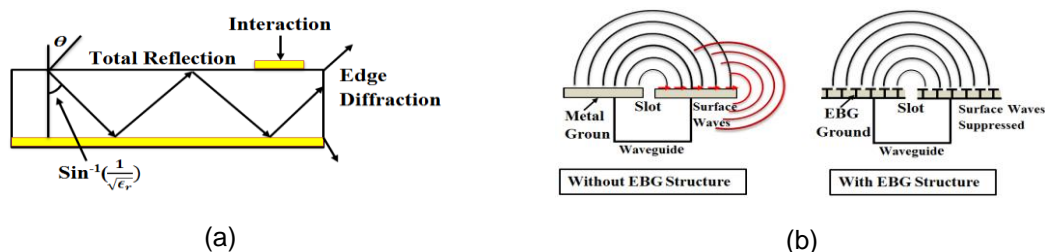


Figure 1. (a) Surface wave propagation in substrate of patch antenna, (b) propagation of surface waves using EBG structure

During last decades, many techniques were developed to reduce surface waves excited by printed antennas. To name only a few: placing an additional dielectric layer over the patch [6] or optimizing the patch shape [7]. Drilling an air cavity below the patch to realize a low effective dielectric constant [8]. Compact circuit design is best achieved on high dielectric constant substrates. As the dielectric constant increases, the surface waves become lower [9], but the side effect for doing this is the band width reduction and this problem can be solve by increasing the substrate thickness [10]. The approach for using EBG is the sutable way to suppres the surface waves wich results from the high and thick bermitivity substrate due to intereduced the stopband around the desired frequency of antenna [11]. Surface wave are TM and TE modes of the substrate. These two modes are characterized by waves attenuating in the transverse direction and having a real propagation constant above the cut-off frequency [12]. The phase velocity of the surface waves is strongly dependent on the substrate parameters  $h$  and  $\epsilon_r$ . Figure 1 (b) shows the blocking of propagation surface wave on waveguide by using EBG (PBG) structure.

The EBG was suggested based on the phenomena of photonic band gap (PBG) in optics [13]. The EBG periodic structure has been applied to microwave planar waveguides can result in pass or stop bands. Two types of EBG, the first one is the mushroom-like EBG surface (with Vias) has been described in [14] and the second type is the uni-planar EBG surface (without Vias) has been explanated in [15]. The vertical vias in uni-planar EBG has been removed, thus the fabrication process became easier, but it is less sensitive for the polarization and incident angle. The main advantages of the mushroom-like EBG surface are the achievement of a wide-ranging bandwidth, a lower frequency and the size of the mushroom-like EBG is smaller than the uni-planar EBG. The feature of surface-waves suppression supports to reducing backward direction and the amount of power wasted, leads to improve antenna performance [16]. Raising the gain of antenna with a good radiating efficiency [17]. For multi-band applications, it is necessary to design dual-band EBG structures by using via, but the fabrication is more complex [18]. Height and via location has been changed in [19] to achieve dual bandgap. Several triple-band EBG structures were also presented in the literature [20, 21]. However, the fabrication still important issue which depending on the number of pin vias, size of EBG, and the position of EBG. In mushroom like EBG without Vias cannot get stop band frequency.

In this paper, a novel design of EBGs, have been introduced from the original mushroom-like EBG structure, the first EBG structure is Double Slotted Type EBG (DSTEGB) and the second EBG structure is Triple Side Slotted EBG (TSSEBG). These novel designs provides triple band gap or band stop of frequency below 10 GHz compared with mushroom EBG structure, wich had only one band gap frequency. When considering on inserting additional features to current designs, the main question is the applications and advantages of doing so. Due to the connection vias between the patch and ground plane, mushroom EBG structure increases manufacturing cost and complexcity. By Replacing each four cells of the Mushroom like EBG by the one of double slotted type EBG (DSTEGB) or triple side slotted EBG (TSSEBG), reduction in the number of unit cells and Vias have been achieved. The most original contribution of this paper is the reduction of number of Vias in EBG unit cells, wich leads to reduce the number of columns and rows of EBGs when integrated with patch antenna.

## 2. EBG Structure and Design

The mushroom-like EBG structure, which is actually a 2-D EBG surface, was initially proposed by [14]. There were four parts in the proposed model: i) ground plane, ii) dielectric substrate, iii) metallic patches, and iv) connecting vias. A distinct feature of stopband was exhibited by these EBG structures for surface-wave propagation. An LC filter array can be used for the explanation of the operation mechanism of the EBG structure. The current, which is flowing through vias, causes the inductor  $L$  effect, whereas the gap among the neighboring patches resulted in the capacitor  $C$  effect.  $W$  is the patch width, gap width is  $g$ , thickness of substrate is  $h$  and  $\epsilon_r$  is dielectric constant. The method to increase the capacitance or inductance will decrease the position of band gap, according to the (3) of the central frequency.

$$L = \mu_o h \quad (1)$$

$$c = \frac{W \epsilon_o (1 + \epsilon_r)}{\pi} \cosh^{-1} \left( \frac{2W + g}{g} \right) \quad (2)$$

Where  $\mu_o$  is the free space permeability,  $\epsilon_o$  is the free space permittivity, and  $\eta$  is the impedance of the free space which is  $120\pi$  (377  $\Omega$ ).

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

$$BW = \frac{\Delta W}{W} = \frac{1}{\eta} \sqrt{\frac{L}{C}} \quad (4)$$

The impedance of the structure is very high at resonant frequency, and hence the structure avoids the emission of any surface waves. This results in a band gap of frequency [14]. A band gap of the EBG can be generated for frequencies at the same band of the operating frequency, by placing the (EBGs) periodically on the antenna substrate. Antenna structure that results from this design can prevent the excited surface waves along the substrate from the propagation. The transmission line model for plane waves additional to surface waves will explain at this section. The EBG cells are placed between the microstrip and ground to form a sandwich-like structure. The all details of design the square shaped mushroom like EBG by using the transmission line technique as shown in Figure 2 (a) was described in [22]. Figure 2 (b) shows the S11 and S21 of the EBG unit cells, which results from the transmission line technique, represents the band gap characteristics for the suggested EBG structure. The S21 illustrate that the EBG structure rejects the surface wave propagation. The EBG structure had been designed to achieve a stop band at 6 GHz. The EBG have a -20 dB band gap from 5.75 GHz to 6.33 GHz with -40 dB at 6 GHz. At this band gap, the propagation of surface will be suppressed and these properties will be used in the surface waves reduction to improve the antenna performance.

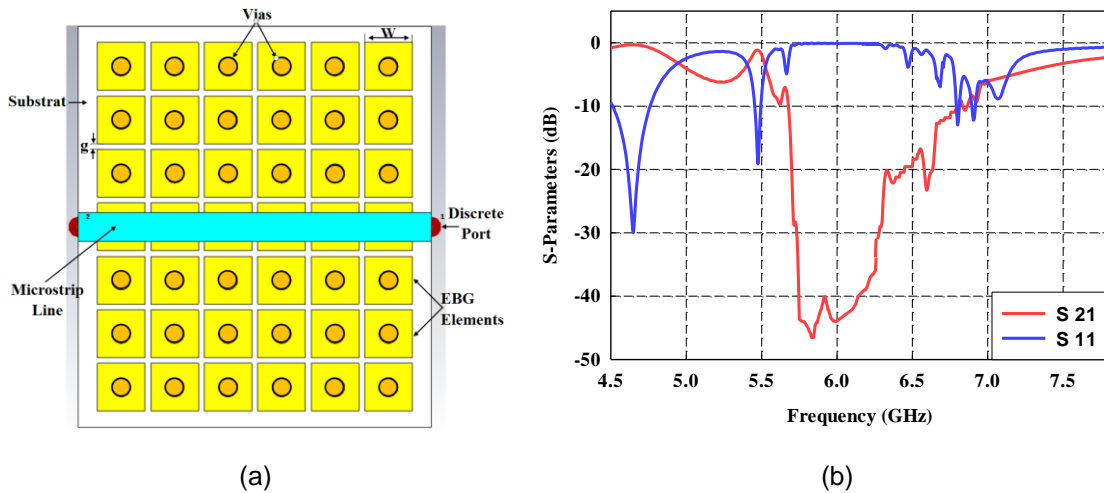


Figure 2. (a) EBG Microstrip transmission line, and (b) Band gab of EBG structure [22]

### 3. Double Slotted Type EBG (DSTEGB)

Figure 3 (a) shows a Double Slotted Type EBG. It is prepared by adjustment of the mushroom like EBG was described in [22]. It consists of a patch and a number of slots, the inductance is produced by different shapes slots and capacitance by the transverse slot [23]. These slots provide extra capacitance, instead of the four gaps as compared to the four elements of the mushroom type EBG. The diameter of the via is 0.9 mm. Two slots which are 1.7 mm and 0.3 mm width in each side are introduced in the DSTEGB. The method to increase the capacitance or inductance will decrease the position of band gap [24]. When the size of EBG unit cell increased, the resonance frequency will shift to the side of lower frequency

because of a rise in the value of capacitance. By inserting the double slots to the new size of EBG will shifting the resonance frequency again to higher frequency, due to a decrease in the value of capacitance. This new EBG structure can replace each four Mushroom like EBG unit cells by one of DSTEBG, at this point the size was reduced and the main advantage was to reduce the number of Vias, finally we reduce the complexity in the design and fabrication. Figure 3 (b) shows the 4 elements of conventional mushroom like EBG structure with 3mm unit cell size for each cell that has been modified to introduce the DSTEBG structure with 5 mm unit cell size. This novel design provides triple band gap or band stop of frequency compared with mushroom EBG structure, which had only one band gap frequency at 6 GHz.

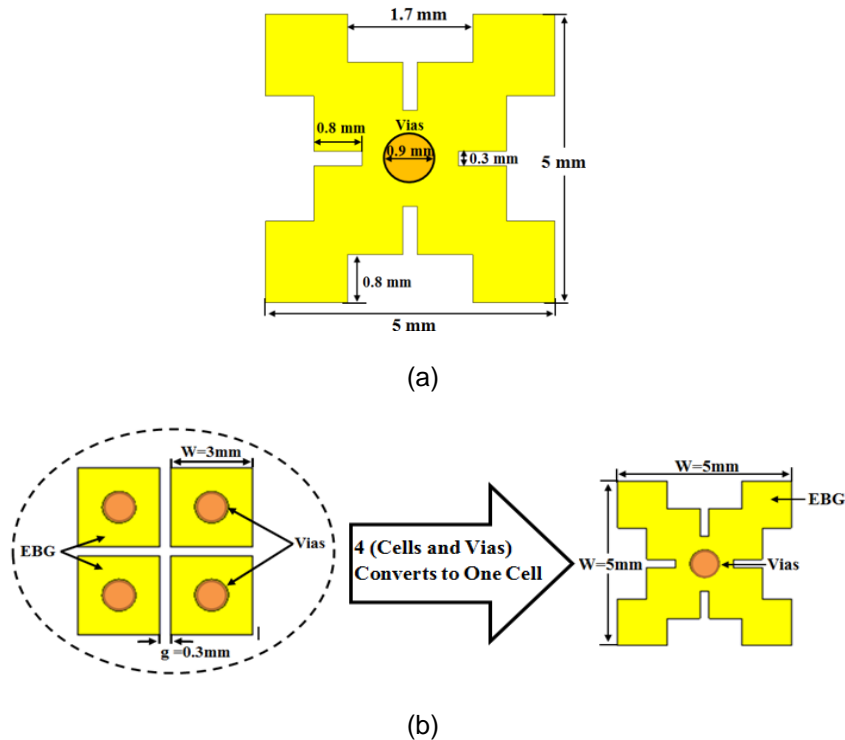


Figure 3. DSTEBG (a) Unit element (b) 4 cells of mushroom like EBG converts to one DSTEBG

### 3.1. Transmission Line Technique for (DSTEBG) Band Gap Characteristics

The transmission line reaction of the EBG depends on the length and width of the slots, size of EBG elements and the gap between them. The DSTEBG unit cells are positioned between the ground plane and microstrip line. The space between the DSTEBG surface and microstrip line is 0.1 mm. CST software has been used to tune the values of DSTEBG width ( $W$ ) and the gap between the unit EBG elements ( $g$ ). Where EBG width  $W=5\text{mm}$ ,  $g=0.3\text{mm}$  and via radius of 0.45 mm connected between the ground plane and patch on a Rogers RT/Duroid 6010 substrate of height  $h=2.74\text{mm}$ , relative permittivity of 10.2. 3 by 3 DSTEBG structure have been simulated with overall dimensions (18 mmx18 mm) as shown in Figure 4 (a). The width of the transmission line is determined as 2.3 mm, which has been calculated using CST MWS to achieve matching with the  $50\ \Omega$  input impedance. A couple of  $50\ \Omega$  discrete ports have been connected at both edges of the transmission line for calculating the DSTEBG band gap characteristics. The new EBG structure illustrates the rejection of the surface wave propagation due to the lower mutual coupling for the forward transmission coefficient ( $S_{21}$ ). Triple band stop frequency was achieved from the simulated result based on -20 dB  $S_{21}$  value as shown in Figure 4 (b). First band is between 2.42 GHz and 2.95 GHz, second band was from 5.82 GHz to 6.3 GHz and the last band had been covered the range between 8.72 GHz and 9.28 GHz. The simulated  $S_{11}$  value was near to 0 dB in the band gap range of frequency, which means the signal that works in the same of this band, cannot propagate on the EBG structure.

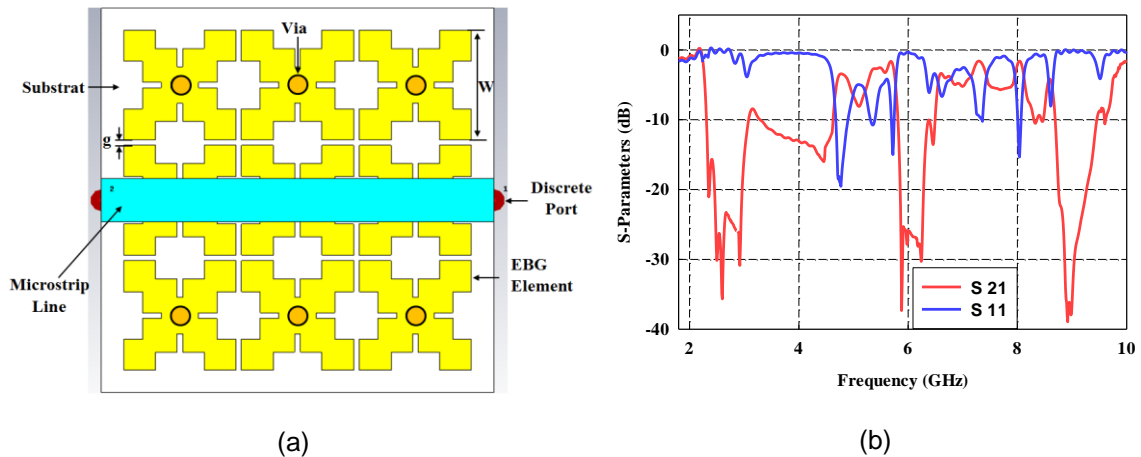


Figure 4. (a) EBG Microstrip transmission line (b) Triple bands of DSTEBG structure

### 3.2. The Effect of Patch Width for DSTEBG Structure

The width of the EBG unit cell is the most important parameter for determining the band gap frequency of this structure. The patch width of the DSTEBG structure has been changed from  $W=4.8$  mm to  $W=5.2$  mm. The width of the smaller slot is set to 0.3mm and the width of the bigger slot is set to 1.7 mm and the gap between the DSTEBG elements is set to 0.3 mm. The first stop band frequency is appears for Double Slotted Type EBG structure at lower frequency ranges, the second stop band is the same band of mushroom like EBG (6 GHz), and the third stop band was appeared at the higher frequency range. Figure 5 (a) shows, that by increasing the patch width of the EBG structure, the band gap frequency is also reduced and shifted to the lower frequency range due to increasing in the capacitance value. The bandwidth of band gap frequency of DSTEBG is comparable compared to Mushroom like EBG structure.

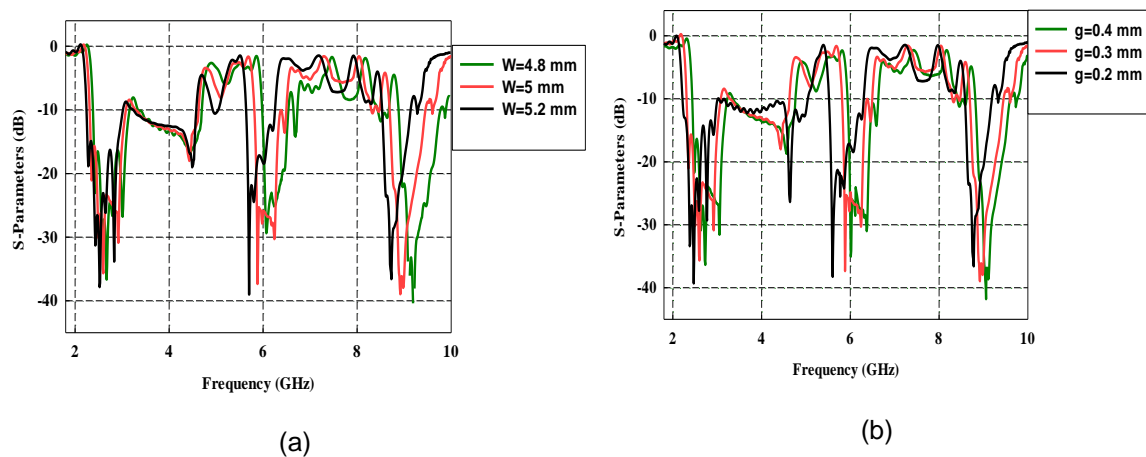


Figure 5. (a) Patch width effect of DSTEBG, (b) Gap width effect of DSTEBG

### 3.3. The Effect of Gap Between The DSTEBG Elements

Gap between the double slotted type EBG (DSTEBG) elements, will specify the capacitance influence according to the LC equivalent circuit. The gap between the structure of DSTEBG elements has been altered as three variation values, started from 0.2 mm until 0.4 mm. DSTEBG unit cell width is set to 5 mm, and the two slots width in each side of this unit cell were setted to 1.7 mm and 0.3 mm. Figure 5 (b) shows, that when increased the value of the gap between the EBG elements, the stop band of the operating frequency will shifted to the higher range of frequency due to decreasing in the capacitance value. Further, as the gap

value reductiones the stop band moves towards the lower range of frequency because of a rise value of the capacitance. In generally, the gap between elements can not considered as the critical value for determining the EBG band gap frequency, and the bandwidth of the band gap frequency can be increased by increased the gap value.

#### 4. Triple Side Slotted EBG (TSSEBG)

Triple side slotted EBG (TSSEBG) as shown in Figure 6 (a). By modification the initially design of the mushroom like EBG structure in [22], consists of patch (5 mmx5 mm) and three rectangular slots in the right and left sides with the same dimensions (1.25 mmx0.3 mm). These slots provide extra capacitance, instead of the four gaps as compared to the four elements of the mushroom type EBG. Vias diameter is 0.9 mm. To reduce the complexity in the design and fabrication we replaced each four Mushroom like EBG unit cells by one of Triple Side Slotted EBG. Figure 6 (b) shows the four elements of convential mushroom like EBG structure with 3 mm unit cell size for each cell that has been modified to interduce the TSSEBG structure with 5 mm unit cell. As the mushroom like EBG patch increases from 3 mm to 5 mm, the resonance frequency will shift to the lower frequency side. By inserting the three slots in each of the right and left sides for the new size of EBG will shifting the resonance frequency again to higher frequency, due to a decreases value of capacitance. This structure provides triple band gap or band stop of frequency compared with mushroom EBG structure.

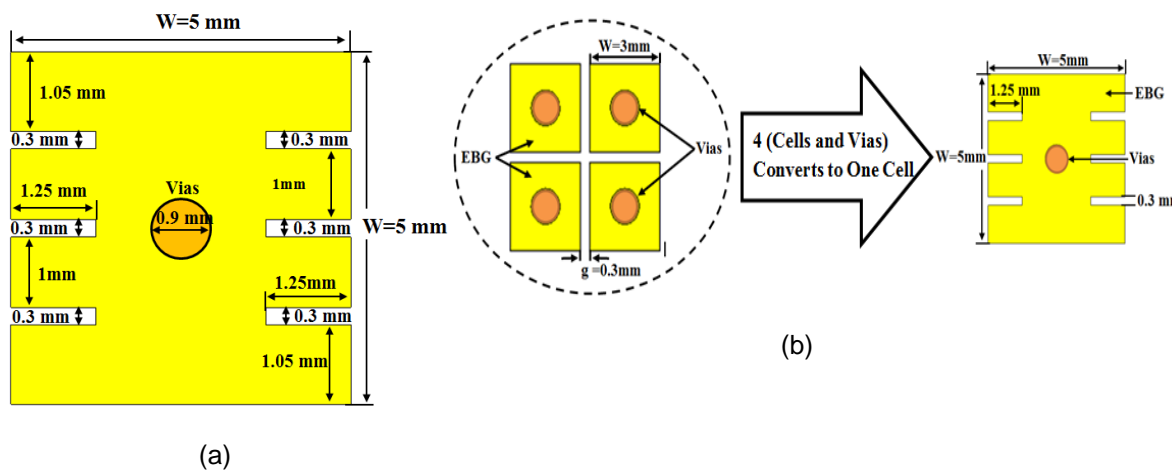


Figure 6. (a) Unit element of TSSEBG (b) 4 cells of EBG converts to one TSSEBG

#### 4.1. Transmission Line Technique for (TSSEBG) Band Gap Characteristics

The TSSEBG cells are placed above the Rogers RT/Duroid 6010 substrate of height  $h = 2.74 \text{ mm}$  and relative permittivity of 10.2, between the ground plane and microstrip line. The distance of  $0.1 \text{ mm}$  is the space between the EBG surface and the microstrip line. The values of unit TSSEBG width  $W = 5 \text{ mm}$ , the gap ( $g$ ) is  $0.3 \text{ mm}$  and via radius of  $0.45 \text{ mm}$ . The dimensions of the 3 by 3 TSSEBG structure has been simulated using the microstrip transmission line, with overall size equal to  $(18 \text{ mm} \times 18 \text{ mm})$  as shown in Figure 7 (a). The transmission line width is determined as  $2.3 \text{ mm}$ , which has been calculated using CST MWS. A couple of  $50 \Omega$  discrete ports have been connected at both edges of the transmission line. The new EBG structure illustrates the rejection of the surface wave propagation in the triple bands gap of frequency, according to the transmission coefficient ( $S_{21}$ ). In Figure 7 (b), triple band stop frequency was achieved from the simulated result based on  $-20 \text{ dB}$   $S_{21}$  value. First band is between  $4.29 \text{ GHz}$  and  $4.65 \text{ GHz}$ , second band was from  $5.66 \text{ GHz}$  to  $6.28 \text{ GHz}$  and the last band had been covered the range between  $7.6 \text{ GHz}$  and  $7.94 \text{ GHz}$ . The main idea is the bandwidth of the band gap frequency covers the operational frequency for the antenna, surface wave suppression can be achieved in case of integrated the antenna with the triple band EBG structure.

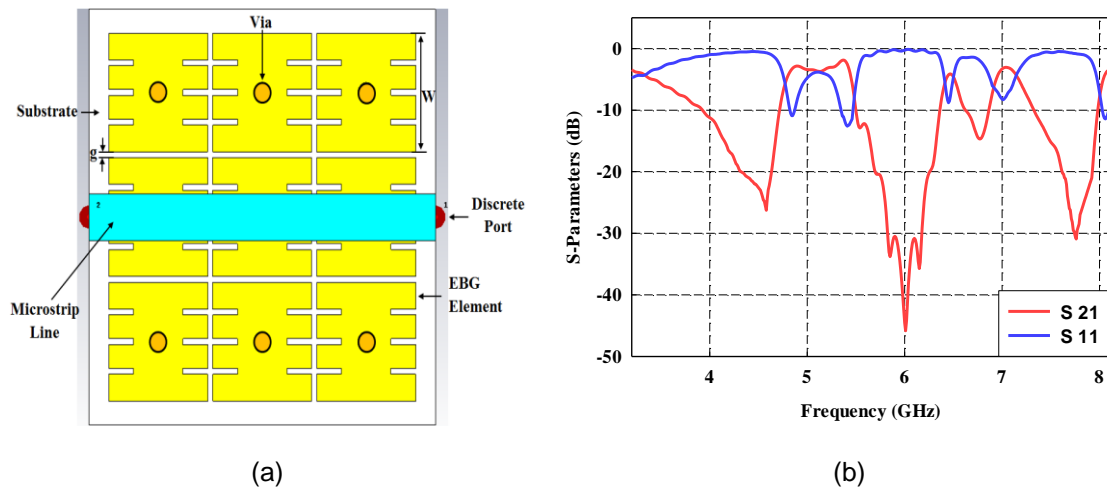


Figure 7. (a) EBG Microstrip transmission line, (b) Transmission characteristics of EBG

#### 4.2. Slot Width Effect of TSSEBG Structure

We studied the effect of patch size and gap width. Increased the diameter of vias will shifted the stop bands to the higher frequency because of the reduction value of inductance [25]. This section deals with the effect of slot width in EBG Design, three various slots width (SW) of TSSEBG are designed and simulated from  $SW=0.2$  mm to  $SW=0.4$  mm. The width of the TSSEBG element is set to 5 mm; gap between the TSSEBG elements is set to 0.3 mm, and via diameter is set to 0.9 mm. The first stop band frequency is appears at lower frequency ranges due to an increase in EBG size (from 3 mm to 5 mm), the resonance frequency will shift to the lower frequency side because of a rise in the value of inductance, the second stop band at 6 GHz is the same band of mushroom like EBG, and the third stop band was appeared at the higher frequency range, by inserting the triple slots to the new size of EBG will shifting the resonance frequency again to higher frequency, due to a decreases value of capacitance.

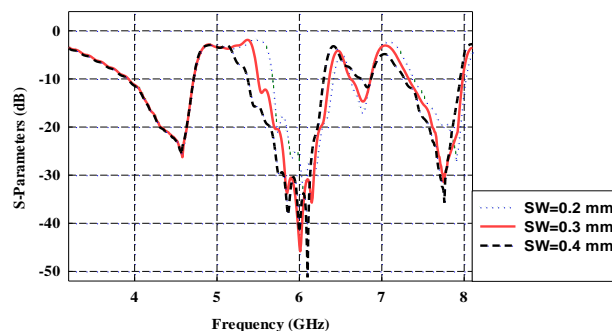


Figure 8. Slot width effect of triple side slotted EBG (TSSEBG)

Figure 8 shows, that by increasing the slot width of the TSSEBG structure, the second and third bands shifted to the side of lower frequency because of an increase value of inductance. The width of slot with 0.3 mm is set to be the best value, in the same time for the lower frequency band, there is no impact of this width difference. The bandwidth of band gap frequency for the structure of TSSEBG is comparable compared to Mushroom like EBG structure especially at second band (6 GHz).

From the comparison in Table 1, according to the -20 dB in lower and higher cut-off frequencies and the bandwidths of the band gap frequency. It can be determined, that two EBG

structures (DSTEBG and TSSEBG) gives better performance in terms of simplicity, triple band gap and reduction in the numbers of vias. DSTEBG and TSSEBG shifts the band to the side of lower frequency because of an increase in EBG size from 3 mm to 5 mm, after inserting the slots the band gap shifted to the lower and higher frequency, result in triple band. The mushroom like EBG band and the second band of TSSEBG have almost the same bandwidth and cut off frequency. DSTEBG in case of comparison to the TSSEBG gives a bigger bandwidth for the first and third band. However, the second band of TSSEBG offers a big bandwidth than the second band of the DSTEBG. It can be concluded that mushroom like EBG is more compact but has a lot of vias, while the TSSEBG has larger bandwidth than DSTEBG in terms of second band; on the other hand the DSTEBG has bigger bandwidth for the first and third band.

Table 1. Different EBGs in Lower cut-off frequencies (LCF), higher cut-off frequencies (HCF), and bandwidths (BW)

Type of EBG	Number of Vias or EBGs	First Band			Second Band			Third Band		
		LCF (GHz)	HCF (GHz)	BW (GHz)	LCF (GHz)	HCF (GHz)	BW (GHz)	LCF (GHz)	HCF (GHz)	BW (GHz)
EBG	42	5.75	6.33	0.63	-	-	-	-	-	-
DSTEBG	9	2.42	2.95	0.53	5.82	6.3	0.48	8.72	9.28	0.56
TSSEBG	9	4.29	4.658	0.368	5.66	6.28	0.62	7.6	7.94	0.34

## 5. Conclusion

The novel designs of EBG have been introduced from the structure of initial mushroom like EBG, the first design of EBG called as Double Slotted Type EBG (DSTEBG) and the second EBG structure is Triple Side Slotted EBG (TSSEBG). These novel designs, for reducing the complexity (reduce the number of unit cells and Vias) provided triple band gap or stop band of frequencies lower than 10 GHz and compared with mushroom like EBG structure which had only one band gap frequency at 6 GHz. The impacts of the unit cell size, gap between the DSTEBG cells on the microstrip transmission line response were considered. In case of increased the size of unit cell, the stop bands will shift to the side of lower frequency because of an increased value of capacitance. As the gap between the EBG cells increases, the stop bands were shifted to the side of higher frequency because of decreased value of capacitance. By increasing the slot width of the TSSEBG structure, the second and third bands are shifted towards the side of lower frequency because of an increases value of inductance. The Mushroom like EBG and the TSSEBG offered the better performance in terms of the lowest resonance frequency and bandwidth, while the DSTEBG has bigger bandwidth for the first and third band. The proposed EBGs can be used in many applications, for example improvement the radiation pattern, gain, directivity, efficiency and bandwidth of antenna, reduction the noise of filters and reduces the mutual coupling between the radiated elements in antenna array.

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