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A COMPACT DEFECTED GROUND MICROSTRIP DEVICE WITH PHOTONIC BANDGAP EFFECTS

S. K. Gupta and K. J. Vinoy

Microwave Laboratory
Department of Electrical Communication Engineering
Indian Institute of Science
Bangalore 560 012, India

Abstract—Filters and other devices using photonic bandgap (PBG) theory are typically implemented in microstrip lines by etching periodic holes on the ground plane of the microstrip. The period of such several holes corresponds to nearly half the guided wavelength of the transmission line. In this paper we study the effects of miniaturization of the PBG device by meandering the microstrip line about one single hole in the ground plane. A comparison of the S-parameters and dispersion behavior of the modified geometry and a conventional PBG device with a straight microstrip line shows that these devices have similar behaviors.

1. INTRODUCTION

Photonic bandgap (PBG) structures are periodic geometries in which the propagation of energy in certain bands of frequency is prohibited [1]. PBG structures, originally studied in the optical region, have found applications in the microwave and millimeter wave circuits recently [2–10]. A microstrip line with PBG structures behaves as a bandstop filter whose performance depends on the lattice structure and other parameters such as periodicity, fill factor and the distribution of the PBG geometry [5].

One easy approach to implement a PBG structure in microstrip circuits is by etching a periodic array of perforations in the ground plane of the microstrip (Figure 1). Holes with various shapes have been extensively investigated. Such a structure can be easily fabricated by printed circuit board (PCB) technologies and hence can be integrated

Corresponding author: K. J. Vinoy (kjvinoy@ece.iisc.ernet.in, kjvinoy@ieee.org).

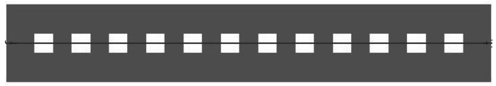

Figure 1. Conventional photonic bandgap structure on a microstrip line with periodically etched ground plane.

easily with other microwave circuits. In addition to uniform devices, various forms of periodic variations in the microstrip-line width have also been investigated [11]. More recently, micromachining based approaches to etch the substrate to realize photonic bandgap effects have also been suggested [12]. The periodicity in all these approaches is half a guided wavelength. To get appreciable frequency selectivity, such a circuit is typically several wavelengths long. Apart from the large overall size, these geometries also pose energy loss by radiations or by coupling on to adjacent components in an integrated circuit. These effects have been the subject of studies by various researchers [9, 10].

Reducing the overall size is a serious concern in the design of microwave components such as filters. Several attempts have been reported to reduce the size of bandpass filters using miniaturized resonant structures [13–17]. In order to reduce the overall dimensions of the PBG device, we investigated the use of a defected ground structure (DGS) consisting of a single hole in the ground plane. Similar to most microstrip PBG configurations, DGS is an etched defect in the ground of a planar transmission line which disturbs the current distribution in the wave guiding structure [18]. This disturbance will change the characteristics of a transmission line and has been suggested as a general approach to reduce the overall area of planar circuits [7]. In order to incorporate all features of PBG, in this approach we use a meandered microstrip line above a single rectangular slot etched on the ground plane.

The proposed geometry behaves as a bandpass filter with stop band behavior similar to that of regular PBG geometries. It may be recalled that a meandered microstrip line itself behaves like a bandpass filter. However it has been observed that the characteristics obtained by including the ground slot is substantially different from that without.

After presenting a brief overview of the PBG theory in the next section, we discuss the results of various parametric studies of the straight device based on numerical simulations in Section 3. In the case of the compact device proposed in Section 4, the effect of an additional geometrical parameter has been studied and its similarity to the conventional PBG based device is established on the basis of dispersion characteristics of the two. Experimental validations are provided in Section 5. These studies aim at demonstrating that the proposed miniaturization approach does not compromise the stopband characteristics of PBG based filters.

2. PBG THEORY

In an infinite periodic transmission line, electromagnetic wave propagation is completely blocked for certain frequencies depending upon the periodicity, due to destructive interference between the multiple scattered waves at the interfaces. This forms the basis for 1D PBG bandstop microwave filters. The general formula for bandgaps in a PBG structure is [1]:

$$p = \frac{n\lambda_g}{2} \tag{1}$$

where $p =$ periodicity, $n =$ band number and $\lambda_g =$ wavelength in medium. The wavelength is related to the effective permittivity of the dielectric substrate by:

$$\lambda g = \frac{c}{f\sqrt{\varepsilon_{eff}}} \tag{2}$$

where $f =$ frequency of EM wave. The effective permittivity, ε_{eff}, of a microstrip line can be estimated from [20]

$$\varepsilon_{eff} = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2\sqrt{1 + 12h/w}} \tag{3}$$

where h and w are the thickness of the substrate and the width of the line respectively. As one may notice, these expressions could be used for determining the center frequency of the rejection band. The width and depth of the rejection band are also required to be controlled within a finite number of periods in a practical application. In order to evaluate the effects of various other design parameters we undertook a parametric study.

3. PARAMETRIC STUDIES AND COMPACT DESIGN

A PBG with the desired center frequency for the first stopband can be designed using Equation (1) by suitably adjusting the periodicity. The substrate intended to be used in this study is Arlon AD1000 with $\varepsilon_r = 10.35$ and the thickness of 0.762 mm. The conductor line on the front side of the microstrip has a width of 0.7 mm which corresponds

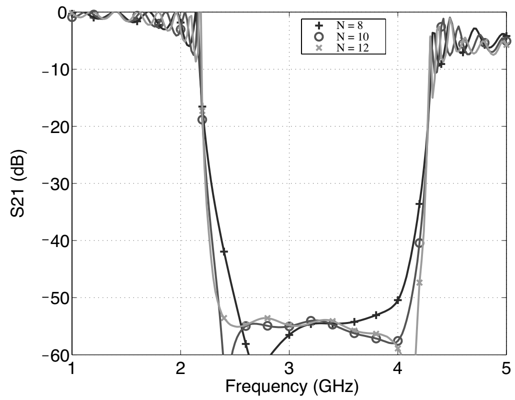

Figure 2. Simulated performance of the PBG as the number of periods is varied.

to a 50 Ω microstrip line. The centre frequency of the stopband for this study is selected to be 3 GHz. The corresponding period is 19.2 mm. The parametric studies presented here are done using a finite difference time domain method based full-wave electromagnetic simulation software (EMPIRE).

Although the theory mentioned in Section 2 is for infinite number of such periodic sections, practical devices with interesting characteristics may be obtained with finite number of such periods. The effect of increasing the number of periods is shown in Figure 2. The length of the hole in the ground plane is equal to half a period. The start of the bandgap and the width of the bandgap remain nearly the same, while the depth marginally changes with the number of periods. It is also noticed that the pass-band ripples decrease as number of periods increases.

The fill factor (FF) is defined as the width of the hole in the ground plane (along the direction of propagation) divided by the period of the PBG. The behavior of the device with a variation in the fill factor from 0.3 to 0.7 has been presented in Figure 3. These indicate that the start frequency of the stopband, the depth and width of the bandgap vary with the fill factor. Furthermore, the passband ripples also depend on this quantity. A fill factor of 0.5 is selected based on this study, as this has the best overall performance.

Moreover, the substrate permittivity affects the propagation constant and impedance of the microstrip line. Hence in another study, we varied this quantity and found that the width and depth of the stopband are also affected by the substrate permittivity. Since this affects the propagation characteristics of the line, the line width

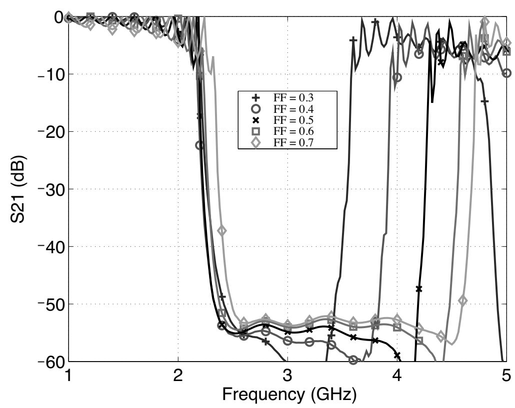

Figure 3. Simulated performance of the PBG as the fill factor (FF) is varied.

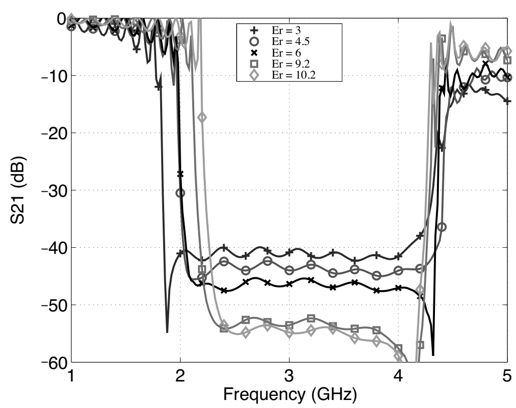

Figure 4. Simulated performance of the PBG as the substrate permittivity (Er) is varied.

is adjusted for 50 Ω in each substrate. The periodicity is also correspondingly modified to be consistent with the theory. As one may notice, the bandwidth reduces, but the depth of the stopband increases with an increase in substrate permittivity. There is also a minor difference in the pass-band ripples.

Based on these observations, we use a PBG with 12 periods and having fill factor of 0.5 as the reference structure. It may be noted that such a design would be 23 cm long and about 1 cm wide, making this impractical. In order to reduce the aspect ratio of this device, we propose to use a meandered microstrip line above a single rectangular slot etched on the ground plane.

4. PERFORMANCE OF THE COMPACT DEVICE AND COMPARISON WITH CONVENTIONAL PBG

As mentioned above, a compact device is designed by using one single (large) hole in the ground plane of the microstrip and the transmission line meandering above it. The schematic of such a device is shown in Figure 5. The unfolded line length of Figure 5 matches exactly with that of the previous design. Instead of periodically distributing holes along the length of the transmission line, a single (larger) hole is used here. The dimensions of the hole in this case would be decided based on the number of PBG cells and the fill factor. A unit cell corresponds to one section of each vertical and horizontal line segments in the figure. The fill factor in this case is defined as the ratio of the length of the line segment directly above the hole in the ground plane to the period. The effects of the fill factor and the number of periods are generally the same as in the case of the straight transmission line with PBG holes in the ground plane.

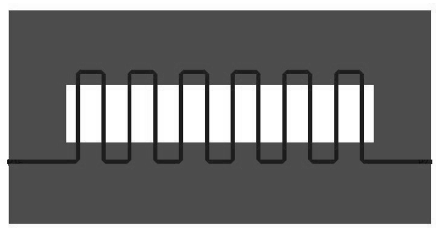

Figure 5. Schematic of the proposed compact device with PBG.

As indicated above, the overall length of the device is significantly compressed by this approach, but this may affect in the performance of the device. A comparison of the scattering parameters for the PBG with 12 periods is shown in Figure 6. There is a significant improvement in the bandwidth for the compact geometry. However this is at the cost of marginal decrease in the rejection band depth and increase in pass-band ripples. For this study the fill factor 0.5 is taken and the number of period is kept constant at 12.

Effect of separation between lines is studied and the variation in S21 profile is shown in Figure 7. It may be noted that the start frequency of the stopband is reduced as the gap increased. This causes the bandwidth to increase with the gap. Therefore, the gap between adjacent lines (and hence the overall size) can be used as a control parameter, to a limited extent. However the passband has sharp ripples which could not be removed completely. Upon further analysis, it has been found that the spikes in the passband of the device are caused by

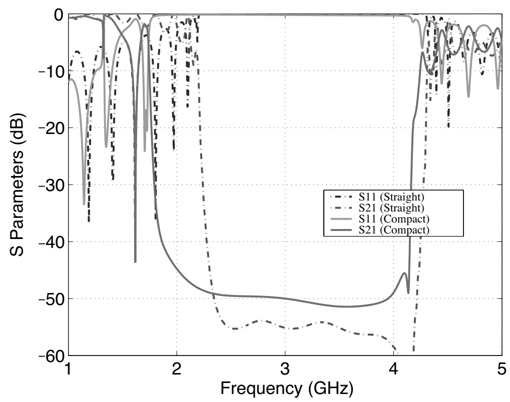

Figure 6. *S*-parameters of the PBG band-stop filter and its compact version.

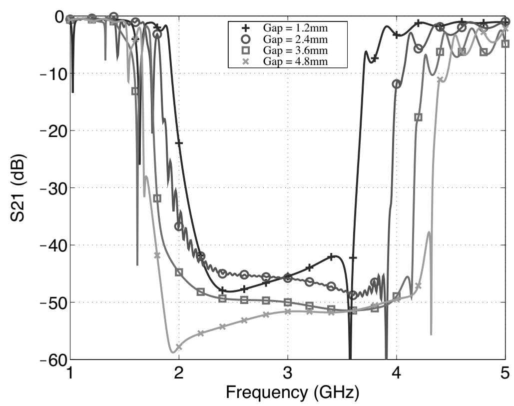

Figure 7. Transmission characteristics (S21) DGS structure with respect to coupling distance.

radiations from the structure, and this aspect will be discussed further in the experimental studies. For practical reasons, we have chosen a separation of 3.6 mm between these parallel lines. This results in reducing the length of the PBG device with 12 periods and having a center frequency of 3 GHz to 5.2 cm from 23 cm in the earlier case. In other words, the maximum dimension of the device is only about half a wavelength (at the design frequency), compared to several wavelengths in the conventional approach. With this modification, PBG based filters may now be employed for low microwave frequencies without compromising on their high stopband and sharp cutoff characteristics.

Although the resultant device is much smaller than the original PBG device, it may not be comparable to the smallest reported in the literature. Several attempts have been reported in recent literature to miniaturize bandpass filters [13–17]. However the sharp roll off and the low rejection band characteristics of the proposed device are significantly better than such compact devices.

In order to establish the similarity between the two devices a comparison is made between the slow wave factors of these devices. In a PBG, slow-waves ($\beta > k$) propagate for frequencies below the bandgap and fast waves ($\beta < k$) propagate at frequencies above the bandgap. The slow or fast wave effects are shown to be more pronounced near the bandgap region, with the transition occurring at the center frequency [21]. As observed from Figure 8, a similar behavior is obtained for the compact device proposed here. It may also be pointed out that near 1.5 GHz, a short frequency band with anomalous dispersion is also observed in the compact device. We believe that this is due to the strong coupling between adjacent line sections in the compact device.

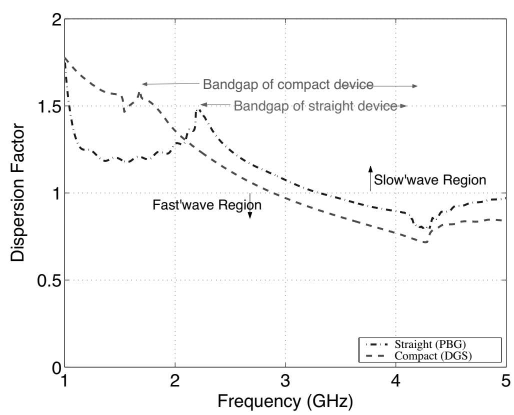

Figure 8. Dispersion factor (β/k) for the straight and compact versions of the PBG.

5. EXPERIMENTAL VALIDATION

A prototype device is fabricated on a microwave laminate (Arlon AD1000 with $\varepsilon_r = 10.35$ and the thickness of 0.762 mm). The centre frequency for the design is selected at 3 GHz. The corresponding period is 19.2 mm. A fill factor of 0.5 is used for both the straight and compact devices. The conductor line on the front side has a width of 0.7 mm (corresponding to 50 Ω microstrip line). A photograph of the fabricated

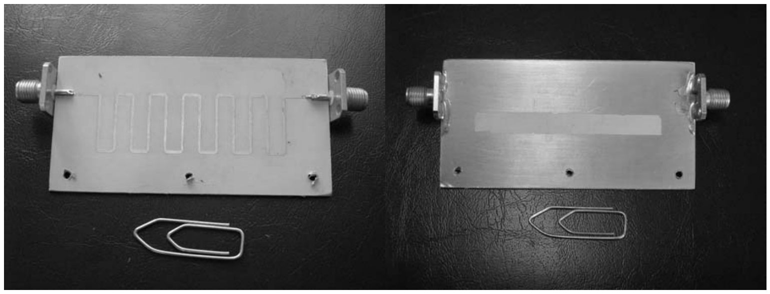

Figure 9. Fabricated prototype of the compact device.

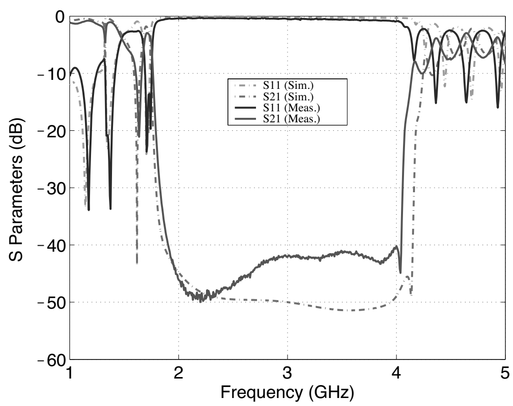

Figure 10. Comparison of the simulated and measured S parameters of straight and compact devices.

compact device is shown in Figure 9. This device is characterized by using a vector network analyzer (Agilent, N5230A). The experimental results shown in Figure 10 agree well with numerical simulations.

In order to investigate energy leaking out from the device we measured the radiation characteristics of the device. These measurements are performed in an anechoic chamber equipped with a single axis positioner. The transmit antenna and one port of a compact device are connected to a vector network analyzer. The second port of the device is terminated with a matched load to emulate typical operating conditions. The radiated power based on this swept frequency measurement in the plane containing the feed ports is shown in Figure 11. The printed side of the device faces the transmit antenna at 180°. The measured data is corrected for free space and cable losses. The transmit antenna gains variations in frequency and is plotted

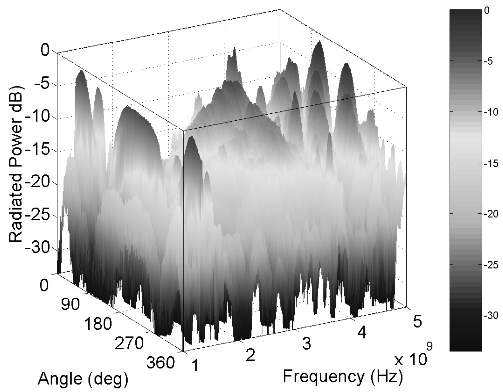

Figure 11. Measured E-plane radiations (normalized) from the compact device.

here after normalization. At all hotspot frequencies radiations occur symmetrically, and in many cases to the front and backside of the device. A comparison of measured data in Figures 10 and 11 indicates that dips in the return loss at pass-band match with frequencies at which significant radiations occur. In other words these dips are not entirely caused by the coupling between the adjacent line segments. This also explains the nature of variation in Figure 7.

6. CONCLUSIONS

It has been shown that the propagation behavior of a meandered microstrip transmission line above a single hole in the ground plane is comparable with that of a conventional microstrip PBG with periodic holes below a straight line. Parametric studies involved in the design of both the conventional device and its modification are shown in detail. The S-parameters and dispersion behaviors of these devices compare well. The dispersion behavior of the proposed compact device matches with that of the conventional PBG, and confirms that the slow-wave to fast-wave transition occurs near the center frequency of the bandgap. It may however be noted that although the approach proposed here reduces the length of the device by about 75not be the most compact filter for a given frequency band. In addition, this approach offers practical convenience as the aspect ratio of the device is significantly different from that of the conventional PBG. Furthermore, these are achieved without compromising significantly on the PBG characteristics. Hence the proposed approach may be used for high performance bandstop filters at low microwave frequencies.

A prototype of the compact device is fabricated and tested. The measured S-parameters of the compact device match with numerical simulations. A swept frequency measurement of the radiated signals from this compact device is also performed to understand the loss mechanisms. These correlate well with S-parameter data for the device and indicate that major ripples in the passband are caused by radiations from the device. These studies support the possibility of miniaturizing PBG based bandstop filters for practical microwave applications.

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