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Microstrip Antennas on Various UC-PBG Substrates

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SUMMARY Microstrip antennas on various Uniplane Compact Photonic BandGap (UC-PBG) substrates are investigated. Particularly, anisotropic characteristics of UC-PBG is studied and applied to the design of microstrip diplexer antennas. Moreover, an Embedded UC-PBG (EUC-PBG) scheme is presented to overcome the strong backward radiation caused by the conventional UC-PBG antennas. Such antennas demonstrate the improved radiation properties over the conventional UC-PBG antennas, and the evidence on surface wave suppression is also demonstrated. Experimental results show very good agreement with theoretical predictions.

key words: *photonic bandgap, microstrip antennas*

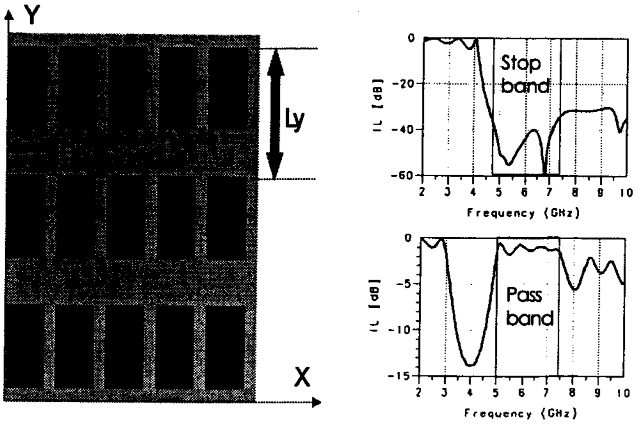
1. Introduction

Photonic Band-Gap (PBG) structures originating from optics [1] have been extensively applied in the microwave region, the application includes the suppression of surface waves, the construction of Perfect Magnetic Conducting (PMC) planes and antenna gain enhancement [2]. More recently, the anisotropic characteristics of PBG structures have been studied [3]–[5] and applied to the design of microstrip diplexer antennas [4], [5] and diplexer filters [6]. In this paper, the anisotropic characteristics of PBG structures are further investigated and applied to the design of a dual linear polarised diplexer microstrip antenna with enhanced Rx/Tx isolation. Uniplanar Compact (UC) PBG introduced by Caloz et al. [3] has the advantage of ease of fabrication, and most UC-PBGs have been designed by etching a periodic pattern on the ground plane. While such configurations are used for microstrip antenna design, the antennas suffer very strong backward radiation and hence reduce antenna efficiency. The concept of EUC-PBG is to fabricate the UC-PBG structures in layers inserted between the ground plane and the top of substrate layer forming a sandwich construction. In this paper, properties of the proposed EUC-PBG are examined. Specifically, the propagation of electromagnetic waves over the EUC-PBG structure is investigated compared with that over the conventional UC-PBGs. Particularly, the characteristics of microstrip antennas on the EUC-PBGs are investigated. Such antennas demonstrate the improved radiation properties over the conventional UC-PBG antennas, and the evidence on surface wave suppression is also demonstrated. For demonstration, all designs are made at 5–7 GHz and simulation results are presented with experimental verification.

2. Microstrip Diplexer Antennas on UC-PBG Substrates

Conventional polarisation diplexing antennas require high performance circuit level filters attached to the transmitting and receiving ports to provide the desired level of isolation. Replacement of these filters by UC-PBGs with two different periods for the x and y (transmit-Tx and Rx-receive) directions, Fig. 1(a), can lead to a much more compact and lower mass design.

A UC-PBG structure shown in Fig. 1(a) has two different periods in the x and y direction respectively. The proposed UC-PBG structure exhibits different central stopband frequencies (Fig. 1(b)) when electromagnetic waves propagate along the two orthogonal edges of the proposed PBG substrate. Such PBG structures also allow wave propagation over a certain frequency band, acting as bandpass filters (Fig. 1(b)). The central stopband frequency can be approximated by [6]



(a) (b)

Fig. 1 (a) An anisotropic UC-PBG pattern. (b) Frequency response of 2D PBG along x direction (top). Frequency response of 2D PBG along y direction (bottom).

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$$f_{C_i} = \frac{C}{2\sqrt{\varepsilon_{eff}} L_i} \quad i = x \text{ or } y \tag{1}$$

where c is the speed of light, L_i is the given period and ε_{eff} is the effective permittivity of PBG substrates (Fig. 1(a)). Such PBG structures demonstrate different attenuation characteristics along different wave propagation directions and they are referred as anisotropic PBGs by Caloz [3]. Clearly enhanced isolation can be achieved if a PBG structure can be found to reject Tx signal but let Rx signal pass at the receiving path, and vice versa at transmitting path [4], [5].

The design of microstrip diplexer antenna with anisotropic PBG structure is based on Eq. (1). The periods can be calculated once the antenna operating frequencies are defined. In our case, these frequencies are 5.2 GHz and 6.0 GHz. At the receiving port, the forbidden band central frequency is set to be 6.0 GHz, and when applying Eq. (1), the period is given as about 12.5 mm. The length of printed slot resonators for PBG structure is set to be about half of a guided wavelength on the microstrip substrate. At the receiving port, it is about 14.6 mm. At the transmitting port, the forbidden bandgap central frequency is determined by the receiving channel frequency, and it should be 5.2 GHz in this case. However, considering the effect of adding PBG structure on the microstrip ground plane, the effective permittivity is reduced and hence the receiving channel frequency shifts down. In this case, the receiving frequency is about 3.1 GHz (Fig. 3), and it gives the period of the PBG along the transmitting channel of about 25.6 mm. The slot width is set to be about 3.8 mm following the above proposed design rule. On top of the substrate lays a conventional microstrip diplexer antenna. For simplicity and comparison, dimensions of the antenna remains unchanged and it is the same as the conventional diplexer antenna discussed above. Therefore, only the ground-plane prototype of the proposed novel anisotropic PBG antenna is shown in Fig. 2(b). It can be seen that the anisotropic characteristics of the PBG are provided by the inherent anisotropy of the rectangular slots with the different periods along two orthogonal directions used by transmitting and receiving channels of the diplexer antenna.

Three types of antennas were fabricated and measured to verify the simulation. They are the conventional microstrip diplexer antenna (Fig. 2(a)), antenna with 1D UC-PBG (a linear array of PBG elements located below the receiving channel transmission line) and the structure of Fig. 2. The return losses and RX/TX isolation of the first two types of antennas are measured and compared in Fig. 3. It can be seen that the conventional diplexer antenna resonating at 5.5 GHz and 6.1 GHz respectively has only about −30 dB isolation between Rx/Tx ports, but with the help of the 1D UC-PBG, the isolation can be improved. It is also evident that the receiving frequency has changed due to the variation of effective dielectric constants caused by periodic slots etched under the antenna feed line at the receiving port on the ground plane. The measurement on the anisotropic UC-PBG diplexer antenna was also performed and the result is shown in Fig. 3. It demonstrates much improved RX/TX isolation over a wider frequency range and shows that the shift of resonant frequencies is now at both of Rx and Tx ports when introducing anisotropic PBG on the whole antenna ground plane.

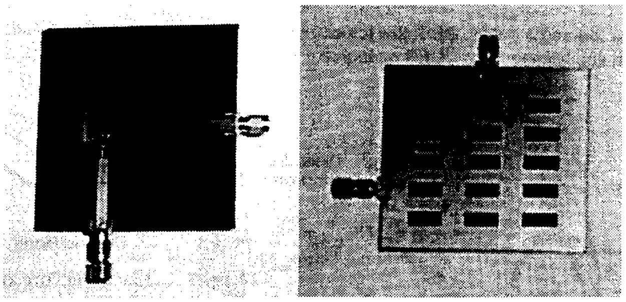

(a) (b)

Fig. 2 (a) Conventional microstrip diplexer antenna prototype. (b) Prototype of anisotropic UC-PBG microstrip diplexer antenna (Ground Plane).

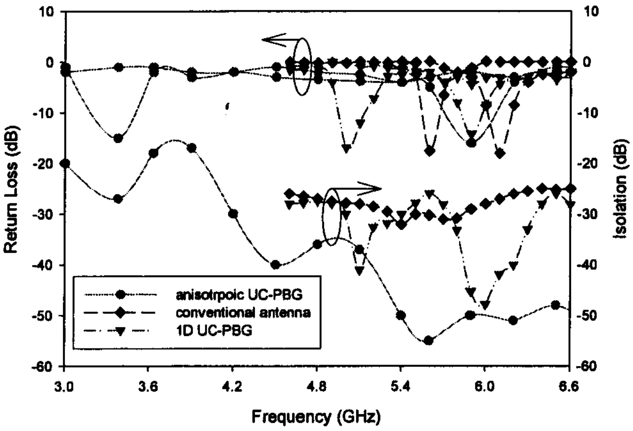


Fig. 3 Comparison of measured return loss and isolation of various antennas.

3. Microstrip Antennas on EUC-PBG Substrates

The Coupled Split Square Ring (SSR) pattern suggested by Pendry and Smith [7]–[9] is used as the PBG element since it can be made resonant at wavelengths much larger than the diameter of the rings. SSRs can be made to resonate when the magnetic field is perpendicular to the plane of rings. The structure and dimensions of SSR are shown in Fig. 4. The resonant frequency of SSR is usually calculated from the approximation of its effective permeability and the full accurate analysis is not trivial. In [8] and [9], empirical formulations are only given for calculating the resonance of

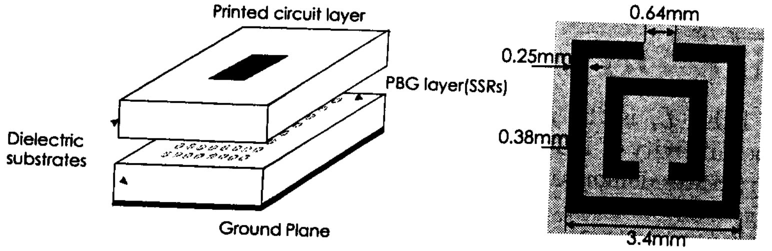


Fig. 4 The structure of EUC-PBGs and its application.

coupled split circular rings. In [9], approximation of the resonant frequency is given for an array of square loop-wire structures, but not applied to the proposed SSRs. Recently Markos et al. [10] applied the transfer-matrix method (TMM) to the numerical studies of SSRs, the dependence of the resonance frequency of the SSRs on the ring thickness, inner diameter, radial and azimuthal gap, as well as on the electrical permittivity of the substrate and embedding medium is presented. In this paper, since the square ring is split, the outer ring of SSR can be approximated as a half-wavelength stripline resonator, the resonant frequency can be easily determined from its physical length. The inner split ring is to generate larger capacitance and thus lower the resonant frequency significantly [8]. In general, the smaller is the gap between the outer and inner rings, the lower resonant frequency will be generated. However, the gap used in this paper is comparable to the width of SSRs (Fig. 4), and thus the frequency lowering is not considerable. This is demonstrated by two numerical simulations using Agilent Momentum^{TM}. The resonant frequency of outer SSR alone is 7.60 GHz, and with coupled inner SSR, it becomes 7.25 GHz. Therefore, the circumference of outer SSRs can be approximated using

$$l \approx \frac{\lambda_g}{2} = \frac{c}{2\sqrt{\varepsilon_{eff}}\, f_{res}} \qquad (2)$$

where f_{res} is the proposed resonant frequency of SSRs, ε_{eff} is effective permittivity of the medium on which SSRs are fabricated and c is the speed of light in free space.

The proposed EUC-PBG is made from an array of SSRs mentioned above. Figure 4 shows structure of the EUC-PBG, where the SSRs are inserted between the ground plane and the top of substrate layer forming a sandwich construction. The planar circuit elements (microstrip patch antenna in this case) can be fabricated on the top of substrate. Figure 5 shows a photograph of the EUC-PBG fabricated on RT/Duroid with substrate thickness 1.524 mm, dielectric constant 3. Since the Coupled SSR has higher Q than the conventional half-wavelength resonator, the proposed EUC-PBGs consisting of coupled SSRs exhibit extremely sharp cut-off in the forbidden band (Fig. 6).

.Microstrip diplexer patch antenna is used to verify the EUC-PBG properties. For simplicity and comparison, two antennas are designed and their dimensions of the antenna remain unchanged. One of the antennas is fabricated on RT/Duroid with substrate thickness 3 mm, dielectric constant 3, and another is fabricated on the proposed EUC-PBG substrate (Fig. 4). The dimensions of the rectangular patch (Fig. 2(a)) are 14.3 mm and 12.5 mm for resonant operation at 5.5 GHz and 6.0 GHz respectively. The 50 Ω transmission line width is 7.6 mm. The widths of the impedance transformers are 1.26 mm. Two antenna characteristics are to be examined to verify the effects of applying EUC-PBGs. They are surface wave suppression and isolation enhancement between two antenna ports. It is

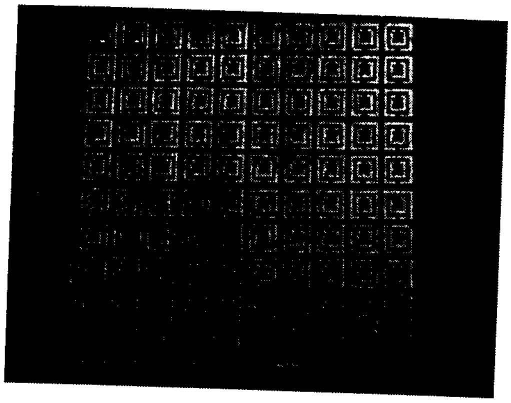


Fig. 5 An array of SSRs for EUC-PBGs.

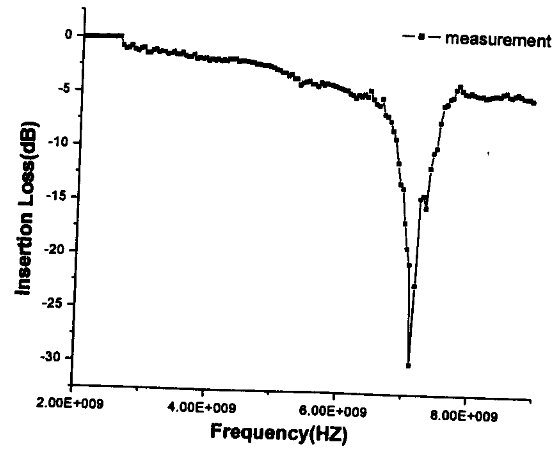
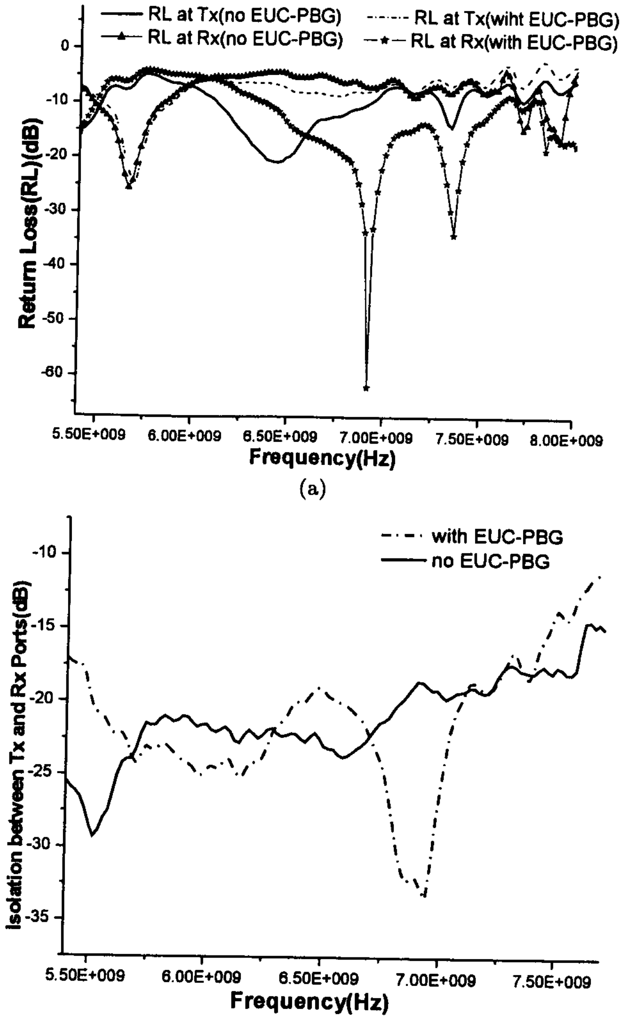


Fig. 6 Simulated and measured EUC-PBG responses.



(a)

(b)

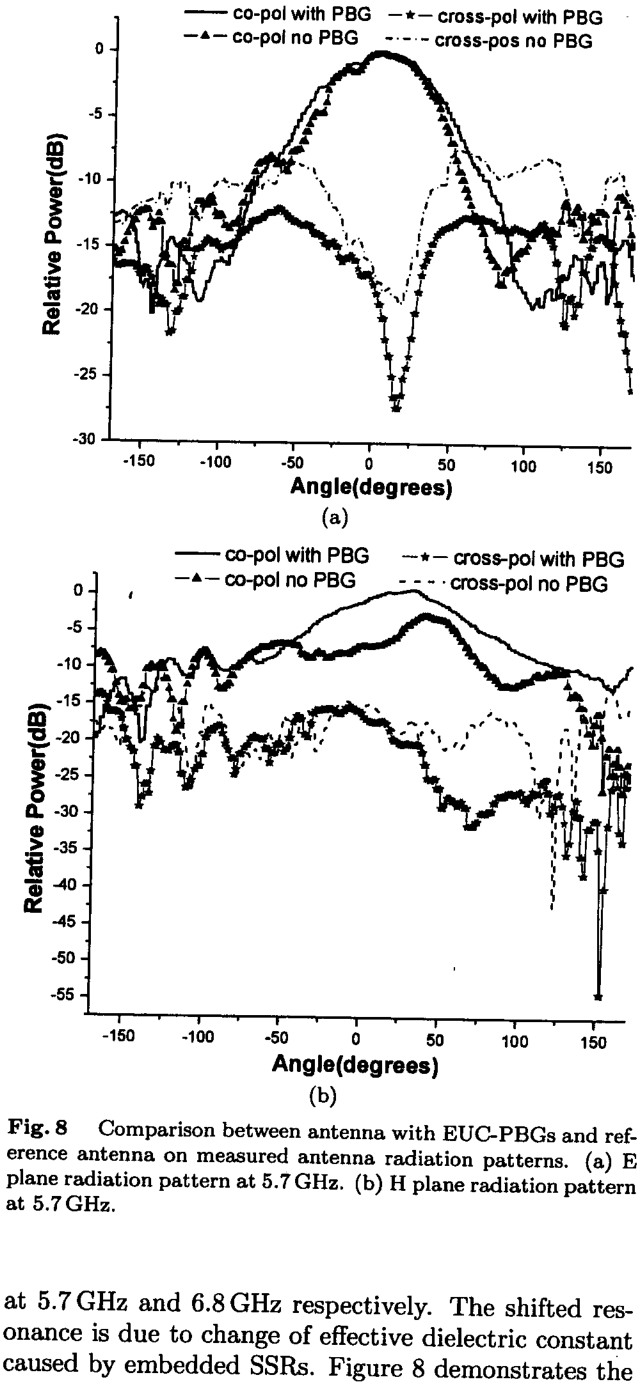
Fig. 7 Comparison between antenna with EUC-PBGs and reference antenna on measured antenna return loss and isolation. (a) EUC-PBG antenna and reference antenna return loss. (b) Diplexer antenna isolation comparison between EUC-PBG antenna and reference antenna.

known that substrate thickness should be chosen as large as possible to maximise antennas bandwidth and efficiency, however, such antennas also possibly excite surface-wave. For maximum operating frequency, the substrate thickness should satisfy [12]:

$$h \leq \frac{0.3c}{2\pi\sqrt{\varepsilon_r}f_u} \qquad (3)$$

where f_u is the maximum operating frequency and ε_r is relative permittivity of the substrate. In our case, ε_r =3.0 and h=3 mm, and therefore the maximum operating frequency f_u is about 2.8 GHz. So the surface-wave contribution to the antenna design is not negligible.

Figure 7 shows that antennas return losses and isolations at different ports. The antenna on conventional dielectric substrate resonates at 5.6 GHz and 6.4 GHz at different ports, which agree with the theoretical predictions. For antenna on the EUC-PBGs, the resonance is



(a)

(b)

Fig. 8 Comparison between antenna with EUC-PBGs and reference antenna on measured antenna radiation patterns. (a) E plane radiation pattern at 5.7 GHz. (b) H plane radiation pattern at 5.7 GHz.

at 5.7 GHz and 6.8 GHz respectively. The shifted resonance is due to change of effective dielectric constant caused by embedded SSRs. Figure 8 demonstrates the improved radiation pattern for the EUC-PBG antenna over the conventional antenna when both are resonant. For the antenna without EUC-PBGs, a lot of ripple and distortion are evident on various cuts of radiation patterns at two different ports. They are due to the violation of additional fields from the surface waves originating at the edges of the substrate. In this case, this effect is mainly contributed by the surface mode TM_0 since this mode has no cutoff. On the contrary, radiation patterns of the antenna on EUC-PBGs are smooth and symmetrical, more importantly, compared with conventional UC-PBGs [4], [5], the antenna backward radiation is reduced and hence its efficiency is

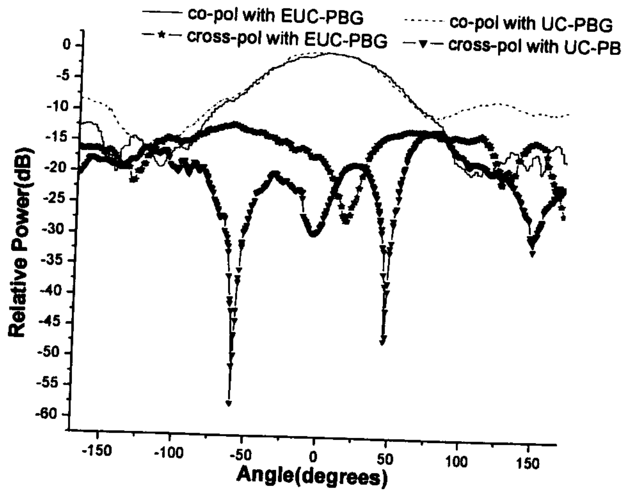


Fig. 9 Comparison between antenna with EUC-PBGs and reference UC-PBG antenna (shown in Fig. 8) on measured E-plane radiation patterns. The EUC-PBG antenna is resonating at 5.7 GHz, and the UC-PBG antenna 5.9 GHz.

further improved (Fig. 9). The isolation between two ports of diplexer antenna is also investigated. Figure 7 shows a little improvement on the isolation. This indicates that surface-wave contribution to the dipelxer antenna isolation can be neglected.

4. Conclusions

Various UC-PBG substrates have been investigated and applied to the design of microstrip antennas. Anisotropic properties of PBG structures can be used to improve diplexer antenna performance. A novel EUC-PBG scheme is also presented to overcome the strong backward radiation caused by the conventional UC-PBG antennas with PBG patterns on the ground plane. Compared with the antenna without PBGs, the evidence on surface wave suppression by EUC-PBGs is demonstrated. Experimental results show very good agreement with theoretical predictions. The SSRs used in this paper can be a very good candidate for PBGs size reduction, and hence opens up the possible applications of PBGs at lower microwave frequencies. In addition the construction of the EUC-PBG antenna is idea for millimetrewve applications where the complete antenna (array of) can be fabricated using multilayer IC technology on silicon or GaAS and combined with active components directly. Moreover, the concept of EUC-PBGs could be extended to the fabrication of novel meta-materials for microwave applications.

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