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Compact Planer Dual Band Circular Shaped Polarization-Dependent Electromagnetic Band Gap Structure to Reduce the RCS

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Abstract—In this paper, a compact planar dual-band circular-shaped polarization-dependent electromagnetic band gap (DCS-PDEBG) structure operates at 2.97 GHz and 7.77 GHz in y-direction and 3.14 GHz and 10.90 GHz in the x-direction. A proposed DCS-PDEBG structure consists of a circular patch inside a square patch with a slot at the center, and the established arrangement gives additional capacitance and compact size. The simulation of the DCS-PDEBG is carried out using the Finite Element Method (FEM) of Ansys High-Frequency Simulator (HFSS) and experimentally validated. A truncated microstrip line (TML) method is used to measure the band gap of the proposed planar DCS-PDEBG structure. Experimental results agree well with simulation one. The periodic size of proposed DCS-PDEBG structure is $0.13\lambda_{2.97\,\text{GHz}} \times 0.13\lambda_{2.97\,\text{GHz}}$, which is a good candidate where compact size is highly desired.

1. INTRODUCTION

The electromagnetic band gap (EBG) is a periodic structure that has unique stopband characteristic which is extensively used in microwave applications like antenna performance improvement, microwave filters, radar cross-section reduction (RCS), etc. EBG configuration consists of periodic nature; therefore, compact size is desirable in such an application. In recent years, several single layer polarization dependent [1–6], single band [1–7], dualband [4, 8–10] planar EBG structures have been reported. An eight-shaped EBG [1] is proposed with a periodic size of $0.158\lambda_{5.94\,\text{GHz}} \times 0.297\lambda_{5.94\,\text{GHz}}$ for reduction of specific absorption rate (SAR) reduction on three-layer body model. Zhu and Langley [8] propose a dual-band planer EBG with the periodic size of $0.32\lambda_{2.45\,\text{GHz}} \times 0.32\lambda_{2.45\,\text{GHz}}$, to improve the performance of a dual-band co-planar patch antenna. Bhavarthe et al. [2] propose a compact two-via hammer spanner type polarization-dependent electromagnetic band gap (TVHS-PDEBG) with a patch size of $0.060\lambda_{2.56\,\text{GHz}} \times 0.060\lambda_{2.56\,\text{GHz}}$. A slotted mushroom-type [3] electromagnetic bandgap structure is proposed with the periodic size of $0.171\lambda_{2.70\,\text{GHz}} \times 0.171\lambda_{2.70\,\text{GHz}}$, to reduce the radar cross-section of microstrip probe feed patch antenna. A dualband PDEBG [9] is proposed with a patch size of $0.063\lambda_{3.44\,\text{GHz}} \times 0.080\lambda_{3.44\,\text{GHz}}$. An application for it is described to realize dual band circular polarization using 3×3 PDEBG surface as a reflector dual dipole antenna. A dual-band eight-shaped polarization dependent mushroom type EBG [4] structure is proposed with a patch size of $0.14\lambda_{3.32\,\text{GHz}} \times 0.07\lambda_{3.32\,\text{GHz}}$ with the application as a polarization reflector. A polarization-dependent EBG [5] surface is proposed with an inclined sheet via patch size of $0.21\lambda_{3\,\text{GHz}} \times 0.21\lambda_{3\,\text{GHz}}$. In this paper, the performance of the surface is analyzed by varying the length, thickness, and inclination of the vias. Nakamura and Fukusako [11] propose a broadband circularly polarized patch antenna using an artificial ground structure with rectangular unit cells as a reflector with a patch size of $0.13\lambda_{6\,\text{GHz}} \times 0.2\lambda_{6\,\text{GHz}}$. A PDEBG [6] structure is proposed with a patch size of $0.16\lambda_{3\,\text{GHz}} \times 0.16\lambda_{3\,\text{GHz}}$ with an application

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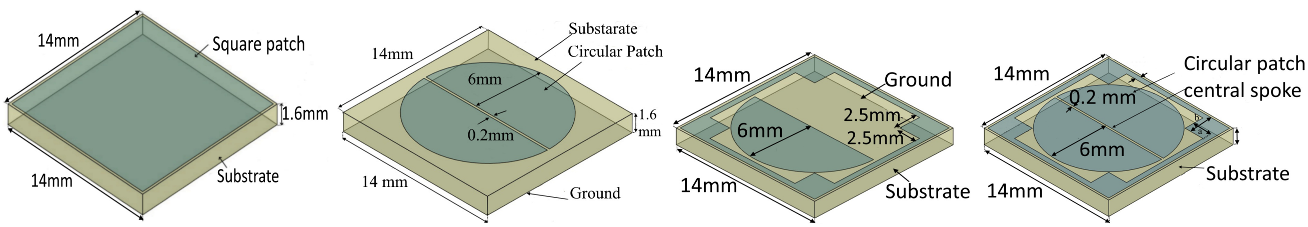
described as a reflector that can control the polarization state of the reflected wave. An EBG [12] is proposed with a patch size of $0.20\lambda_{3\,\mathrm{GHz}} \times 0.20\lambda_{3\,\mathrm{GHz}}$ for application of dipole antenna. In this, switching elements are used on the ground to obtain the reflection phase for reconfigurable circular polarization. Chen et al. [10] propose a checkerboard surface with two different planar EBG structures with a patch size of $0.15\lambda_{3.4\,\mathrm{GHz}} \times 0.15\lambda_{3.4\,\mathrm{GHz}}$ to reduce the RCS. Reported EBG structures are not suitable for low-frequency applications due to large patch size and are limited to give polarization-dependent characteristics. Therefore in this paper, a compact dual-band planar polarization-dependent electromagnetic band gap (DCS-PDEBG) is proposed with an application of DCS-PDEBG to reduce RCS. Section 2 provides the design of the proposed DCS-PDEBG with a reflection phase diagram. The bandgap measurement is described in Section 3. Section 4 explains the application of the proposed EBG structure to reduce RCS. Finally, conclusions are drawn in Section 5.

2. UNIT CELL OF PROPOSED DCS-PDEBG AND REFLECTION PHASE DIAGRAM

Unit cell design and reflection phase of the planar EBG structure can be characterized by a parallel LC resonator with resonant frequency (f_c) [4]

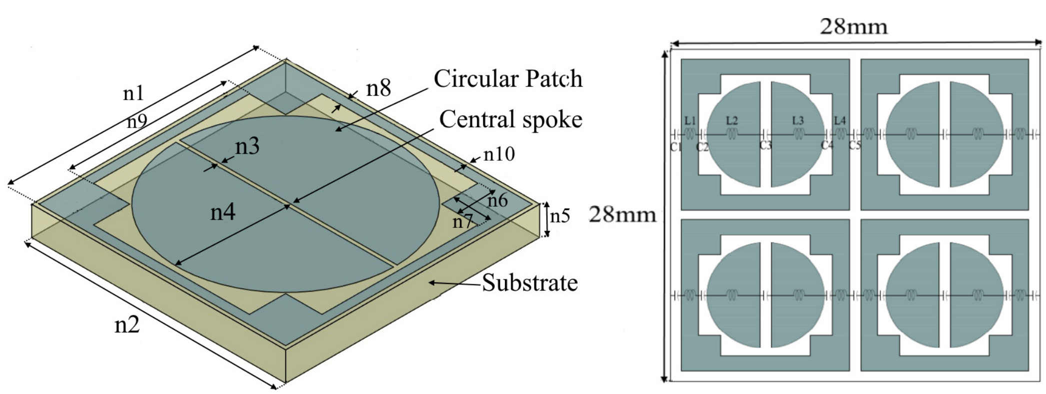
$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The inductance (L) is formed due to the patch of the EBG, and the gap in the EBG structure gives the capacitance (C). Parallel LC is formed due to the ground plane and EBG patch. To achieve size reduction and multi-band operations, a circular shape patch inside a square patch with a slot at the center is created as shown in Figure 2(a). The progress of the proposed DCS-PDEBG from simpler square patch EBG is shown in Figure 1. The configuration of the 2 × 2 cell of the proposed EBG is



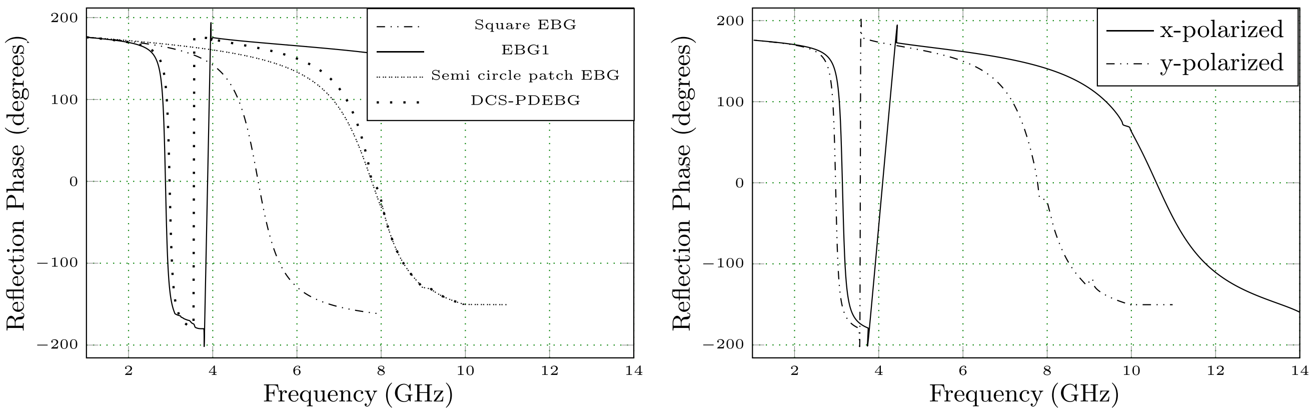
(a) (b) (c) (d)

Figure 1. Evolution of proposed dual-band circular shape polarization-dependent electromagnetic band gap (DCS-PDEBG) structure. (a) Square patch EBG, (b) EBG1, (c) semi circle patch EBG, (d) proposed DCS-PDEBG.



(a) (b)

Figure 2. (a) Unit cell of DCS-PDEBG. (b) Configuration of 2 × 2 cell of proposed DCS-PDEBG.



(a) (b)

Figure 3. (a) Simulated reflection phase of different evolution stages of DCS-PDEBG. (b) Simulated reflection phase of DCS-PDEBG in x and y polarization.

shown in Figure 2(b). Capacitance C_1 is due to the gap between two EBG patches. Capacitance C_2 is formed due to the gap between the inner circular patch and outer square ring, and capacitance C_3 is due to the center slot. Inductance L_1 is due to the outer ring, and L_2 is formed due to the inner half circular ring [13, 15]. To analyze dual-band characteristics, the proposed single unit cell is simulated in FEM-based Ansys High-Frequency Structure Simulator (HFSS). The reflection phase diagram of the single unit cell is plotted as shown in Figure 3(a) with a plane wave kept illuminating 90 degrees. The parameters of the proposed DCS-PDEBG are substrate dielectric constant $\varepsilon_r = 2.2$, substrate height $(n_1) = 13.6$ mm, $(n_2) = 14$ mm, gap $(n_3) = 0.2$ mm, circular patch radius $(n_4) = 6$ mm, $(n_5) = 1.6$ mm, $(n_6) = 2.5$ mm, $(n_7) = 2.5$ mm, $(n_8) = 0.5$ mm, $(n_9) = 8.6$ mm, $(n_{10}) = 0.2$ mm. The proposed EBG is polarization-dependent. Different center frequencies are observed as per polarization. The reflection phase diagram Figure 3(b) shows x- and y-polarizations. For y-polarization, f_{c1} is observed as 2.97 GHz, and f_{c2} is observed as 7.77 GHz. For x-polarization, F_{c1} is observed as 3.14 GHz, and f_{c2} is 10.90 GHz (reflection phase = 0 degree). The lower cutoff frequency and higher cutoff frequency of the first resonance in y-polarization are $f_{c1(l)}$ 2.40 GHz and $f_{c1(h)}$ 3.43 GHz respectively shown in Figure 4. Similarly, the lower cutoff frequency and higher cutoff frequency of the second resonance are $f_{c2(l)}$ 6.70 GHz and $f_{c2(h)}$ 7.88 GHz, respectively, with a bandwidth of 1.18 GHz and 1.48 GHz, respectively. An increase in the gap (g) between substrate and patch will increase the first band center frequency f_{c1}, with the second band center frequency constant. With increment in the radius (r) of a circular patch and keeping gap (g) constant, decrement in second band center frequency f_{c2} is observed for both x- and y-polarizations. The proposed EBG consists of a circular patch with a rectangular strip at the center. The outer square ring is arranged with four square inner corners to achieve compactness, which results in higher capacitance. To achieve circular polarization properties for the proposed DCS-PDEBG, rectangular symmetry is maintained.

3. EXPERIMENTAL RESULTS

To verify the band gap properties of the proposed planar DCS-PDEBG, 5×5 cells are fabricated and tested. The truncated microstrip line (TML) method [2, 16] is used for testing of band-gap properties of the proposed EBG structure. The proposed DCS-PDEBG cells are printed on a Rogers RT/duroid 5880 (tm) substrate with a dielectric constant $(\varepsilon_r) = 2.2$, loss tangent $(\tan\delta) = 0.0009$, and substrate height of 1.6 mm. The distance between the microstrip line and EBG cells is 2 mm. Other parameters of the DCS-PDEBG cells are the same as mentioned in Section 2. The photograph of the fabricated prototype, measurement setup, measured and simulated S_{21} are shown in Figure 4. A dual band-gap property is observed from Figure 4 in both directions for the proposed EBG structure. In the y-direction, the first band gap is observed at a center frequency of 2.97 GHz with a lower cut-off frequency of 2.40 GHz and a

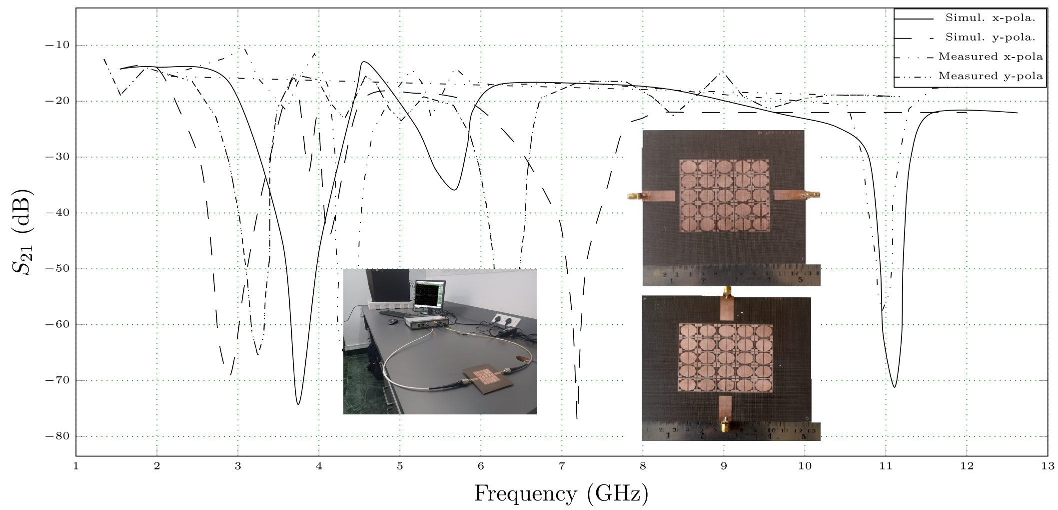


Figure 4. Photograph of measurement set up, simulated and measured S_{21} for the DCS-PDEBG using truncated microstrip line method.

Table 1. Comparison of polarization, S_{21}, and EBG patch size with previous work.

Sr. No.	Name of EBG	No. of Bands	f_c (GHz)	h (mm)	ϵ_r	Polarization	S_{21} (dB)	EBG Patch Size
[1]	Eight Shape EBG	01	5.94	0.7	1.7	P.D.	−29 dB	$0.158\lambda_{5.94\,\text{GHz}} \times 0.297\lambda_{5.94\,\text{GHz}}$
[2]	TVHS-PDEBG	01	2.56, 3.29	1.5	4.4	P.D.	−65 dB, −58 dB	$0.060\lambda_{2.56\,\text{GHz}} \times 0.060\lambda_{2.56\,\text{GHz}}$
[3]	Slot EBG	01	2.70	4	2.2	P.D.	N.M.	$0.171\lambda_{2.70\,\text{GHz}} \times 0.171\lambda_{2.70\,\text{GHz}}$
[4]	ES PDEBG	02	3.32, 5.67	1.57	2.2	P.D.	−62 dB, −32 dB	$0.14\lambda_{3.32\,\text{GHz}} \times 0.07\lambda_{3.32\,\text{GHz}}$
[5]	Inclined Sheet via PDEBG	01	3	1.6	4.4	P.D.	N.M.	$0.21\lambda_{3\,\text{GHz}} \times 0.21\lambda_{3\,\text{GHz}}$
[6]	Rectangular PDEBG	01	3	4	2.2	P.D.	N.M.	$0.16\lambda_{3\,\text{GHz}} \times 0.16\lambda_{3\,\text{GHz}}$
[7]	DPEBG	01	7.5	0.76	2.43	N.M.	−40 dB	$0.058\lambda_{7.5\,\text{GHz}} \times 0.058\lambda_{7.5\,\text{GHz}}$
[8]	Zhu EBG	02	2.45, 5	1.1	1.38	Coplanar	−18 dB, −40 dB	$0.32\lambda_{2.45\,\text{GHz}} \times 0.32\lambda_{2.45\,\text{GHz}}$
[9]	PDEBG	02	3.44, 6.24		3.5	Circularly Polarized	N.M.	$0.063\lambda_{3.44\,\text{GHz}} \times 0.080\lambda_{3.44\,\text{GHz}}$
[10]	Chen EBG	02	3.4, 9.4	6.35	2.2	Planar EBG	N.M.	$0.15\lambda_{3.4\,\text{GHz}} \times 0.15\lambda_{3.4\,\text{GHz}}$
[11]	AG-EBG	01	6	3.2	2.2	Circularly Polarized	N.M.	$0.13\lambda_{6\,\text{GHz}} \times 0.2\lambda_{6\,\text{GHz}}$
[12]	Reconfigurable EBG	01	3.56	3.2	4.3	Circular Polarisation	N.M.	$0.166\lambda_{3.56\,\text{GHz}} \times 0.166\lambda_{3.56\,\text{GHz}}$
[P.E.]	DCS-PDEBG (P.E.)	02	2.97, 7.77	1.6	2.2	P.D.	−90.44 dB, −78.32 dB	$0.13\lambda_{2.97\,\text{GHz}} \times 0.13\lambda_{2.97\,\text{GHz}}$

Note, P.D. = Polarization Dependent, N.M. = Not Mentioned, P.E. = Proposed EBG higher cut-off frequency of 3.43 GHz, and the second band gap with a center frequency of 7.77 GHz with a lower cut-off frequency 6.70 GHz and a higher cut-off frequency 7.88 GHz. In the x-direction, the first band gap is observed at a center frequency of 3.14 GHz with a lower cut-off frequency of 2.54 GHz and a higher cut-off frequency of 3.44 GHz, and the second band gap with a center frequency of 10.90 GHz. The proposed DCS-PDEBG is compared with the reported EBG in terms of patch size, return loss, and polarization dependent as sown in Table 1. It is observed that the proposed EBG is of $0.13\lambda_{2.97\,\text{GHz}}$ size with polarization dependence. The difference between measured and simulated results is due to manufacturing errors and ideal infinite periodic structures utilization in simulations.

4. APPLICATION

In this section, the application of the proposed EBG structure to provide radar cross-section reduction is demonstrated. Radar cross section (RCS) is the parameter that gives the ability of radar target to reflect the signals in the trans-receiver direction, hence RCS reduction is an important aspect while low visibility radar targets are designed. To reduce the RCS, various methods have been reported in the literature like circuit loading, shaping, materials, etc. [14, 17]. EBG structures exhibit band-stop characteristics with multi-band operations; therefore, these characteristics can be used to reduce the RCS. A checkerboard surface with the proposed EBG structure to reduce the RCS for two frequencies is shown in Figure 5. The proposed dualband EBG structure exhibits 0° reflection phase at 2.97 GHz

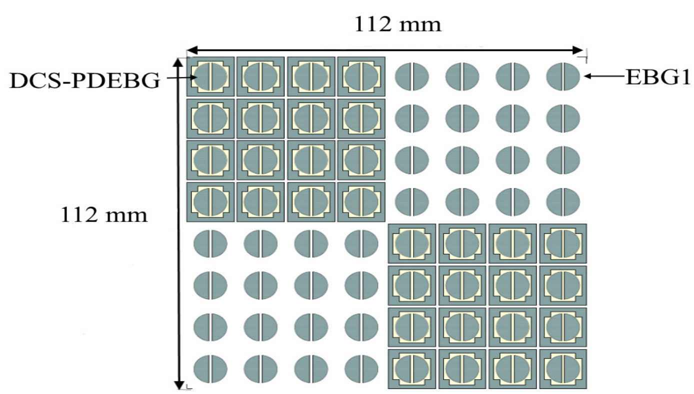


Figure 5. The dual-band checkerboard surface with 4 × 4 EBG structure.

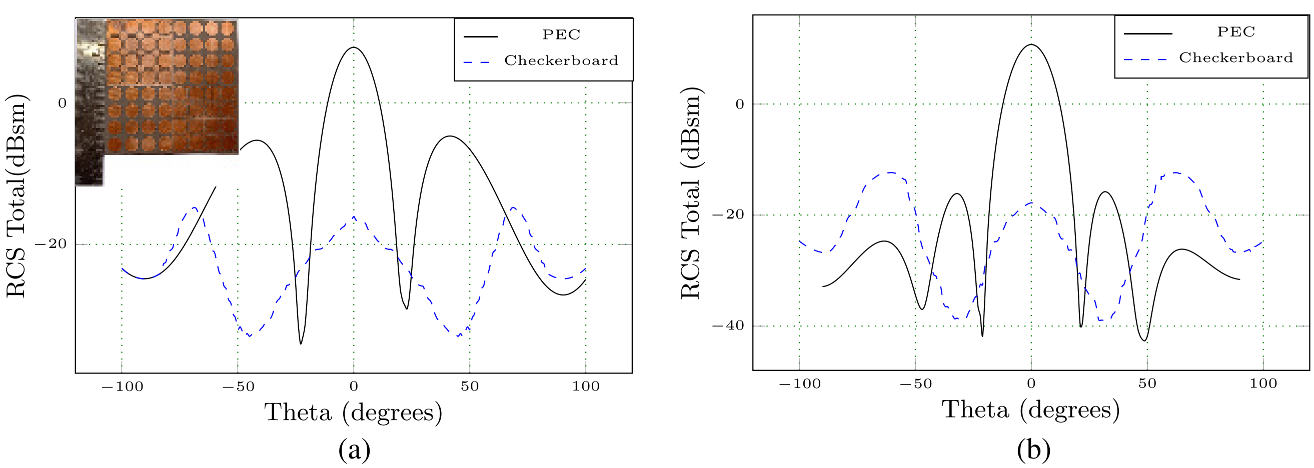


Figure 6. RCS pattern for checkerboard surface along the principal planes with proposed EBG and perfect electric conductor (PEC) at (a) 2.97 GHz, (b) 7.77 GHz.

and 7.77 GHz in the y-direction and 3.14 GHz and 10.90 GHz in x-direction. In further application, y-direction properties are considered, as they give lower resonance frequency than that in the x-direction. At zero reflection phase, the scattered field gets canceled in the normal direction. The dimensions of the DCS-PDEBG structure are the same as mentioned in the earlier section.

A dualband checkerboard surface with the proposed EBG structure is shown in Figure 5 and is simulated and fabricated with overall dimensions of 112 mm × 112 mm. The measured RCS with the proposed EBG checkerboard and PEC at 2.97 GHz and 7.77 GHz is shown in Figure 6. It is clear that compared to the PEC surface, the EBG checkerboard surface gives more than 18 dB RCS reduction at both the operating frequencies with the same periodic size. Therefore, it shows that the proposed planer dual EBG structure is useful where compact size is highly desirable.

5. CONCLUSION

In this paper, the DCS-PDEBG and circular patch EBG structure has been presented. The proposed EBG structure has been simulated and validated experimentally. The periodic size of this planar EBG structure is $0.13\lambda \times 0.13\lambda$, at resonance frequency 2.97 GHz. In the x- and y-directions, it gives polarization properties. The center strip and outer ring lead toward the compactness of the proposed PDEBG structure. The radius of the center circular patch and the center strip is responsible for variation in the center frequency for both the resonances in the x- and y-directions. Simulated and experimental results prove that compared to the rectangular PDEBG, slot EBG, and eight-shaped PDEBG, the proposed planar PDEBG presents 18.75%, 23.13%, and 55% reduction in the center frequency with respective to the lower band gap. The application of the proposed PDEBG is also presented as a checkerboard surface to reduce the RCS. Therefore, the proposed PDEBG structure is very useful for polarization-dependent applications where compact size is highly desirable.

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