Design of a highly miniaturized novel electromagnetic bandgap (EBG) material for performance improvement in microwave components

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Abstract. In this paper, a new uniplanar compact spiral-shaped asymmetric electromagnetic bandgap structure for a low-profile antenna is proposed. The proposed EBG design is constructed, with four spiral-shaped radiators are combined with centre element, which printed on an FR-4 dielectric material. The miniaturisation of the EBG unitcell has been achieved by increasing the electrical length of the radiating element. The overall dimensions of the proposed EBG structure is very low about only \(0.03 \lambda_0 \times 0.03 \lambda_0\) (\(\lambda_0\) is the free space wavelength at the resonating frequency of 2.4 GHz). Miniaturization of the proposed EBG structure is 86% obtained when compared to conventional EBG structure for 2.4 GHz. This spiral-shaped EBG design can adequately suppress surface wave and it exhibits effective band-stop response at resonant frequency 2.4 GHz. The proposed EBG structure also provides improved performance especially peak gain, when it is placed beneath the antenna. A significant improvement in peak gain up to 1.7 dB and 15% bandwidth at resonant frequency 2.4 GHz has been achieved after integration with proposed EBG design.

Keywords: Asymmetric EBG, low-profile antenna, miniaturisation, surface wave, band-stop response

1. Introduction

With the advanced development of wireless communication, especially wireless sensor networks (WSNs) are gaining more importance and growing up in the electronic system. Electromagnetic bandgap (EBG) is an artificial structure that generates a stopband to prevent or assist the propagation of EM waves of particular frequency bands. EBG structures can be arranged in a form of a periodic pattern of radiation elements on dielectric materials [1]. The applications of EBG can vary from different fields like RFID, absorbers, spatial filters, circuit analogue (CA), antennas, reflectors, bandstop or bandpass filters and metamaterial [2]. The purpose of the EBG structure is to mitigate electromagnetic noise in electronic devices. Moreover, the EBG designs are mainly used to improve the radiation performance by suppressing the surface wave over the printed antenna technology. EBG structures having special features and good performance while it is attached with microstrip patch antennas. Moreover, EBG loaded antenna structure very high gain without any other performance’s degradation [3].

Nowadays, different electromagnetic bandgap structure (EBG) has been analysed and reported for printed planar antenna systems [4]. A modified dual-layer mushroom EBG structure used to improve
performance and mutual coupling reduction in patch antenna array [5]. A compact uniplanar electromagnetic bandgap (UC-EBG) is used for wireless body area network (WBAN) applications. The addition of 2×3 UC-EBG on the backside of the monopole antenna which exhibits gain improvement from 2.1 to 5.6 dB at 2.4 GHz [6]. Another work investigated a textile-based split-ring shaped EBG unitcell for WBAN applications. The split-ring shaped EBG is added with the partial ground which provides improved performance such as compact size, enhanced gain and SAR reduction [7]. The ground plane of the curved slotted antenna has been replaced by fractalized uniplanar compact electromagnetic bandgap (F-UC-EBG) to achieve the improved antenna performance such as fractional bandwidth, peak gain and radiation efficiency [8]. Especially, Sierpinski fractal-shaped EBG provides more effective results in radiation performance [9]. A distorted uniplanar compact electromagnetic band-gap (DUC-EBG) which acted as a resonating element of a bandpass filter for UWB applications. This EBG structure provides passband characteristics over a frequency range of UWB band (3.1 - 10.6 GHz). Moreover, EBG structures are used to reduce the radar cross-sectional (RCS) of the developed planar antenna [10]. Further, the addition of two spiral inductances with planar EBG which achieves the multiband behaviour. A dual-band EBG design operates at 1.8 and 2.4 GHz using infinitesimal dipole with circular symmetric geometries [11]. Multiple cylindrical holes are periodically created on the perimeter of ellipse shaped EBG structure with different radius. These band-gap structures integrated with a patch antenna to suppress the surface wave propagation and gain increment [12].

Recent years, most of the printed antennas are designed to be compact for many applications. Therefore, the EBG structure should be designed with compact size for antenna performance improvement. In practice, EBG has usually difficulty in modifying its physical size and therefore, shrinking the size of an EBG structure is one of the most critical concerns to be solved [13]. Among the various EBG configurations, some of the shapes are achieving compactness by increasing the electrical length of its radiating element, such as mushroom shape, meander line, spiral shape, fork-like shape, etc [14]. The uniplanar types of the EBG are the more attractive and suitable for compact planar antenna systems. Due to its simple design and ease of fabrication over the grounded vias or holes, uni-planar EBG structures have great attention from the researchers. A uni-planar EBG has been achieved 61 % size reduction thereby, increasing the effective inductance and capacitance of the patch by using double folded bend [15]. Better miniaturization achieved in interdigital EBG reflector by use of meandering the radiating elements. An interdigital EBG (ID-EBG) can reduce from 30 to 40 % in its overall size by increasing the fringe capacitor of periodic interdigital elements on the patch [16]. Recently, spiral-like structures provide more attracted designs and better radiation performance. A spiral-shaped EBG structure provides multiband behaviour with up to 30 % size reduction when compared to conventional mushroom-like EBG structure [17]. A combination of spiral and broken shape radiators which produces the large inductance and capacitance value and it can be obtained 66% size reduction [18].

The main aims of the proposed design are as follows.
1. Design and develop a highly miniaturized UC-EBG structure for 2.4 GHz frequency.
2. The proposed design should be fabricated on inexpensive and easily available FR4 dielectric substrate material for reducing the costs with material loss.
3. To achieve a better performance of the miniaturized antenna when it is placed above the proposed EBG design.

In this study, a novel highly miniaturized EBG structure, which made up of spiral-shaped resonator with a size of 3.75 × 3.75 mm is proposed. The size of the EBG unitcell is reduced by increasing the electrical length of the resonator, and it is embedded on the FR4 substrate with 1.6 mm thickness. The EBG provides a stopband characteristic at 2.4 GHz to demonstrate the EBG, the proposed design integrated with the existing low-profile antenna and analysed their results. The proposed EBG significantly enhanced the antenna gain up to 1.7 dB and 210 MHz improvement in the impedance bandwidth.
2. EBG unit cell design and simulation results

The unit cell of this novel compact UC-EBG structure is composed of four-arm spiral shaped resonators connected with the centre element. The design configuration of the proposed EBG is given in Figure 1, which is printed on the FR4 dielectric substrate with 1.6 mm thickness. It can be that the single spiral resonator is mirrored structure of all other resonators which provides the symmetric geometry. The proposed UC-EBG unit cells are equivalent to parallel LC resonant circuit is formed by inductance due to the spiral resonators and capacitance due to the gap between the adjacent spiral arms. While increasing the number of turns in spiral resonator which provides high inductance and capacitance and effectively decreases the resonant frequency of a UC-EBG unit cell. Meanwhile, the miniaturization is obtained without increasing the overall area. The whole parameters of a single EBG unit cell is given in Table 1.

![Design configuration of the proposed symmetric UC-EBG.](image)

**Table 1.** Design parameter of the proposed EBG structure.

| Parameter | a   | t   | d   | L1  | L2  | L3  | L4  |
|-----------|-----|-----|-----|-----|-----|-----|-----|
| Value (mm)| 3.7 | 0.1 | 0.075 | 1.78 | 1.58 | 1.38 | 1.18 |

The proposed UC-EBG structure is simulated using CST Microwave Wave Studio software. The initial structure of the design comprises a simple square-shaped patch on FR-4 substrate. To achieve better miniaturization, the square shape patch was reduced to 0.1 mm thick spiral shape resonator. The inductance and capacitance value are high while increasing the electrical length of the patch. The overall electrical length of the single resonator is 21.16 mm. Therefore, the size of the proposed EBG structure is reduced to 3.75×3.75 mm and side length also reduced to 3.7 mm.
To validate the proposed EBG design, appropriate boundary conditions and exciting field vectors at ports was chosen. Since these EBG unit cells are used as a ground, a TEM wave propagates in the medium between the radiating element and the ground to create resonance. The proposed EBG is fixed between the waveguides on the negative and positive Z-axis. Boundary conditions for a perfect electric field and perfect magnetic field are set towards the X-axis and Y-axis, respectively. The Simulation arrangement of the proposed EBG is given in Figure 2. To analyse the electromagnetic properties of the proposed EBG, the reflection coefficient \( S_{21} \) and the transmission coefficient \( S_{11} \) is calculated. The \( S \)-parameter value of the proposed SRR structure is illustrated in Figure 3. It is evident from the transmission coefficients \( S_{21} < -10 \) dB, also the bandstop response of the compact UC-EBG structure is the range between 2.39 GHz and 2.585 GHz at centre frequency 2.45 GHz. It can be observed that the EBG design provides wider bandwidth and relative transmission characteristics. The effective bandgap width of the proposed design reaches 15%, and transmission coefficients \( S_{21} \) can be efficiently attenuating in the stopband.

![Figure 2. Simulation arrangement of the proposed EBG structure.](image)

### 3. Parametric analysis

The parametric study of the proposed UC-EBG has been analysed by varying the different design parameters.

#### 3.1. Number of turns \( (n) \)

The number of turns of the spiral resonator in the radiating patch is mainly for miniaturizing the proposed EBG. The variation of the reflection coefficient with the number of resonator turns is illustrated in Figure. 4a). The number of turns is getting increased; the resonant frequency of the design shifting towards the lower end. For using one turn with the centre element, the operating frequency of the structure lied at 8 GHz. By using three turns with the centre element, the resonating
frequency shifting from 8 GHz to 4.1 GHz. Finally, the proposed EBG had resonated at 2.4 GHz with 190 MHz bandwidth by using five turns. Moreover, sidelength is reduced to 3.7 mm.

3.2. Variation of line thickness (t)

The obtained reflection coefficient of the design by varying the line thickness of the spiral shaped resonator is given in Figure 4b). It is noticed that the line thickness can affect the reflection coefficient and the entire bandwidth of the proposed EBG. The line thickness (t) is varied from 0.3 to 0.1 mm. While decreasing the line thickness of the resonator, the reflection coefficient of design is also getting decreased. So, the optimized line thickness of the spiral arm is chosen as 0.1 mm.

3.3. Variation of line gap (d)

Next, the analysis is considered the gap between the spiral line (d), vary from 0.125 mm to 0.075 mm in Figure 4c). The reflection coefficient shifted towards to lower band with decreasing the gap between the spiral line. At \( d = 0.075 \) mm, the operating frequency is obtained at 2.4 GHz. So, the desired value of the gap between the spiral line is kept at 0.075 mm.

![Figure 4](image-url)

**Figure 4.** Parametric sweeps on the reflection coefficient. a) Variation on number turns, b) Variation of line thickness (t) and c) Variation of line gap (d).
4. Performance analysis of the proposed EBG on a miniaturized antenna

To demonstrate the performance of the proposed UC-EBG design, it is placed beneath the existing low-profile antenna and analyses the performance. Because of the unit cell boundary condition, the EBG structure can act as another ground plane with a specific distance \((d << \lambda_0/2)\) for integrated antennas. Usually, surface waves of the antenna which radiates the EM waves towards the EBG plane. Those EM waves are reflected by the EBG plane, but that reflected waves are in-phase, instead of out-of-phase. The unit cell of the EBG surface which allowing that the in-phase signals travel into the antenna surface. In other words, the current direction of the reflected waves is in constructive, instead of destructive interference with incident EM waves, resulting in the improved antenna performance [19]. The integration of an antenna with the EBG as can be viewed as Figure 5.

![Figure 5](image)

Figure 5. Working mechanism of the EBG plane on the antenna.

The design of the proposed EBG structure is placed under the metamaterial-based triangular patch antenna [20]. Here, 3×3-unitcells are arranged with the same size and 0.1 mm regular interval for performance improvement. The design setup of the proposed EBG unitcells on a printed miniaturized antenna is shown in Figure 6a). The antenna is located at the centre area of the EBG surface. The separation between the antenna and EBG structure is air medium with dielectric constant \((\varepsilon_0=1)\). This gap has been optimized to improve the antenna radiation characteristics of the main lobe.

![Figure 6](image)

Figure 6. Triangular patch antenna with proposed UC-EBG structure. a) Design configuration and b) Simulated return loss of antenna with EBG and without EBG.
4.1. Impedance bandwidth

A comparative curve of return loss for triangular patch antenna with and without EBG is shown in Figure 6b). It is observed that the antenna without EBG structure obtained impedance bandwidth of 80 MHz, which is ranging from 2.38 GHz to 2.46 GHz. Meanwhile, the proposed EBG structure integrated with antenna effectively increased the frequency range from 2.35 GHz to 2.56 GHz with a bandwidth of 210 MHz. From these results, it is observed a good impedance matching for an operating frequency of 2.4 GHz when the proposed EBG is integrated. Moreover, the gap (g) between the antenna and EBG as increases, the resonant frequency of the structure is shifting towards the higher end. Therefore, the gap between the elements is properly selected to avoid the huge variation in the frequency shift. As the desired value of the gap between the antenna and EBG is kept from 5 mm to 10 mm. The simulation performance of the antenna on the proposed EBG structure is summarized in Table. 2.

| Antenna          | Return loss on 2.4 GHz (dB) | Bandwidth (MHz) | Peak gain (dB) |
|------------------|-----------------------------|----------------|---------------|
| Without EBG      | -38                         | 80             | -5.1          |
| With EBG         | -27                         | 210            | -3.4          |

4.2. Peak gain

Moreover, the simulated gain of the integrated antenna is analysed without and with EBG structure. The variation in the simulated peak gain of both stages is plotted in Figure 7. It is clearly showing that the peak gains the antenna is getting increased when it is placed over the spiral shaped EBG structure. The gain of the EBG integrated miniaturized antenna can be enhanced by up to 1.7 dB while properly choosing the combination of EBG unitcells and air gap (g). Further, the simulated radiation efficiency of the integrated antenna is also getting little bit of improvement in comparison to the antenna without EBG. It is evident that the proposed EBG offers good miniaturization and improved performance compared to the other size reduction techniques reported in the literature.

![Figure 7. Simulated peak gains of the antenna with and without EBG.](image-url)
5. Conclusion
A novel, highly miniaturized and symmetric uniplanar EBG (UC-EBG) structure for performance enhancement of low-profile antenna is successfully designed, simulated and analysed. By introducing the four-arm spiral-shaped resonator on the top layer, the electrical length is increased up to 21.1 mm. Therefore, the inductance and capacitance of the proposed EBG is significantly increased and reduced its overall size into 3.75 mm × 3.75 mm. Moreover, the proposed EBG provides wider bandwidth (15 %) and an enhanced peak gain (up to 1.7 dB) while it is integrated with an existing low-profile antenna. Miniaturization of the proposed EBG structure is 86 % obtained when compared to conventional EBG structure for 2.4 GHz. Based on its compact size, low cost, and good simulation and radiation performances which are very attractive design for low profile planar antenna system.

6. References
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