A Review Paper on Electromagnetic Band Gap structure

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Abstract : In this paper, review of single, dual, and multi band gap Electromagnetic Band gap structures is presented. Analysis of each structure in terms of size, band gap center frequency, number of layers, periodic length is done systematically. This paper will give the proper direction to the new researcher in the field of Electromagnetic Band gap structures.

IndexTerms— Dispersion diagram, Dual-band gap, Electro- magnetic Band Gap (EBG) Structure, Size reduction.

I. INTRODUCTION

Electromagnetic Band-Gap (EBG) structures have become important in the microwave and antenna area as many applications can be obtained from their characteristics. In recent years, several EBG structures has been proposed. It has been reported that, period of EBG should be half wave length at the stop band frequency, so the EBG structure have large size at the lower frequency.

II.REVIEW OF ELECTROMAGNETIC BAND GAP STRUCTURE

In 1999, D. Sievenpiper et al [1] investigated a novel metallic type of periodic mushroom type electromagnetic band gap (MT-EBG) structure as shown in Table I which has high impedance at its resonance frequency. They have proved that, MT-EBG structure reflects electromagnetic waves with no phase reversal like artificial magnetic conductor (AMC) structure. In this work, lumped element model was also presented which predicts the stop band properties of MT-EBG structure. They proved that, proposed MT-EBG structure is useful to enhance the performance of low profile antenna.

F. Yang et al [2] introduced a finite-difference time domain (FDTD) analysis of mushroom type-EBG (MT-EBG) structure as shown in Table I for mutual coupling reduction in probe feed patch antenna. To prove the stop band characteristics of MT-EBG, E-plane coupled micro-strip antennas are simulated using FDTD method on a substrate with dielectric constant (εr) = 10.2, and height (h) = 2 mm. The size of each antenna is 7 mm × 5 mm with $0.75\lambda 5.8$GHz distance between them. The MT-EBG is inserted between two patch to reduce the mutual coupling. The parameters of the MT-EBG are: EBG patch width (w) = 3 mm, gap between two adjacent EBG (g) = 0.5 mm, and the radius of each via (r) = 0.2 mm with band gap center frequency (fc) = 5.8 GHz. Due to stop band characteristics of EBG, mutual coupling between two patch antenna reduced by 10 dB at 5.80 GHz.

L. Yang et al [3] reported a compact fork-like EBG as shown in Table I for microwave application. In fork-like EBG, to achieve the compactness per EBG cell, additional capacitance was formed between the neighboring edges of the slot and the stretched strip from an adjacent patch. To measure the band gap property of fork-like EBG, 5 × 5 cells were fabricated on substrate with (εr) = 2.7, substrate height (h) = 2.00 mm. Other parameters were: the length of the square patch (w) = 4 mm, width of slot (s) = 1 mm, and length (lp) = 3 mm, width of the stretched strip (D) = 0.5 mm, and length (Ls) = 3 mm, and distance between two adjacent fork-EBG (g) = 0.5 mm. The suspended micro-strip line method was used for measurement. For fork-like EBG, 4.63 GHz to 4.98 GHz band gap with center frequency of 4.8 GHz was reported.

In 2007, E. Rajo-Iglesias et al [4] proposed a edge located via EBG (ELV-EBG) as shown in Table I by shifting the position of via towards the edge of EBG patch to achieve the compactness. To measure the band gap property of ELV-EBG, probe method was used. 4 × 6 cells of EBG are fabricated on FR-4 substrate with (εr) = 4.4, substrate height (h) = 1.50 mm. Other parameters of ELV-EBG were: EBG patch size (w) = 7mm, gap beteen two adjacent ELV-EBG (g) = 2 mm, and radius of each via (r) = 0.1 mm. Since presented ELV-EBG had rectangular symmetry, therefore measurement was conducted in both x-and y-direction. Measured band gap center frequency of ELV-EBG was 3.83 with 20 % size reduction as compared to CLV-EBG.

X. L. Bao et al [5] proposed a dual-band fractal EBG struc- ture as shown in Table I for GPS application. The Minkowski fractal structure was used to achieve the compactness in dual- band fractal EBG structure. The parameters of EBG structure were: period of EBG (P) = 32.5 mm, patch size of each EBG (w) = 28 mm, radius of the each via (r) = 0.5 mm, for the 1st and 2nd iteration each side width was replaced according to fractal generator. For validation of band-gap properties of fractal EBG was fabricated on FR-4 substrate with dielectric constant (εr) = 4.0, and height (h) = 1.52 mm. The presented fractal EBG gave two band-gaps. The first band gap was from 1.16 GHz to 1.32 GHz and the second was from 1.45 GHz to 2.10 GHz.

Q. R. Zheng et al [6] introduced a spiral shape-EBG (spiral- EBG) as shown in Table I in which capacitance between two elements increases and therefore compactness was achieved. 6 × 6 cells of spiral-EBG are fabricated on substrate with (εr) = 2.65, substrate height (h) = 2 mm for band-gap measurement. Other parameters of spiral-EBG chosen as: the periodic spacing (a) = 5.6 mm, the gap between neighboring elements (2g) = 0.2 mm, the width of micro-strip line (2s) = 0.5 mm, the length of micro-strip line (l) = 11.8 mm, radius of the via (r) = 0.4 mm. A band gap reported for spiral-EBG was from 3.01 GHz to 3.44 GHz with center frequency 3.25 GHz. By adjusting the length of the strip, the central frequency of band-gap varied over a wide frequency range.

H. R. Cheng et al [7] proposed a compact double reverse split rings-EBG (RSR-EBG) as shown in Table I for fractal micro-strip antenna application. 3 × 5 cell of proposed EBG was simulated on substrate with (εr) = 2.2, substrate height (h) = 2 mm and suspended micro-strip line were used for measurement. Other parameters of RSR-EBG were: patch size (w) = 4.5 mm, RSR width (cx) = 0.3 mm, gap between two adjacent RSR-EBG (g) = 0.3 mm, radius of the via (r) = 0.2mm. Reported band gap bandwidth was from 4.72 GHz to 8.0 GHz (S21 ⩽ 10 dB) with center frequency 6.36 GHz.

J. Liang et al [8] proposed a tunable EBG structure as shown in Table I by using PIN diode. In this work, two hard-wire connections for each EBG unit cell are added for the switch on' state, to provide the electrical connection between via pads and ground plane. In case of switch off' state these wires are taken off. The parameters of each unit cell of EBG structure were: EBG patch width (w) = 5 mm, gap between two EBG structure (g) = 2 mm, radius of each via (r) = 0.2 mm. To measure the tunble properties of this EBG, 3 × 6 cells were fabricated on FR-4 with dielectric constant (εr) = 4.4, and height (h) = 31 mil. Suspended micro- strip line method was used for the measurement. When PIN diode was in off state, band gap was present with center frequency of 1.86 GHz, whereas for on state of PIN diode it was with center frequency of 2.52 GHz.

X. Chen et al [9] proposed Meandering Slotted EBG (MS- EBG) as shown in Table I for the suppression of the surface wave. Cross slots and meandering slots gives the two surface wave suppression band gaps. The geometry parameters of the MS-EBG were (w) = 9.5 mm, (g) = 0.5 mm, (t) = 4 mm, (r) = 1.5 mm, (d) = 0.25 mm, (sl) = 8.4 mm, (sw) = 0.2 mm, (p) = 2 mm, (sl1) = 2.7 mm. MS-EBG plate with 12 × 12 unit cells were fabricated on substrate with (εr) = 2.2, thickness = 4 mm. The transmission coefficient was measured using a pair of shield loops by a VNA HP8719ES. The first surface-wave band gap was from 3.4 to 4.64 GHz in Γ-X direction and from 3.2 to 4.92 GHz in Γ-M direction. The second surface-wave band gap was from 7.32 to 10.00 GHz in Γ-X direction and from 7.24 to 10.4 GHz in Γ-M direction.

L. Peng et al [10] proposed a compact and polarization dependent mushroom type EBG using Complementary Split Ring Resonator (CSRR) as shown in Table I for multi band gap applications. In this type of EBG, CSRRs significantly enlarge capacitance of the CLV-EBG in both X and Y-direction. Thus, the first band gap center frequency decreases in all directions compared with CLV-EBG. The geometry parameters of CSRR-EBG are (εr) = 2.2, (h) = 2.5 mm, (r) = 0.3 mm, (W) = 7.3 mm, (g) = 0.2 mm, (W1) = 6.5 mm, (W0) = 0.5 mm, (a) = 0.2 mm, (g0) = 0.2 mm. Simulation and optimization results for the CSRR-EBG were calculated using CST Microwave Studio 2009. To measure the band gap properties of CSRR-based EBG, 7 × 7 lattice of the EBG were fabricated. The measurements were conducted with an Agilent E5071C ENA series network analyzer. Truncated microstrip line at the both ends was used for measurement. The first band gap was defined in both X and Y-directions from 3.30 to 5.05 GHz. The second band gap of the CSRR-based EBG was from 6.05 to 6.75 GHz in Y-direction.

T. Masri et al [11] presented a combination of mushroom type EBG (MT-EBG) and modified Minkowski EBG structure to improve the single port dual-band micro-strip array. Here EBG structures operate like a band rejecter, separating the branch of feed lines which are feeding two different groups of arrays of patch antennas. In this work MT-EBG and modified Minkowski having parameters as: patch width (w) = 3 mm, gap between two EBG (g) = 0.5 mm. 3 × 3 cell of this combine structure were fabricated on FR-4 substrate with dielectric substrate (εr) = 4.4, and height (h) = 1.50 mm. This combine structure exhibits two band gap i.e. 1st for MT-EBG with center frequency at 2.4 GHz and 2nd for modified Minkowski EBG at 5.8 GHz.

D. Nashaat et al [12] introduced Embedded Spiral EBG (ES-EBG) as shown in Table I for patch antenna array appli- cation. ES-EBG consists of four arms spiral, embedded with a mushroom-type EBG and spiral patches. The material used for substrate was RT/D 6010 with (εr) = 10.2, thickness (h) = 2.5 mm. The ES-EBG had vias of radius = 0.25 mm and overall EBG patch 6 mm with dimensions of spiral arm width and gap between arms = 0.5 mm. To evaluate the reflection coefficient phase of the EBG ES-EBG, the normal incidence angle was used. In measurement of band gap properties of ES- EBG, E8364A Vector Network Analyzer (VNA) was used. ES- EBG exhibited band gap with center frequency at 8.4 GHz.

S. Ullah et al [13] introduced a sheet via polarization dependent EBG (sheet via-PDEBG) structure as shown in Table I. The properties of presented PDEBG structure are varied with via angle and length. Unlike several other methods which make use of rectangular EBG patch to achieve polarization characteristics, in this case they have used square patch. The parameters of sheet via PDEBG structure were: width of the square patch (w) = 21 mm, gap between adjacent PDEBG (g) = 2 mm. the length of the sheet via (ls) = 8 mm, thickness of the via (vt) = 2 mm. For measurement of the band gap properties, sheet via PDEBG were fabricated on FR-4 substarte with dielectric constant (εr) = 4.5, and height (h) = 1.60 mm. A band gap with center frequency 2.20 GHz in x-direction and 3.40 GHz in y-direction for inclination angle of 00 were observed in the measurement.

S. L. Huh et al [14] introduced new design technique and analysis for an Embedded EBG (E-EBG) as shown in Table I. In this work, they have designed three types EBG, two-layer EBG structure, three-layer E-EBG, and three-layer E-EBG with vias. These three EBG structures were fabricated on the FR4 substrate with (εr) = 4.4, thickness of 165 μm and copper as metal layer with thickness of 35.6 μm. The unit cell size for each case is 26 mm with EBG layer consists of 25 unit cell. For the three-layer E-EBG with vias, six vias were used per port. Agilent 8714 ET RF NA was used to measure S-parameter for each type of structure. For two-layer EBG structure has band-gap from 1.1 GHz to 2.3 GHz with isolation level -75 dB, whereas three layer E-EBG does not have any band gap. With interconnecting vias between the top and bottom planes, three layer E-EBG structure exhibited band-gap whose range was same to that of the two layer EBG structure. This design technique is very usefulfor load board applications.

L. Peng et al [15] presented EBG structure as shown in Table I with compact size and multi-band gaps. The presented EBG was formed by etching dual U-shaped slots symmetrically with respect to one axis of the ELV-EBG. For the measurement 2 of band-gap properties of the DAU-EBG, 6 × 6 lattice was constructed on substrate with (εr) = 2.2 and substrate height (h) = 2.00 mm. Other parameters of DAU-EBG are (r) = 0.3 mm, (g) = 0.2 mm, (w) = 8.8 mm, (a) = 7.8 mm, b = 0.5 mm, c = 6.9 mm, d = 0.2 mm, i = 1 mm, j = 0.2 mm, k = 5.7 mm, and m = 6.4 mm. The Agilent E5071C NA was used in S parameter measurement. Monopole antenna method was used to measure the transmission coefficient in X-and Y-direction. For DAU- EBG, three band-gaps in X-direction and two band-gaps in Y-direction were obtain. The first band-gap in X-direction was 2.3-2.6 GHz and 2.5-2.9 GHz in Y-direction. The second and third band-gaps include 4.1-5.0 GHz and 5.9-6.6 GHz in X-direction with second band in Y-direction includes 4.8-6.0 GHz. By adjusting the slot parameters, resonant frequency of the DAU-EBG can be tuned within a certain range.

C. D. Wang et al [16] proposed a compact size; wide stop band bandwidth four layers an interleaved EBG structure as shown in Table I. This EBG structure was implemented in four layer of substrate. Two patches with same dimensions were embedded in upper and bottom substrates. Two via were present per unit cell of EBG. First via was present between bottom and third layer while second via between upper and second layer. Each via was interleaved in respective substrate. Parameters of each unit cell of interleaved EBG structure were taken as: width of upper and bottom layer(a) = 4 mm, width of second and third layer (p) = 3.8 mm, distance between two via (v) = 0.21 mm, radius of each via (rr) = 0.0375 mm. For the measurement of band gap property of interleaved EBG, a substrate with dielectric constant (εr) = 7.8, and height (h) = 4.5 mm were used. Due to multi-layer structure, this EBG gives wide band gap bandwidth from 1.9 GHz to 6.12 GHz.

H. Yi et al [17] proposed dual band; rectangular type polarization-dependent EBG structure as shown in Table I as a reflector of dual-band dipole antenna to realize circular polarization. This PDEBG structure consists of an outer rectangular ring and an inner rectangular patch. The parameters of the each unit cell PDEBG structure were as: length of the unit cell (l) = 6.8 mm, width of the unit cell (w) = 4.95 mm, width of the outer ring (wo) = 0.25 mm, length of the inner patch (li) = 5.8 mm, width of the inner patch (wi) = 3.3 mm, gap between two adjacent PDEBG (g) = 1 mm. A 3 × 3 cells of this PDEBG structure were fabricated on substrate with dielectric constant (εr) = 3.5, and height (h) = 1 mm. Presented PDEBG had two band gaps. In lower band gap was from 3 GHz to 3.50 GHz whereas higher band gap was from 6.01 GHz to 6.16 GHz.

W. Chen et al [18] presented Circular type of EBG (C- EBG) as shown in Table I for the wide band RADAR cross section reduction application. The unit cell of the EBG with a circular shape has radius of 3 mm, was located on the top of a Rogers RT/duroid 5880 substrate (εr) = 2.2 and substrate height (h) = 6.35 mm with gap between two patches was 9.0 mm. Reflection coefficient, phase, and magnitude of this C-EBG unit cell was simulated using Ansys HFSS. The resonance frequency of C-EBG was 7.27 GHz with magnitude of the reflection coefficient was -0.014 dB.

Table 1: Summary of reported EBG structures.

Ref. patch	No. of layers size SB/DB/PD	ε_r h (mm)	f_c1/f_c2 (GHz)	EBG at λc
[2]	Single	10.2	5.80/N.A.	$0.058\lambda_c$
	SB	2.00		
[3]	Single	2.70	4.80/N.A.	$0.112\lambda_c$
	SB	2.00		
[4]	Single	4.40	3.83/N.A.	$0.089\lambda_c$
	SB	1.50		
[5]	Single	4.00	1.24/1.78	$0.112\lambda_c1$
	DB	1.52		
[6]	Single	2.65	3.23/N.A.	$0.060\lambda_c$
	SB	2.00		
[7]	Single	2.20	6.36/N.A.	$0.095\lambda_c$
	SB	2.00		
[8]	Single	4.40	1.86/2.52	$0.031\lambda_c1$
	DB	0.79		
[9]	Single	2.20	4.02/8.66	$0.127\lambda_c1$
	DB	4.00		
[10]	Single	2.20	3.82/6.40	$0.093\lambda_{cx}$
	PD	2.50		
[11]	Single	4.40	2.4/5.8	$0.024\lambda_c1$
	DB	1.50		
[12]	Single	10.2	8.4/N.A.	$0.168\lambda_c$
	SB	2.50		
[13]	Single	4.50	2.20/3.40	$0.154\lambda_{cx}$
	PD	1.60		
[14]	Two	4.40	1.7/N.A.	$0.147\lambda_c$
	SB	3.20		
[15]	Single	2.20	2.52/2.50	$0.072\lambda_{cx}$
	PD	2.00		
[16]	Four	7.80	4.01/N.A.	$0.051\lambda_c$
	SB	4.50		
[17]	Single	3.50	3.44/6.24	$0.063\lambda_{cx}$
	PD	1.00		
[18]	Single	2.20	7.27/N.A.	$0.145\lambda_c$
	SB	6.35		
[19]	Single	4.30	2.05/4.98	$0.099\lambda_c2$
	DB	1.58		
[20]	Single	2.20	3.4/9.4	$0.136\lambda_c1$
	DB	6.35		
[21]	Two	2.65	5.00/7.50	$0.083\lambda_c1$
	DB	2.00		
[23]	Single	2.20	2.70/3.40	$0.171\lambda_{cx}$
	PD	4.00		

SB = Single Band, DB = Dual Band, PD = Polarization Dependent.

In 2016, J. P. Shinde et al [19] proposed a M-shaped EBG structurer as shown in Table I for dual band gap applications. This EBG consists of conducting vias and spiral groove etched on FR substrate with (εr) = 4.3 and substrate height (h) = 1.58 mm. The length of the M-shape groove gives the equivalent (L). Unit cell size of each EBG is a 6 mm × 6 mm. Diameter of each via is (dia) = 0.6 mm. The spacing between the adjacent M-EBG unit cell was 1 mm with (s) = 1 mm, (n) = 0.75 mm, (m1) = 4 mm, and (m2) = 5 mm. The characteristics of M-shape EBG were measured by using Suspended Micro- strip Line (SMSL) method. For M-shape EBG, first band gap was centered at 2.05 GHz with bandwidth of the stop band was 600 MHz, and the second band gap is centered at 4.98 GHz having bandwidth of the stop band 1.005 GHz.

W. Chen et al [20] proposed a dual-band square type EBG with square loop on EBG patch (Chen-EBG) as shown in Table I for radar cross section reduction. Reflection coefficient phase of an EBG structure was 00 at its resonance frequency where as for perfect electric conductor (PEC) it was 1800. This property of EBG structure was used in this [18] work. Parameters of each unit cell of chen-EBG were: EBG patch width (W) = 12 mm, width of outer width (Wo) = 1 mm, inner square patch width (Wi) = 6.3

mm, For fabrication, a substrate with dielectric constant (εr) = 2.2, and height (h) = 6.35 mm. From simulated results, Chen-EBG exhibited two band gaps at 3.4 GHz and 9.4 GHz.

S. Zhang et al [21] introduced a compact, simple structure and dual-band two-layer edged located vias and inter digital EBG (TELI-EBG) structure as shown in Table I. TELI-EBG consists of two dielectric substrates. The inter digital and square patch were present on the front and back of the upper substrate respectively while ground planeis present on the back of the lower substrate. To get the inductance two vias were present on the opposite edge of the upper and lower substrate. The major parameters of the TELI-EBG were: EBG patch size (a) = 5 mm, size of inter digital structure (m1) = 0.8 mm, distance between two inter digital structure (g) = 0.2 mm. TELI-EBG structure were fabricated on the lower and upper substrate with dielectric constant (εr) = 2.65, height (h) = 2 mm. This EBG structure exhibited dual band gap property at 5 GHz and 7.5 GHz with 30 % size reduction compared to ELV-EBG.

J. Zhang et al [22] introduced a wide band gap slot fractal Uniplanar Compact EBG (UC-EBG) structure as shown in Table I based on 3rd iteration of Moore Space Filling Geometry UC-EBG (MSF-UC-EBG). In this work, two types of MSF-UC-EBG structures, fabricated on FR4 with (εr) = 4.4 and Rogers RO-3010 with (εr) = 10.2 were designed. Transmission Line (TL) method was used to measure the band gap characteristics of MSF-UC-EBG. For FR based MSF-UC- EBG parameters are taken as (w) = 1.6 mm, (g) = 1.9 mm, (d) = 1.9 mm, (h) = 1.0 mm, (wid gap) = 2 mm, (len gap) = 2 mm, (strip wid) = 10 mm, and for Rogers based MSF-UC- EBG parameters were taken as (w) = 1.9 mm, (g) = 1.6 mm, (d) = 1.6 mm, (h) = 0.6 mm, (wid gap) = 6.8 mm, (len gap) = 5.8 mm, (strip wid) = 5.4 mm. For FR based MSF-UC-EBG, band gap was observed from 1.43 to 5.89 GHz with relative bandwidth of 121.8% and for Rogers based MSF-UC-EBG, band gap was observed from 1.09 to 4.57 GHz with relative bandwidth of 122.9%.

Z. J. Han et al [23] introduced a slot-type polarization dependent EBG (slot-PDEBG) as shown in Table I to enhance the gain and reduce the radar cross section (RCS) of a patch antenna. In slot-PDEBG, pair of a symmetric Y-oriented rectangular slot on the EBG patch were presented to get different electrical paths in x-and y-polarization which gives different band gap properties in x- and y-direction. Different parameters of the slot-PDEBG are as: width of EBG patch (W) = 19 mm, gap between two adjacent PDEBG (G) = 2 mm, radius of via (r) = 0.05 mm, width of each slot (ws) = 2.8 mm, length of each slot (ls) = 15.5 mm, and distance between two slot (d) = 6 mm. To measure the polarization dependant properties of the slot-PDEBG, 5× 5 cell were fabricated on the substrate with dielectric constant (εr) = 2.2, and height (h) = 4 mm. For slot-PDEBG, band gap were present at 2.70 GHz in x-direction and at 3.40 GHz in y-direction. The summary of reported EBG structures is given in Table 1.

III. CONCLUSION

In this paper, review of single, dual, and multi band gap Electromagnetic Band gap structures is presented. Analysis of each structure in terms of size, band gap center frequency, number of layers, periodic length is done systematically. Proper summary of reported EBG structures is also provided at the last. This paper will give the proper direction to the new researcher in the field of Electromagnetic Band gap structures.

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