A Novel Two-Layer Compact Electromagnetic Bandgap (EBG) Structure and Its Applications in Microwave Circuits[*]

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Abstract- - This paper presents a novel two-layer Electromagnetic Bandgap (EBG) structure. The studies on the characteristics of the cell are carried out numerically and experimentally. A lumped-LC equivalent circuit extracted from the numerical simulation is used to model the bandgap characteristics of the proposed EBG structure. Also, the influences of geometric parameters on the operation frequency and equivalent LC parameters are discussed. Based on the studies, a meander line high performance bandstop filter and a notch type duplexer are designed and measured. The investigations show the potential applications of these EBG structures in microwave and RF systems.

Key Words- - Electromagnetic bandgap, microstrip line, filter, duplexer

I. Introduction

Recently, Photonic Bandgap (PBG) structures have become one of the most interesting areas of research. These structures consist of one-, two- or three-dimensional finite periodically perforated dielectric/metallic material or ground planes that forbid the propagation of all electromagnetic waves within a particular frequency band (called the bandgap). This property permits additional control over the behaviour of electromagnetic waves other than conventional guiding and filtering structures. The research work was originally done in optical region, where they were called PBG (Photonic Bandgap) [1]. Although there exist some debates over terminology with respect to these structures [2], now their applications have been extended to a wide frequency range, even to the microwave and millimetre-wave ranges. Due to their unique frequency selective characteristics and excellent slow-wave transition property, they can be used as frequency selective layers and antenna radomes. In addition, the PBG structures can be employed in integrated circuit and antenna designs to reduce cross-talk or suppress surface waves, or configurate radiation patterns [3-5]. These structures will play an important role in MIC and MMIC designs [6].

The PBG structure is in principle practically an electromagnetic bandgap (EBG) structure since it has been scaled to microwave and millimeter-wave frequency [7]. The planar EBG structures have attracted much more interests in microwave and MMIC applications because they are simple to manufacture and easy to be integrated monolithically with other circuits [8-11]. For these structures, each of unit lattices can roughly be modeled by parallel LC resonant circuit [12]. However, such

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structures suffer from their large dimensions. To achieve stopband, too many EBG cells need to be arranged with a period of half wavelength at the centre frequency of the stopband. This makes it unsuitable for applications at low frequency. One way to alleviate this problem is to introduce additional inductance and capacitance by etching lattices with some new shapes, which can make the structure more compact [13] or to embed the metallic strips, such as dipoles or tripoles into the dielectric, called metallodielectric EM bandgap (MEMBG) [14][15].

In this paper, a novel compact two-layer structure for the microstrip application is proposed as a bandgap design. In this structure, a shorted patch is placed between the strip and a ground plane, which disturbs the electromagnetic field distribution. This disturbance causes the energy resonating between the patch and shorting pin at a certain frequency. An equivalent circuit based on lumped LC elements is used to model each cell of proposed structure. The equivalent circuit parameters are extracted by means of the EM simulations and network synthesis theory. The effects of each geometric dimension on the equivalent circuit parameters are described. Based on the proposed EBG structure and equivalent circuit model, two useful designs in S band are investigated numerically and experimentally. Compared with the conventional EBG structures cutting off apertures or slots onto the ground plane, this novel structure is more compact and suitable for microwave applications. Furthermore, this structure can completely prevent unwanted radiation from the apertures in the back-slotted EBG designs.

II. Analysis of the Proposed EBG Cell

1. Structure Description

Fig.1 shows 3-D architecture of the proposed 2-layer structure cell based on 50-ohm microstrip line design, which horizontally place a square patch under the strip, and with a thin via shorting the patch to the ground plane. In this figure, *a* and *b* are the length and width of the patch, d_1 and d_2 denote the distance form shorting position related to the patch edges.

2. Frequency Characteristics

In order to investigate the frequency characteristics of the proposed EBG cell in Fig.1, we do EM simulations by FDTD program and Ansoft ^{TM}Ensemble separately. The substrate for simulation is Roger 4003 with 1.57mm thick and a dielectric constant of 3.38. The microstrip width is 3.7 mm corresponding to a 50-ohm transmission line. The other dimensions are as follows: a=14 mm, b=14 mm, L=30 mm, $d1$=7 mm, $d2$=4 mm, h_1=0.81mm, h_2=0.81mm. The S-parameters for the structure indicated are shown in Fig.2 (a), in which the straight line is EM simulation results, while the dash-dotted line is by measurement with HP8751 network analyzer. The slight difference might be due to the fabrication errors. Fig.2 (b) shows the simulated and measured group delay of this structure. It should be noted that there comes up with a negative group delay (-30 ns) around the rejecting frequency (2.25 GHz). It proves that, near this region, there are distinctive variations in both amplitude and phase delay.

3. Equivalent Circuit Parameter Extraction

All these results show that there is an attenuation pole located at 2.25 GHz. It is well known that, in filter design theory, an attenuation pole can be generated by the inductance and capacitance elements. In this structure, the patch adds to the effective capacitance of microstrip, the thin shorting via under the patch provides inductive reactance. Combining the capacitance with inductance and standard transmission lines, we get the equivalent circuit in Fig.3.

In order to obtain a lumped circuit model for the proposed EBG structure, we now use network analysis method to extract the parameters for the supposed equivalent circuit in Fig.3 from already achieved scattering parameters.

The steps to extract the circuit parameters are as below:

1) Find transmission attenuation pole location ? $_0$ from S parameters
2) Transform S parameters to Z parameters, and find the immediate pole position ?$_z$ of Z
3) Solve equations for Z matrix to get LC parameters

First we form the ABCD matrix: $[A]_{abcd} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$, then it is transformed to Z matrix,

$$[Z] = \frac{Z_0}{Y_r Z_0 \cos^2 q + j\sin 2q} \cdot \begin{bmatrix} \cos 2q + jY_r Z_0 \sin 2q/2, & 1 \\ 1, & \cos 2q + jY_r Z_0 \sin 2q/2 \end{bmatrix} \quad (5)$$

in which, q denotes electric length of the transmission line ($2p\,l/l_g$), and

$$Y_r = \frac{1}{R + jwL + 1/jwC} \quad (6)$$

For ease, we suppose the network is lossless, and

$$\frac{1}{jw_z L + \frac{1}{jw_z C}} Z_0 \cos^2 q + j\sin 2q = 0 \quad (7)$$

$$\frac{1}{\sqrt{LC}} = w_0 \quad (8)$$

By solving these two equations, we can get the L, C parameters of the equivalent circuit.

$$C = 2tgq \frac{w_z^2 - w_0^2}{w_z w_0^2 Z_0}, \quad L = \frac{1}{w_0^2 C} \quad (9)$$

Table I show the extracted equivalent-circuit parameters for the proposed EBG cell in Fig. 1. The circuit simulation results for the obtained equivalent circuit are compared with EM simulation and measurement results in Fig.2 (a) (Dotted line).

Table I Extracted equivalent circuit parameters for the proposed EBG cell

Structure Dimensions	a=b=14mm, d1=7mm, d2=4mm, ?=65^o
Capacitance C (pF)	0.48
Inductance L (nH)	10.45
Attenuation Location (GHz)	2.24
Impedance Pole location (GHz)	2.32

4. Influence of the Geometric Dimensions

The patch area is increased by adding its width, and keeping the shorting position in the center of the patch. As indicated in table II, the extracted effective capacitance and inductance in the equivalent circuit model will change, and this will cause a lower cut-off frequency on the whole. The shifting trend with the patch width is shown in Fig. 4.

Table II LC Parameters of Extracted equivalent circuit for different patch size (a=14mm)

b (mm)	L (nH)	C (pF)
12	10.48	0.37
16	11.98	0.43
20	13.96	0.46

Fig. 5 describes how the resonant frequency is shifted when moving the shorting position. This characteristic makes it rather convenient to adjust the design to a certain stopping frequency when the patch size has been decided. Fig.6 shows the simulated current distribution on the patch at resonant frequency. As can been seen, the patch with the shorting pin acts as the resonant load capacitance-coupled to the microstrip. Moving the shorting pin will change the current flow pattern on the surface, which will cause the structure resonating in a different frequency. Another interesting phenomenon is that moving the position in d_2 direction has steeper shift.

By the aid of EM simulation software, the heights and dielectric constants of the two layers are also changed separately to see the influence (Fig. 7(a)-(b)). The rejection frequency increase steadily with h_1, versus with h_2. When changing the substrate dielectric of top layer (e_{r1}), there is only small drift of operation frequency. However, when changing the dielectric constant of bottom layer (e_{r2}), the rejection frequency moves rapidly. The extracted equivalent LC parameters for different h_2 are listed in Table III.

Table III LC Parameters of Extracted Equivalent Circuit for different substrate height

h_2 (mil, h_1=32)	L (nH)	C (pF)
16	27.69	0.14
32	10.49	0.43
48	7.06	0.72

From the simulation results and extracted LC parameters, it is demonstrated that changing the patch width, moving the shorting position along transverse direction, and altering the dielectric constant of the bottom substrate may allow more change in *L*, *C* parameters, so as to achieve more obvious shift in resonance frequency. This is easily to be explained by its physical structure. As indicated at the beginning of this section, this EBG structure is basically an electrically coupled resonant structure. So the patch width in the current flowing direction and bottom layer configuration will affect the resonant frequency obviously.

III. Design Examples

1. Meander Microstrip Line Bandstop Filter

This microstrip notch filter is designed with meander lines cascading seven EBG structures periodically. As shown in Fig. 8, the whole structure is fabricated on a two-layer Roger 4003 substrate, with relative permittivity e_r=3.38 and substrate height h_1=h_2=32mil. All the cells are with the same dimensions (a=b=13mm, d_1=d_2=6.5mm) except in the corner where d_1=d_2=6.2mm. The resonant cells are connected with quarter-wavelength microstrip lines which act as J-inverters. The simulation and measurement S-Parameters are displayed in fig. 9. A wide stopband (about 17.3%) with small ripples exists from 2.3 to 2.8 GHz and the maximum insertion loss reaches 50 dB.

2. Antenna Notch Type Duplexer

Duplexer is a device, which allows a transmitter operating on one frequency and a receiver operating on a different frequency to share one common antenna with a minimum of interaction and degradation of the different RF signals. Duplexer is the key component that allows two way radios to operate in a full duplexer manner. Duplexers are often configured with several filters. There are many ways to combine filters to perform duplxer operations. It relies upon the characteristic of the filter used in the duplexer. The notch type duplexer uses several notch filters to reject unwanted signals in the center frequency. Fig.10 is the structure of the duplexer for base station application (Rx:1.92-1.98GHz, Tx:2.11-2.17GHz). The duplexer was built using Roger dielectric sheets with e_r=3.38. For the EBG cell used in Rx filter, a=12mm, b=16mm, d_1=6mm, d_2=3.5mm; for the Tx filters, a=12mm, b=18mm, d_1=6mm, d_2=3.5mm. Fig.11 is the simulated and measured S parameters of the duplexer. The experimental results show the designed duplexer can provide excellent isolation (minimum 48.5dB from Rx to the antenna and 41.7dB from the antenna to Tx) between the two channels. The measured maximum insertion loss in each passband is 1.22dB (Rx channel) and 1.97dB (Tx channel) separately.

IV. Conclusion

We have proposed an EBG structure for microstrip applications in L and S band. The main idea is that this structure utilises the resonator coupled to the microstrip to provide a distinguished bandgap property. We have also investigated into the structure and discussed the influences of the tunable geometric parameters on its resonant characteristic. With 3D EM simulations and circuit analysis method, LC parameters of the equivalent circuit are extracted. Based on the structure simulation and equivalent circuit extraction, some useful design examples are developed theoretically and experimentally. The numerical simulation and measurement results agree very well. The proposed structure and its equivalent circuit potentially provide a new idea to design more efficient EM structures for microwave and RF circuit applications, such as filters, phase shifter, and other passive circuits.

References

[1] E. Yablonovitch, “ Inhibited spontaneous emission in solid-state physics and electronics,” *Physical Review Lett.*, Vol. 58, No.20, May 1987, pp.2059 -2062.

[2] A. Oliner, “ Periodic structure and photonic-band-gap terminology: historical perspectives,” in *Proc. 29th Eur. Microw. Conf.*, Vol. 3, Munich, Germany, Oct.1999, pp.295-298.

[3] H. Y. Yang, N. G. Alexopoulos and E. Yablonovitch, “ Photonic bandgap materials for high-gain printed circuit antennas,” *IEEE Trans. on Antennas and Propagation*, Vol.45, Jan.1997, pp. 185-186.

[4] V. Radisic, Y. Qian and T. Itoh, “ Broad-band power amplifer using dielectric photonic bandgap structure,” *IEEE Microwave and Guided Wave Letters*, Vol. 8, Jan.1998, pp.13-14.

[5] H.Contopanagos, L. Zhang and N. G. Alexopoulos, “ Thin frequency selective lattice integrated in novel compact MIC, MMIC, and PCA architectures,” *IEEE Trans, on MTT*, Vol. 46, No.11, pp. 1936-1948.

[6] L. Zhang, “ Finite-element based techniques for the modelling of PBG materials,” *Electromagnetics*, 1999, pp. 225-239.

[7] Shau-Gang Mao, and Ming-Yi Chen, “A Novel Periodic Electromagnetic Bandgap Structure for Finite-Width Conductor-Backed Coplanar Waveguides,” *IEEE Microwave and Wireless Components letters*, Vol. 11, No.6, June 2001, pp261-263.

[8] F. Falcone, T. Lopetegi, and M. Sorolla, “ 1-D and 2D photonic bandgap microstrip structures,” *Microwave and Optical Technology Letters*, Vol. 22, No. 6, Sept. 1999, pp.411 -412.

[9] H.Y.David Yang, " Theory of microstrip lines on artificial periodic substates," *IEEE Trans. on Microwave Theory and techniques*, Vol. 47, May 1999, pp. 629-635.

[10] F. Yang, Y. Qian, R. Coccioli, and T. Itoh, " Analysis and application of photonic band-gap (PBG) structure for microwave circuits," *Electromagnetics*, 1999; 19(8): 241-254.

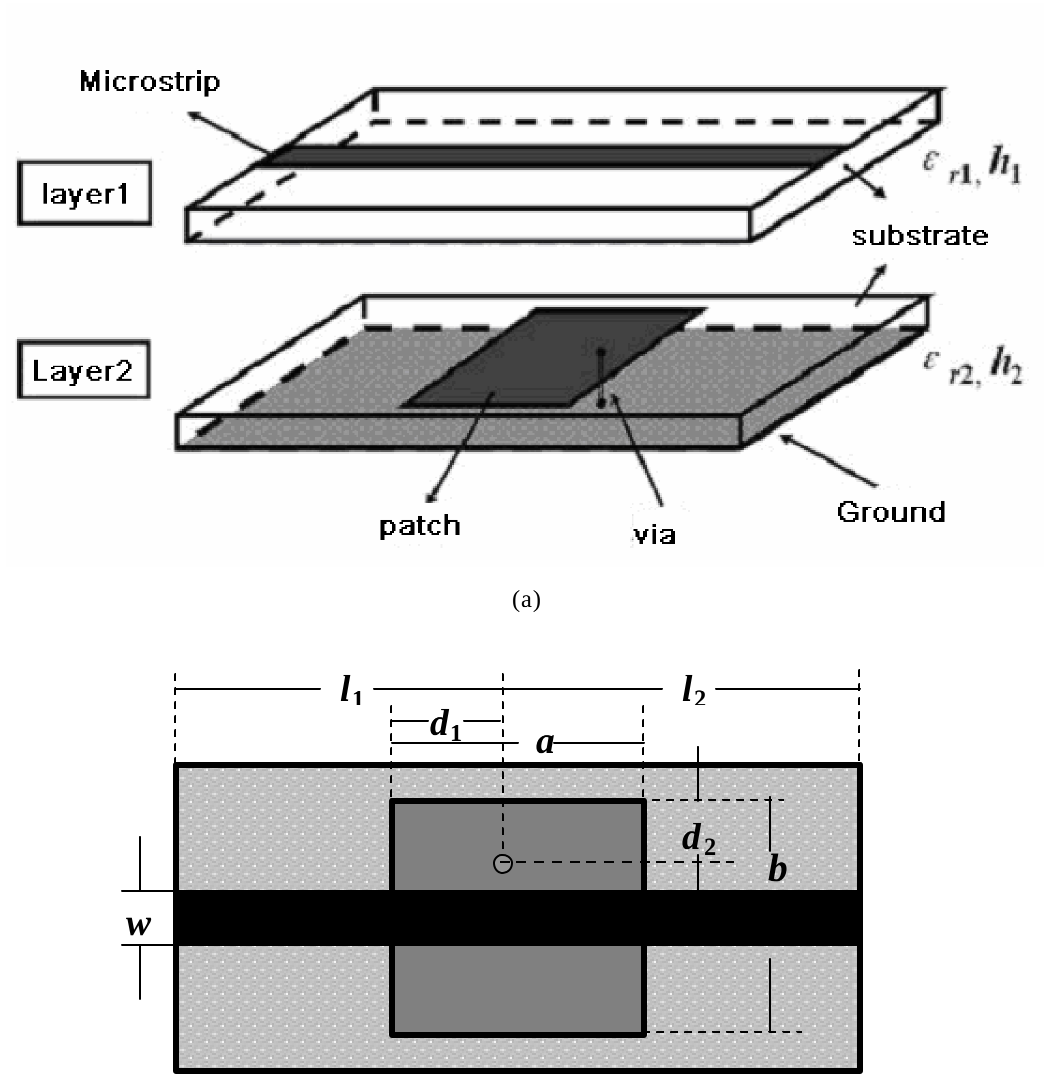
[11] T.Y. Yun, and K. Chang, "Uniplanar one-dimensional photonic-bandgap structures and resonators," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 49, Mar. 2001, pp. 549-553.

[12] J. S. Park, C. S. Kim, H. T. Kang, G. Y. Kim, K. H. Park, and D. Ahn, " A novel resonant microstrip RF phase shifter using defected ground structure," *30th European Microwave Conf.*, Paris 2000, France, pp. 72-75.

[13] F.R. Yang, K.P. Ma, Y.X. Qian, T. Itoh, "A uniplanar compact photonic-bandgap (UC-PBG) structure and its applications for microwave circuits," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 47, Aug. 1999, pp. 1509-1514.

[14] Dan Sievenpiper, Lijun Zhang, Romulo F. Jimenez Broas, Nicholas G. A., and Eli Yablonovitch, " High-Impedance Electronic Electromagnetic Surfaces with a Forbidden Frequency Band," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2059-2074, Nov. 1999

[15] Y.L.R. Lee, A. Chauraya, D. S. Lockyer and J. C. Vardaxolou, "Dipole and tripole metallodielectric photonic bandgap (MPBG) structures for microwave filter and antenna applications", *IEE Proceeding-Optoelectronics*, Vol. 147, No. 6, pp.395-400, December 2000



(a)

(b)

Fig.1 Description of the proposed EBG structure (a) 3-D view (b) top view

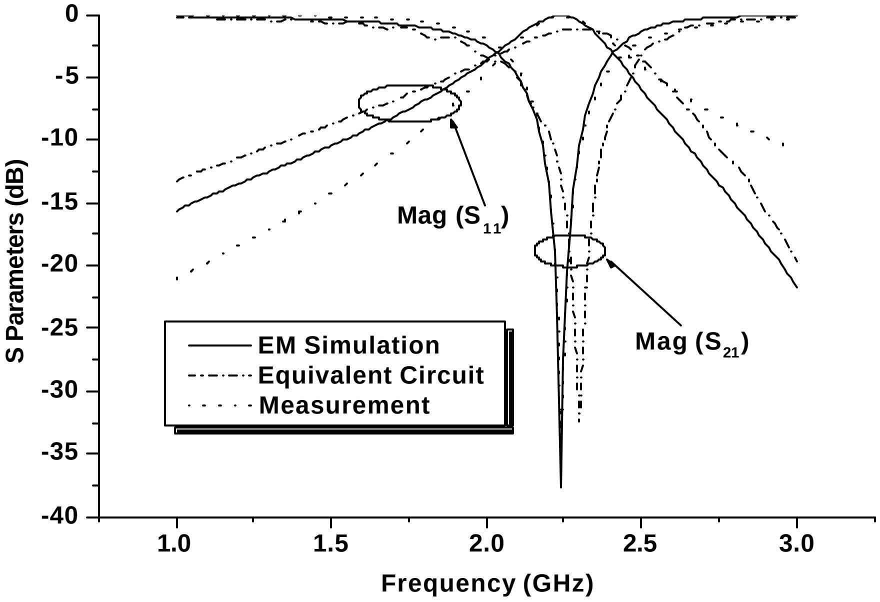


Fig. 2 (a) S parameters for the EBG cell

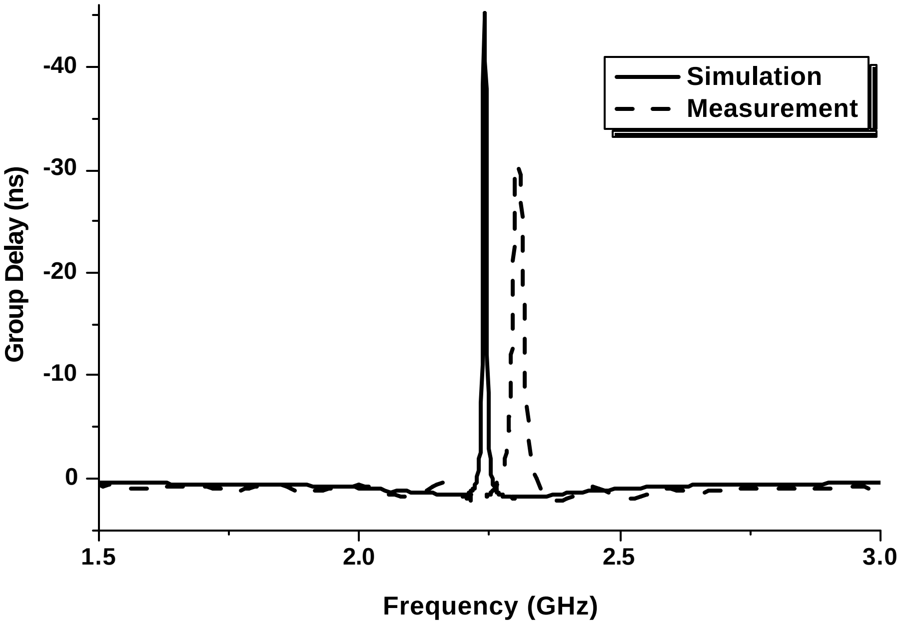


Fig.2 (b) Simulated and measured Group delay with the EBG cell

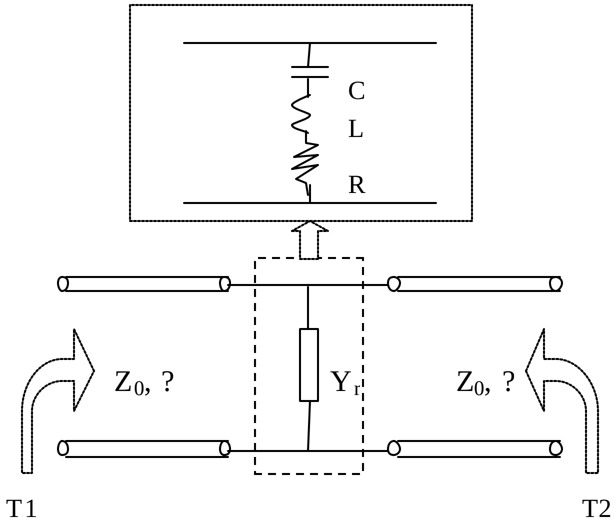


Fig.3 Equivalent circuit model of one EBG cell

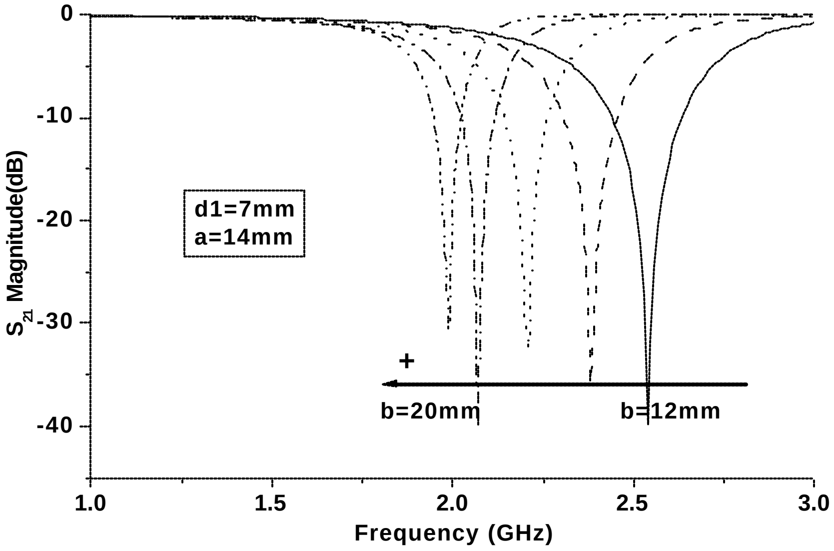


Fig.4 Resonant frequency shift with patch width

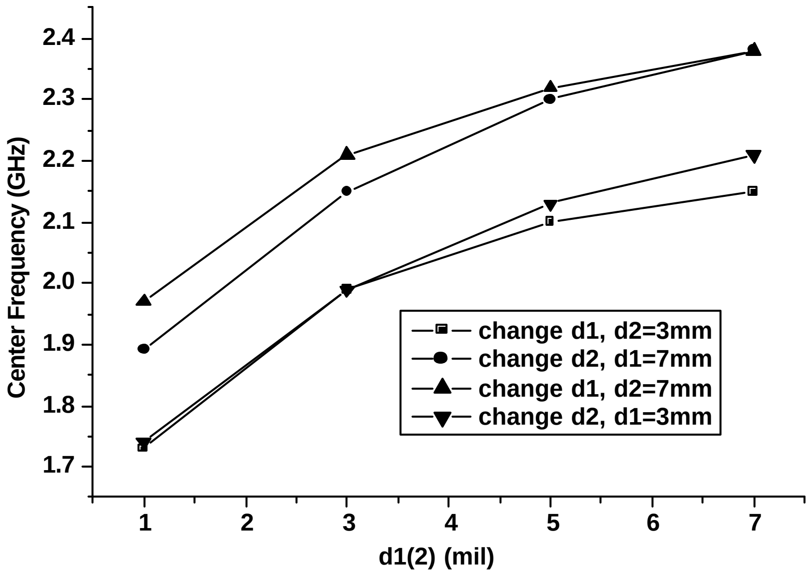


Fig .5 Resonant frequency shift with shorting via position

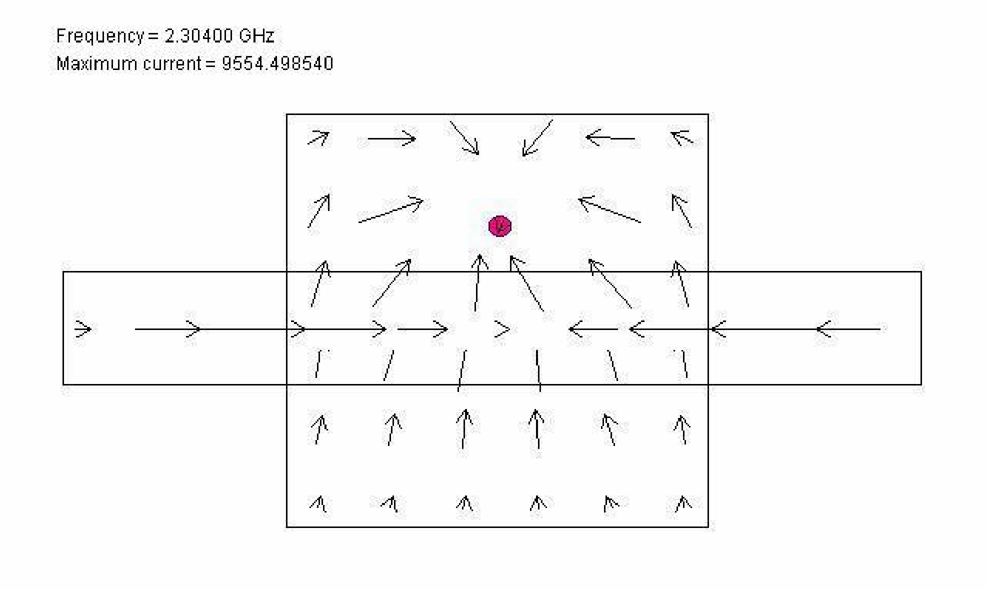


Fig.6 Current distribution among the EBG cell at resonant frequency

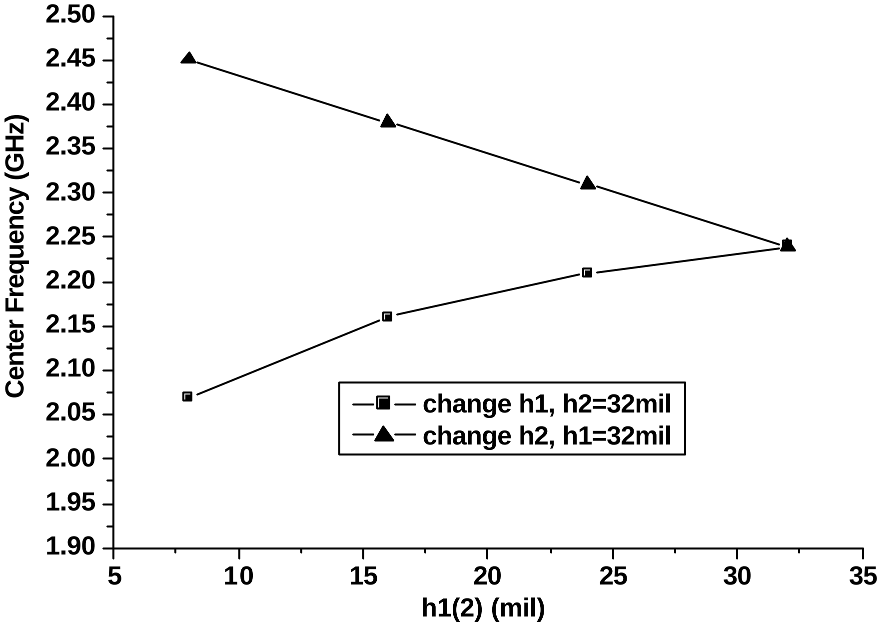


Fig. 7(a)

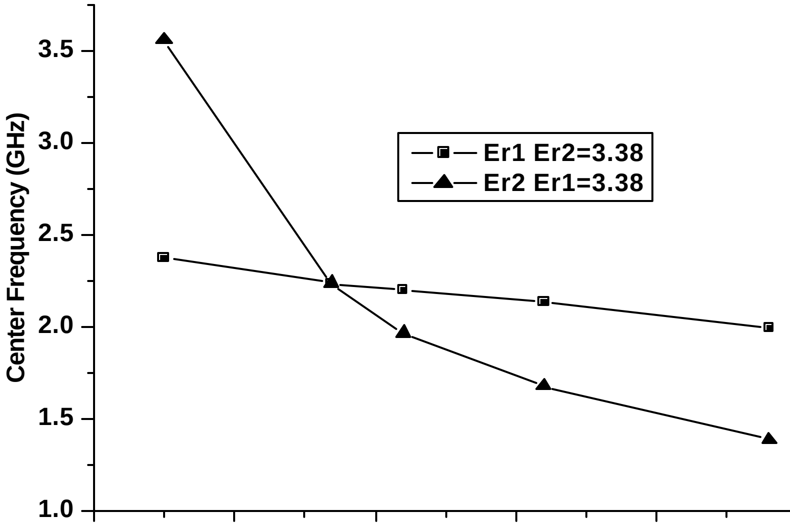


Fig .7 (b)

Fig. 7 Resonant frequency shift with upper and lower substrate
(a) height (b) dielectric constant

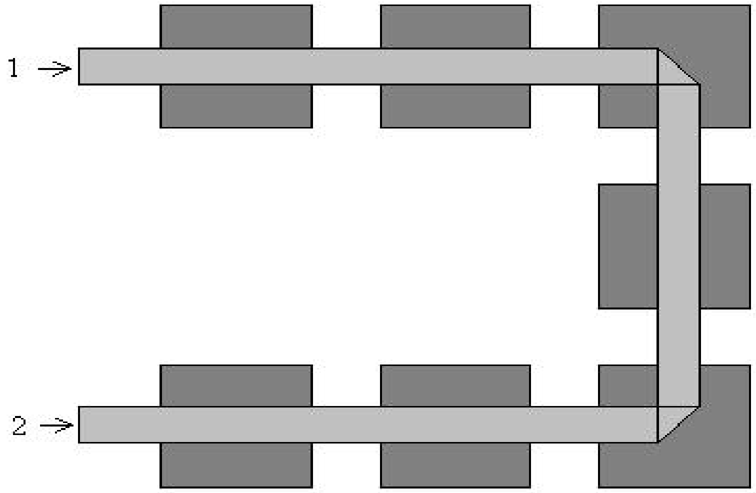


Fig. 8 The meander microstrip line bandstop filter with EBG cells

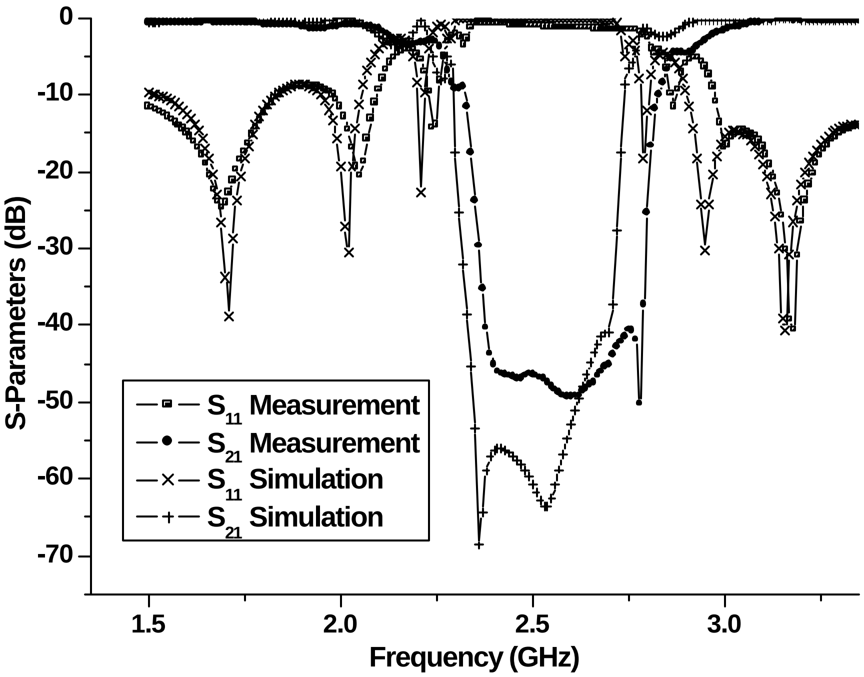


Fig. 9S parameters of the bandstop filter with EBG cells

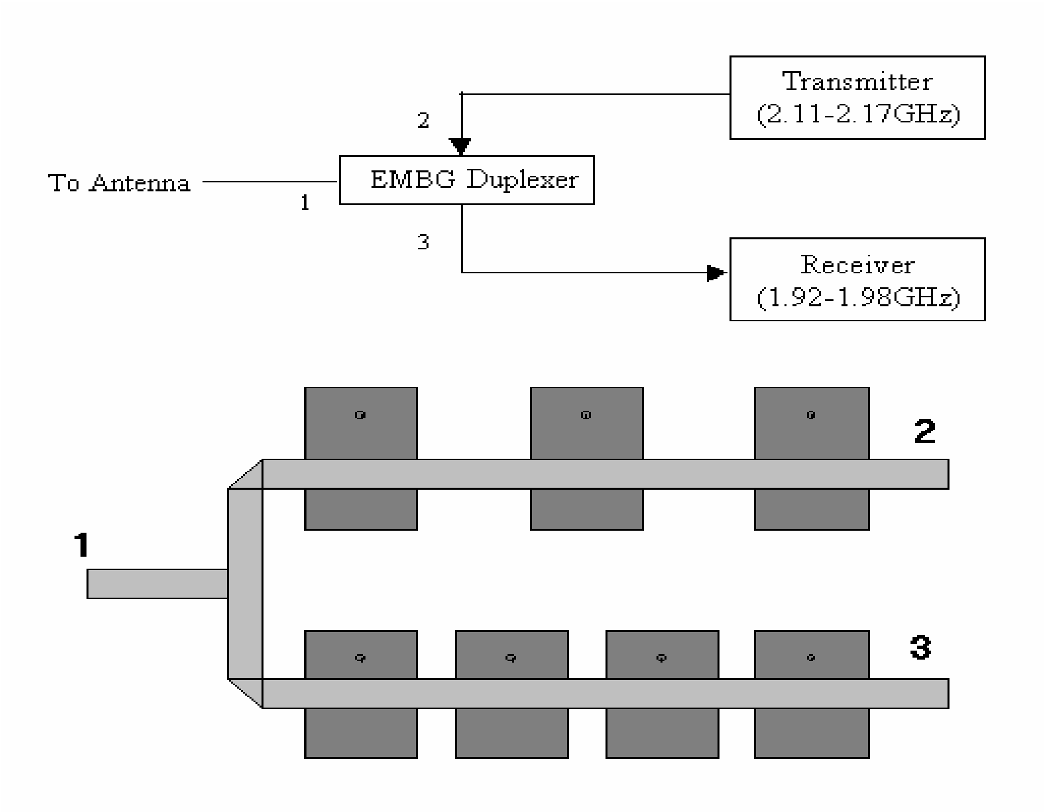
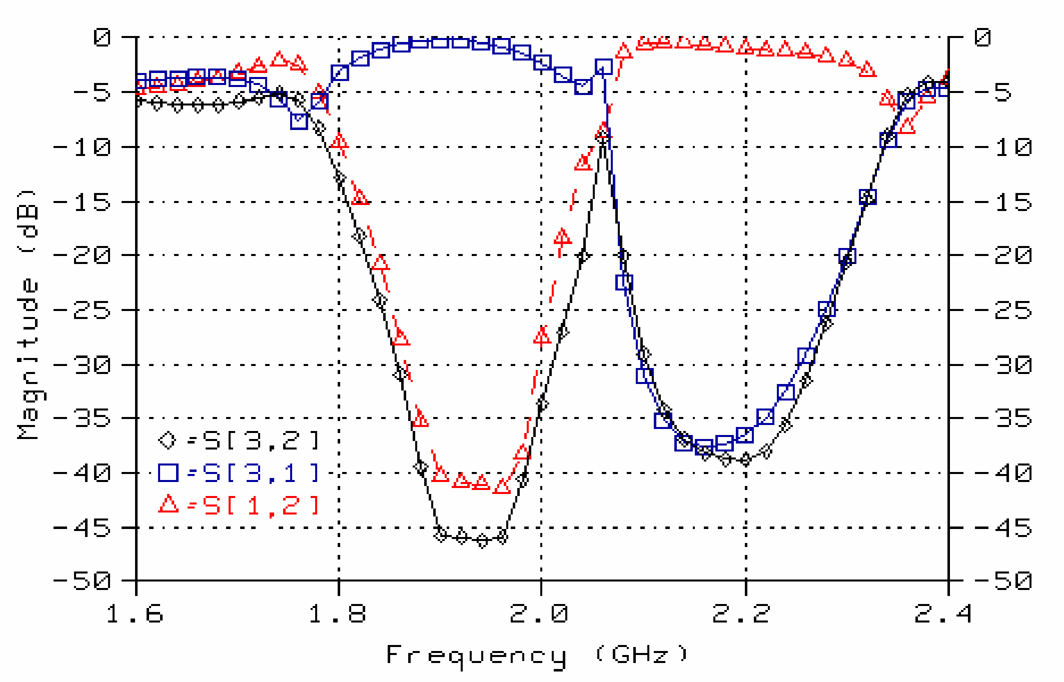
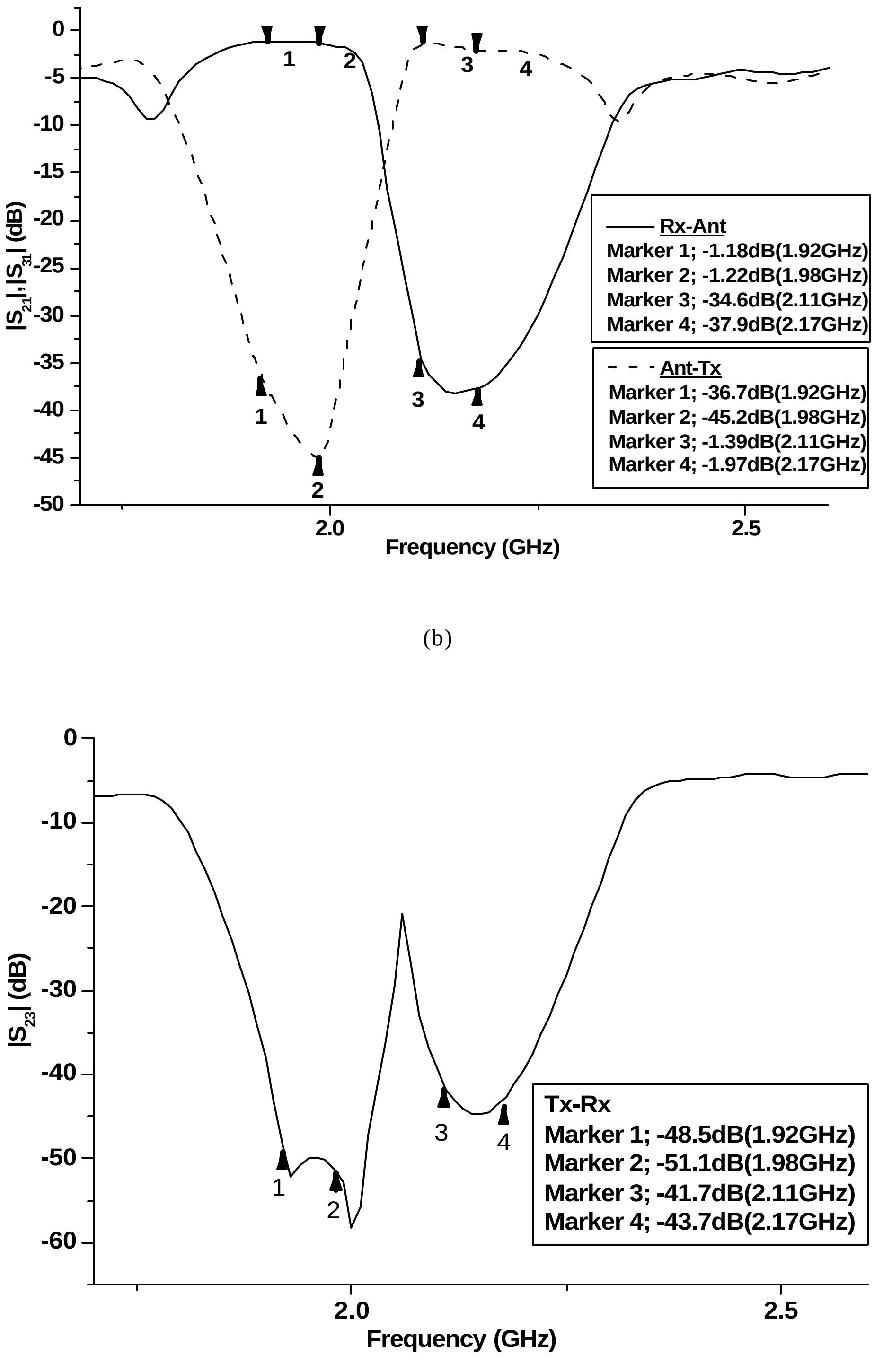


Fig. 10 Configuration of the designed duplexer with proposed EBG structure



(a)



(b)

(c)

Fig. 11 Simulated and measured S-parameters of the antenna duplexer

(a) Simulated and measured (b) Insertion loss at Rx-Antenna channel and Antenna-Tx channel

(c) Isolation between Rx/Tx