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Analysis of Resonant Frequency for Electromagnetic Bandgap Structure Based on Phase Coherence

Jun Wang, Huansheng Ning and Ling-Feng Mao[1]

School of Electronic and Information Engineering, Beihang University, Beijing, [1]School of Urban Rail Transportation, Soochow University, Suzhou, China

ABSTRACT

A new method based on phase coherence for resonant frequency analysis of the electromagnetic bandgap (EBG) structure is proposed in this paper. Based on a simplified analysis model of reflected and transmitted waves, the resonant frequencies of reflection coefficient for two-unit cells are achieved through the phase of transmission coefficient for one-unit cell. For the purpose of method verification, a microstrip EBG structure is simulated and measured, which shows great consistence of resonant frequency between phase coherence method analysis and actual simulation/measurement. Since the proposed method explains the resonance of EBG structure from the interference of electromagnetic waves level, it has a clear physical meaning. Moreover, it may provide a convenient way for the characteristic analysis of EBG structure.

Keywords:
Electromagnetic bandgap, Interference, Microstrip, Phase coherence, Resonant frequency.

1. INTRODUCTION

Electromagnetic bandgap (EBG) structures are periodic structures with a frequency bandgap prohibiting the propagation of electromagnetic waves [1]. Recently, various types of implemented EBG structures have been widely used for many microwave applications, such as surface wave suppression in antennas, ultra-wideband filters, and EBG waveguides [2-5]. Resonance phenomenon is very common for EBG structures which can be clearly seen in [6-10]. Since the resonant frequency plays an important role in the characteristics of EBG structures, the method for analyzing and predicting resonant frequency is rather necessary. The equivalent circuit model has been extensively employed to explain and predict the resonant frequencies [7,10,11]. However, this method can only analyze the characteristics accurately for a certain class of EBG structures at relatively low frequencies. Because the electromagnetic effects at higher frequencies are stronger and more difficult to model, it is very hard and complicated to drive a model which can give accurate prediction through a wide range frequency.

Interference of electromagnetic waves is the combination of separate electromagnetic wave in the same region of space to produce a resultant wave [12]. When the resultant wave exhibits amplitude greater/less than that of the individual wave, this superposition is referred to as constructive/destructive interference, which is attributed to the phase coherence in essence and performs interesting phenomena in many situations [13-16]. The resonance phenomenon of EBG structure can be regarded as the constructive and destructive interference of the reflected waves or transmitted waves; thus, the method based on phase coherence will give a clearer physical meaning compared with the equivalent circuit method.

In this paper, the principle of phase coherence is introduced to analyze the resonant frequency for EBG structure. First, a simplified model of reflected and transmitted waves is given, through which the strengthened resonant frequencies of reflection coefficient for two-unit cells can be explained. Then, a microstrip EBG structure is simulated and measured for the phase coherence method verification. Finally, the reasons for the absence of some resonant frequencies, which do not occur in the phase coherence method analysis, are also discussed.

2. PHASE COHERENCE METHOD

Phase coherence is the essential cause of constructive and destructive interference. Specifically, when two waves are in phase (phase difference constant is even multiple of π) everywhere in space, they interfere constructively, while two waves are out of phase (phase difference constant is odd multiple of π), they interfere destructively. This concept can be introduced to explain the resonant frequency of EBG structure. For the consideration of convenient analytical expression and method validation, the resonant frequency analysis of two-unit cells is conducted based on the characteristic of one-unit cell for the EBG structure. Figure 1a shows the analysis of reflected waves and transmitted waves for the unit cell, and we assume that the incident power is transmitted along the z-direction. Henceforth, the incident wave $V_I(z)$, the reflected wave $V_{R1}(z)$, and the transmitted wave $V_{T1}(z)$ of one-unit cell can be written as follows:

$$\begin{aligned} V_I(z) &= A_I \exp(-j\beta z) \\ V_{R1}(z) &= A_{R1} \exp\left[j(\beta z + \Phi_R)\right] \\ V_{T1}(z) &= A_{T1} \exp\left[-j(\beta z + \Phi_T)\right] \end{aligned} \tag{1}$$

Where, A_I, A_{R1}, and A_{T1} is the amplitude of incident wave, reflected wave, and transmitted wave respectively, Φ_R and Φ_T is the phase delay of reflected wave and transmitted wave correspondingly.

Based on the characteristic of the unit cell, the reflected and transmitted waves of two-unit cells in Figure 1b may be achieved as:

$$\begin{aligned} V_{T2}(z) &= A_{T2} \exp\left[\text{-j}(\beta z + 2\Phi_T)\right] \\ V'_{R2}(z) &= A'_{R2} \exp\left[\text{j}(\beta z + \Phi_R + \Phi_T)\right] \\ V_{R2}(z) &= A_{R2} \exp\left[\text{j}(\beta z + \Phi_R + 2\Phi_T)\right] \end{aligned} \tag{2}$$

Where, A_{T2}, A'_{R2}, and A_{R2} are the amplitudes of the above reflected or transmitted waves. Here, we neglect the amplitude variations caused by each unit cell and focus on the interference of reflected waves. The reflected wave $V_{R1}(z)$ is resulted from the reflection of the first unit cell. The reflected wave $V'_{R2}(z)$ is the result of the transmitted wave $V_{T1}(z)$ reflected by the second unit cell. The reflected wave $V_{R2}(z)$ is obtained from the transmission of the reflected wave $V'_{R2}(z)$ through the first unit cell. Therefore, the resultant reflected wave is

$$\begin{aligned} V_R(z) &= V_{R1}(z) + V_{R2}(z) \\ &= A_{R1} \exp\left[\text{j}(\beta z + \Phi_R)\right] + A_{R2} \exp\left[\text{j}(\beta z + \Phi_R + 2\Phi_T)\right] \\ &= \exp\left[\text{j}(\beta z + \Phi_R)\right]\left[A_{R1} + A_{R2} \exp(\text{j}2\Phi_T)\right] \end{aligned} \tag{3}$$

and the constructive interference of reflected waves occurs at

$$\Phi_T = n\pi \qquad n = 0, \pm 1, \pm 2, \pm 3 \cdots \tag{4}$$

From (4), we can infer that if the phase delay of transmitted wave Φ_T at a certain frequency introduced by the unit cell is multiple of π, the constructive interference of reflected waves should be appeared at this frequency. From the viewpoint of scattering matrix, this leads to the strengthened resonance of reflection coefficient S_{11} for two-unit cells of EBG structure. For the phase delay Φ_T, it is equal with the phase of transmission coefficient S_{21} and can be obtained by simulation or measurement of one-unit cell. The above analysis process of phase coherence method indicates its definite physical meaning and provides a convenient way for the resonance prediction of two-unit cells.

3. METHOD VERIFICATION AND DISCUSSION

In this section, we will test the ability of phase coherence method with a microstrip EBG structure presented in [9]. The periodical rectangle patterns of this EBG structure shown in Figure 2 are etched in the conductor line of microstrip. The substrate used in the simulations has a relative permittivity 2.55 and a thickness of h = 1.50 mm. The microstrip width W_L is chosen as 4.50 mm corresponding to 50-Ω characteristic impedance. The

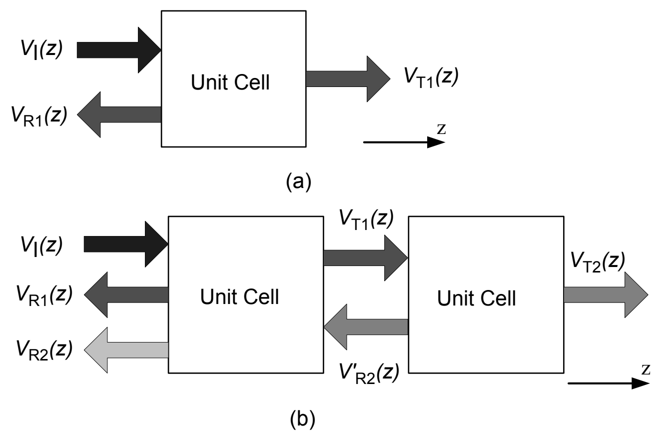

Figure 1: Analysis of reflected and transmitted waves for EBG structure (a) One unit cell and (b) Two unit cells.

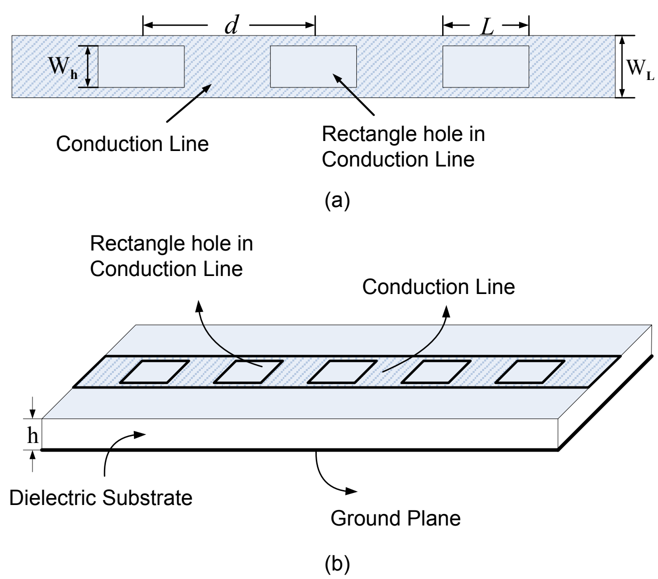

Figure 2: Microstrip EBG structure (a) Configuration of the rectangle hole in conduction line; (b) Three-dimensional view of the microstrip EBG structure.

width of the rectangle hole W_h is chosen as 4 mm to get a wide and deep bandgap, and the length of the rectangle hole L is 10 mm. The period of the rectangle-etched pattern d is 20 mm, with forecasting center frequency of the stopband at 5.15 GHz from the Bragg scattering condition. To obtain an obvious resonant reflection coefficient, the unit cell is made up of five rectangle holes. Both the unit cell and two-unit cells of the microstrip EBG structure are simulated by full-wave solver (HFSS) and fabricated for phase coherence method verification. And, Figure 3 shows the final fabricated microstrip EBG structure.

The simulated S-parameters of the unit cell for microstrip EBG structure agree well with the measurement in Figure 4. Both the simulated and measured transmission coefficient show an obvious bandgap around 5 GHz, consistent with the forecasting center frequency of the stopband. The simulated and measured phase of transmission coefficient for the unit cell is shown in Figure 5. Based on the constructive interference of reflected wave condition (4), the strengthened resonant frequencies of reflection coefficient for the two-unit cells of microstrip EBG structure can be explained and predicted. The predicted resonant frequencies from the simulated and measured phase are listed in the second column of Tables 1 and 2, respectively. For the purpose of method verification, the two-unit cells are simulated and measured to get the strengthened resonant frequencies of reflection coefficient. Figure 6 shows the simulated and measured results of S-parameters, and the strengthened resonant frequencies of reflection coefficient from simulation and measurement are listed in the third column of Tables 1 and 2, respectively.

The deviation in the fourth column of Tables 1 and 2 represents the frequency difference between

Table 1: Strengthened resonant frequency analysis based on simulated phase prediction and full-wave simulation of two-unit cells

Number	Prediction (GHz)	Simulation (GHz)	Deviation (GHz)	Relative error (%)
0	1.78	1.70	0.08	4.70
1	2.66	2.66	0.00	0.00
2	3.49	3.56	-0.07	1.96
3	4.18	4.34	-0.16	3.68
4	5.93	6.19	-0.26	4.20
5	6.63	6.57	0.06	0.91
6	7.45	7.45	0.00	0.00
7	8.29	8.39	-0.10	1.19

Table 2: Strengthened resonant frequency analysis based on measured phase prediction and measurement of two unit cells

Number	Prediction (GHz)	Measurement (GHz)	Deviation (GHz)	Relative error (%)
0	1.76	1.71	0.05	2.92
1	2.62	2.66	-0.04	1.50
2	3.43	3.52	-0.09	2.56
3	4.08	4.26	-0.18	4.22
4	5.97	6.18	-0.21	3.40
5	6.61	6.54	0.07	1.07
6	7.41	7.42	-0.01	0.13
7	8.24	8.33	-0.09	1.08

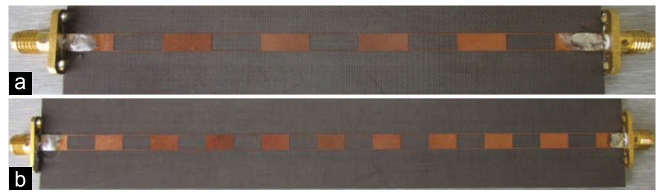

Figure 3: Fabricated microstrip EBG structure (the bottom ground plane is not shown) (a) One unit cell and (b) Two unit cells.

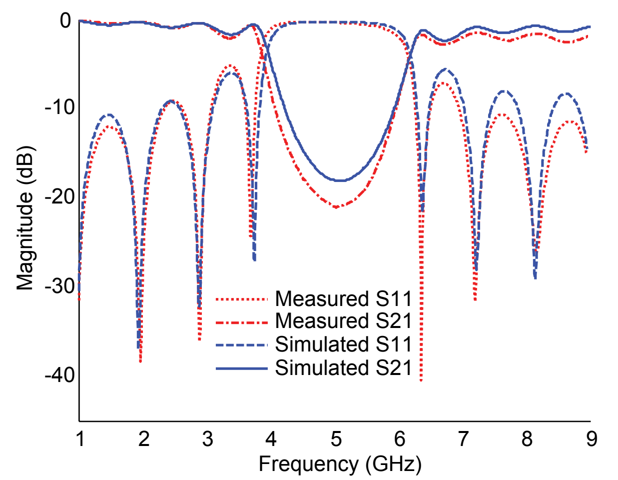

Figure 4: Simulated and measured S-parameters of the unit cell for microstrip EBG structure.

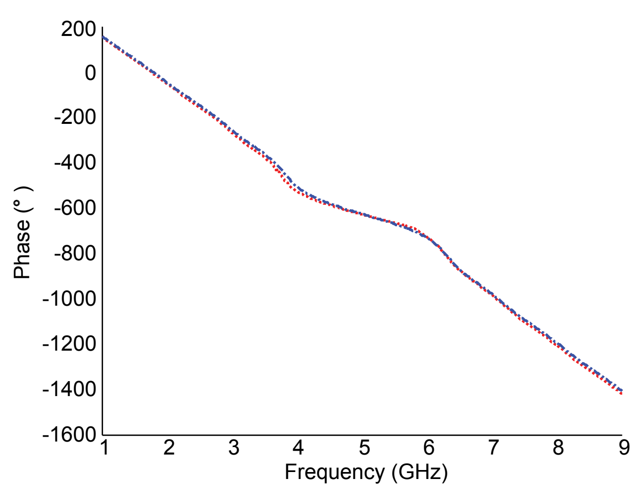

Figure 5: Simulated and measured phase of transmission coefficient for the unit cell.

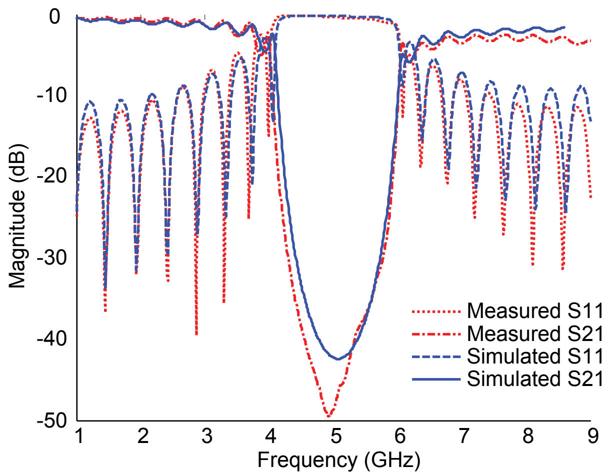

Figure 6: Simulated and measured S-parameters of two unit cells for microstrip EBG structure.

phase coherence method prediction and simulation/measurement of the two-unit cells. The relative errors in Tables 1 and 2 are all below 5%, demonstrating the validity of phase coherence method. It should be noted that not all of the strengthened resonant frequencies for reflection coefficient of two-unit cells can be analyzed with the phase coherence method. In fact, for the two-unit cells of microstrip EBG structure, there are more than eight strengthened resonant frequencies listed in the tables.

The above difference may be explained from two aspects. First, we do not use the minimum repeated unit cell (analogous to the primitive unit cell of crystals in solid state physics) to obtain an obvious resonant reflection coefficient for the convenience of method verification. Therefore, some resonant frequencies are missing without considering the interaction among different rectangle holes in one-unit cell or two-unit cells. Second, in order to simplify the analysis process, the phase coherence method in section 2 is only focused on two main reflected waves caused by the two-unit cells. Actually, there are more than two reflected waves at the incident port in Figure 1b. For instance, the reflected wave $V'_{R2}(z)$ can be first reflected by the first unit cell and the second unit cell, and then transmitted by the fist unit cell to the incident port, leading to another reflected wave. And, the interaction of this reflected wave with the reflected wave $V_{R1}(z)$ and $V_{R2}(z)$ is not considered in the above analysis model. However, the simplified analysis model of phase coherence method can explain most resonance of two-unit cells with a clear physical meaning and demonstrate its convenience for resonance prediction of two-unit cells, which will give helpful information for the characteristic analysis of the EBG structure.

4. CONCLUSION

This paper proposes a novel phase coherence method for analyzing the resonant frequencies of EBG structure. The strengthened resonant frequencies of reflection coefficient for two-unit cells are analyzed through the phase of transmission coefficient for one-unit cell. A microstrip EBG structure is used to testify the method and a great resonant frequency consistence is achieved between the phase coherence method analysis and the actual simulation/measurement. The phase coherence method shows its definite physical meaning and great convenience for the resonance analysis of EBG structure.

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REFERENCES

1. JD Joannopoulos, SG Johnson, JN Winn, and RD Meade,"Photonic Crystals: Modeling the Flow of Light," (2nd Ed). Princeton: Princeton Univ. Press; 2008.
2. R Kumar, and JP Shinde, "On the Effect of Fractal Electromagnetic Band Gap on Antenna Performance," *IETE J Res*, vol. 56, pp. 333-9, Jan. 2011.
3. R Coccioli, FR Yang, KP Ma, and T Itoh, "Aperture-coupled patch antenna on UC-PBG substrate," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 11, pp. 2123-30, Nov. 1999.
4. M Rotaru, and J Sykulski, "Compact electromagnetic bandgap structures for notch band in ultra-wideband applications," *Sensors*, vol. 10, pp. 9620-9, 2010.
5. YS Abdo, MR Chaharmir, J Shaker, and YM Antar, "Efficient excitation of an EBG guide designed using a defect triangular lattice of holes," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 167-70, 2010.
6. JW Baik, SM Han, C Jeong, J Jeong, and YS Kim, "Compact ultra-wideband bandpass filter with EBG structure," *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 10, pp. 671-3, Oct. 2008.
7. H Kim, and RF Drayton, "Development of analysis method of electromagnetic bandgap structures to predict EBG behavior based on circuit models," in *IEEE Antennas Propag. Soc. Int. Symp.*, Albuquerque, pp. 1951-4, 2006.
8. ZC Hao, W Hong, JX Chen, XP Chen, and K Wu, "Compact super-wide bandpass substrate integrated waveguide (SIW) filters," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 9, pp. 2968-76, Sep. 2005.
9. G Zhang, N Yuan, Y Fu, and C Zhu, "A novel PBG structure for microstrip lines," in *Proc. 3rd Int. Conf. Microw. Millimeter Wave Technol.*, pp. 1040-2, Aug. 2002.
10. D Ahn, JS Park, C S Kim, J Kim, Y Qian, and T Itoh, "A design of the low-pass filter using the novel Microstrip defected ground structure," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 1, pp. 86-92, Jan. 2001.
11. B Mohajer-Iravani, and OM Ramahi, "Wideband circuit model for planar EBG structures," *IEEE Trans. Adv. Packag.*, vol. 33, no. 1, pp. 169-79, Feb. 2010.
12. JW Jewett Jr., and RA Serway, *"University physics for scientists and engineers* (Eighth Edition)," ch. 18, Beijing: China Machine Press; 2010.
13. T Yong, "The Bakerian lecture: Experiments and calculations relative to physical optics," *Philos. Trans. R. Soc. London*, vol. 94, pp. 1-16, 1804.
14. M Greiner, I Bloch, O Mandel, T W Hänsch, and T Esslinger, "Exploring Phase Coherence in a 2D Lattice of Bose-Einstein Condensates," *Phys. Rev. Lett.*, vol. 87, no. 16, pp. 160405-1—-4, Oct. 2001.

15. F Gerbier, A Widera, S Fölling, O Mandel, T Gericke, and I Bloch, “Phase coherence of an atomic Mott insulator,” *Phys. Rev. Lett.*, vol. 95, no. 5, pp. 050404-1—-4, Jul. 2005.

16. L Mao, and Z Wang, “An analytical approach for studying the resonant states in mesoscopic devices using the phase coherence of electron waves,” *Superlattices Microstruct*., vol. 43, pp. 168-79, 2008.

AUTHORS

Jun Wang was born in Anhui, China. He received the B.E. degree in electronic and information engineering from Anhui University. He is currently working towards the Ph.D. degree in electronic engineering at Beihang University. His research interest includes the characterization and application of metamaterial.

E-mail: junwang@ee.buaa.edu.cn

Huansheng Ning received the B.S. degree from Anhui University in 1996 and Ph.D. degree in Beihang University in 2001. Now he is an Associate Professor in School of Electronic and Information Engineering, Beihang University, China. His current research focuses on Internet of Things, aviation security, electromagnetic sensing and computing. He has published more than thirty papers in journals, international conferences/workshops, and four books.

E-mail: ninghuansheng@buaa.edu.cn

Ling-Feng Mao received the Ph. D degree in microelectronics and solid State Electronics from the Peking University, Beijing, P. R. China, in 2001. He is a professor in Soochow University. His research activities include modeling and characterization of semiconductor devices and circuits, the fabrication and modeling of integrated optic and microwave devices and circuits.

E-mail: mail_lingfeng@yahoo.com.cn

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