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USING ELECTROMAGNETIC BANDGAP SUPERSTRATE TO ENHANCE THE BANDWIDTH OF PROBE-FED MICROSTRIP ANTENNA

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Abstract—In this paper, the effect of Electromagnetic Bandgap (EBG) Superstrates on return loss of the Probe-Fed Microstrip Antenna (PFMA) has been examined. Originally the EBG superstrate layer made by Frequency Selective Surface (FSS) layers is used to increase the directivity of the PFMA, but to increase the efficiency of the whole structure including the PFMA and EBG superstrate it is necessary to have suitable impedance matching. In this paper the EBG superstrate as a resonance load to the primary radiation source (PFMA) and then by choosing the appropriate geometrical parameters of the structure we can obtain suitable impedance matching beside the directivity enhancement of the primary radiation source.

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1. INTRODUCTION

Electromagnetic Bandgap Materials are periodic structures that are composed of dielectric, metal or metallo-dielectric materials. These structures can prevent wave propagation in special directions and frequencies therefore they can be used as spatial and frequency filters. There are several configurations of EBG structures that can be used in antenna applications [1]; these configurations can be classified into three categories:

- High Impedance Surfaces as two dimensional EBG structures that can be used as microstrip antenna substrate to eliminate the surface wave [2–5]
- Artificial Surfaces such as Artificial Magnetic Conductors and Reactive Surfaces to design low profile antennas [6–10]
- High Directive Resonator Antennas which are designed on the basis of creating defects in a uniform EBG structure. The defects lead to producing special frequencies in the bandgap of the structure in which the EM wave can propagates. In defect modes the structure operates as a spatial and frequency filter with high quality factor. If a primary radiation source is embedded in defected EBG structure it is possible to make its radiation pattern directive in the defect frequencies. There are several configurations of EBG structures that can be used to design high directive resonator antenna such as multilayer dielectric plates [11–14], multilayer plates made by dielectric or metallic rods [15–18] and multilayer Frequency Selective Surfaces (FSS) [19–21].

For some primary radiation sources such as microstrip patch antennas or aperture antennas the EBG structure can be configured as a superstrate. The main goal of using this configuration is to make the radiation pattern of primary source more directive. But, beside this purpose it is necessary to increase the efficiency of the whole structure so that the reflected power becomes low enough and renders good impedance matching. In this paper, we study the effect of EBG superstrate made by FSS layers on the Return Loss (RL) of the antenna. We show that the EBG superstrate not only improves the antenna directivity but also increases its bandwidth. In this study we use the probe-fed microstrip antenna as the primary radiation source and an FSS layer with loop elements as the superstrate.

2. METHOD OF ANALYSIS

Figure 1 shows the basic geometries that we consider in analyzing the antenna. These geometries consist of two ideal plates with special reflection and transmission coefficients and a primary radiation source. In our study we use the FSS layer as a superstrate and the probe-fed microstrip patch antenna as primary radiation source. Also, depending on the number of the operating frequencies we can use one or more FSS layers. To determine the characteristics of the superstrate layer we consider it and its image in the ground plane as depicted in Figure 1b.

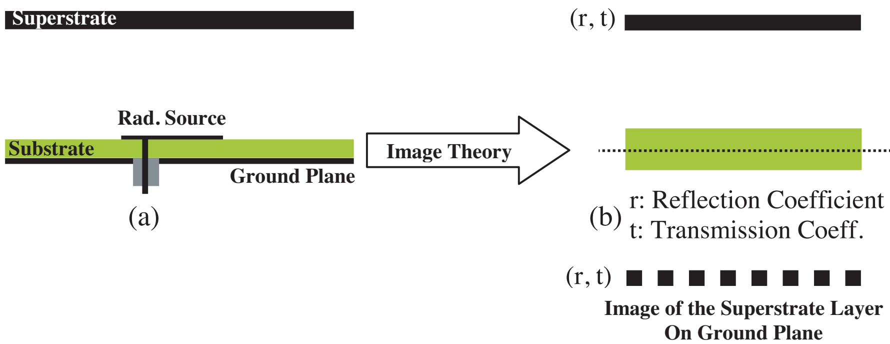


Figure 1. (a) Microstrip antenna and superstrate layer (b) Using image theory to analysis of structure as EBG.

By considering the transmission matrix of each layer we can obtain the transmission matrix of whole structure. In FSS layers the transmission matrix equation of each layer can be determined numerically. Ideally, each layer transmission matrix is:

$$M_1 = \begin{bmatrix} \frac{1}{t} & -\frac{r}{t} \\ \frac{r}{t} & \frac{t^2 - r^2}{t} \end{bmatrix}$$

Also in free space the transmission matrix of free space between the superstrate layer and its image is:

$$M_2 = \begin{bmatrix} e^{j\phi_0} & 0 \\ 0 & e^{-j\phi_0} \end{bmatrix}$$

Therefore, the total transmission matrix is:

$$M_{\text{total}} = M_1 \times M_2 \times M_1 = \begin{bmatrix} \frac{1}{T} & -\frac{R}{T} \\ \frac{R}{T} & \frac{T^2 - R^2}{T} \end{bmatrix}$$

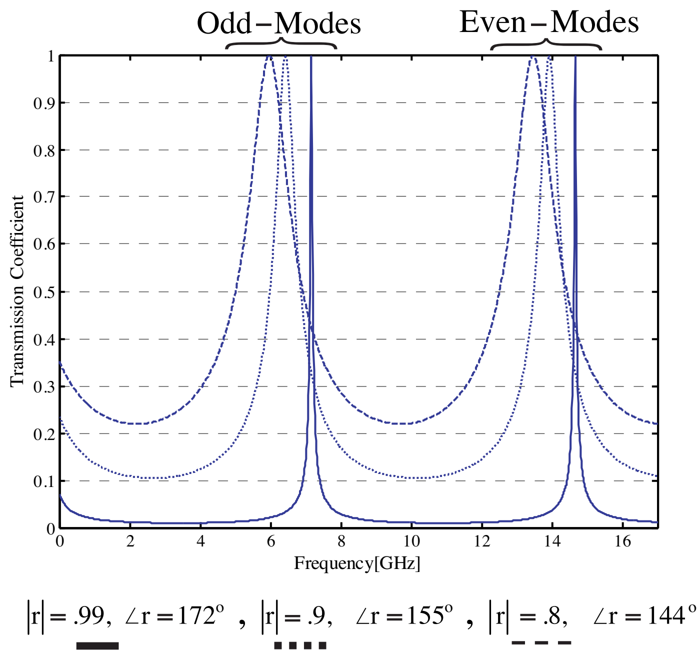


Figure 2. Total transmission coefficient of two-layer structure for different values of magnitude and phase of r of each layer and distance layers $= 30\,\text{mm}$.

where after some derivations the total transmission and reflection coefficients become:

$$T = \frac{t^2 e^{-j\phi}}{1 - r^2 e^{-j2\phi}} \quad \text{and} \quad R = \frac{r[1 + (t^2 - r^2)e^{-j2\phi}]}{1 - r^2 e^{-j2\phi}}$$

in which $\phi = k_0 d$.

It can be seen that the total transmission of the structure depends on the distance of the layers and also the transmission and reflection coefficients of each layer. Figure 2 shows the total transmission coefficient of the structure versus frequency. The little displacements of the resonance frequencies is due to the phase of reflection coefficient of the superstrate layer and also the quality factor of the structure at each resonance frequency depends on the magnitude of reflection coefficient r of superstrate layer.

One of the most useful features of using the FSS in the design of the superstrate layer is that we can adjust its reflection coefficient and obtain the desired quality factor at each resonance frequency. An

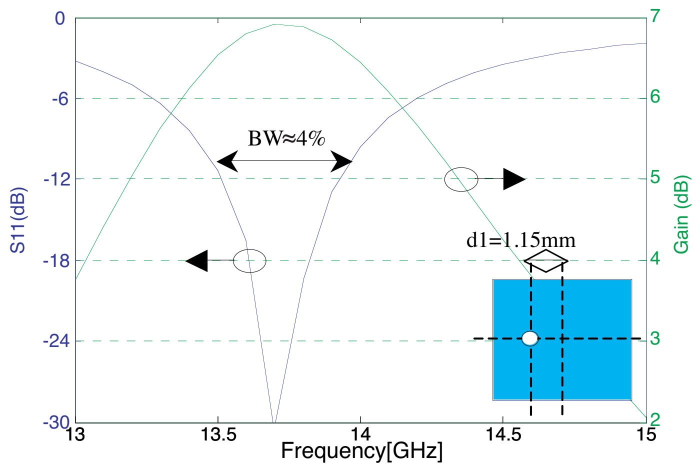


Figure 3. (a) Return loss of probe fed microstrip antenna (b) Directivity and gain of probe fed microstrip antenna.

important point that must be mentioned here is that only the even resonant frequencies in Figure 2 can be used because it is necessary that the tangential electric fields on the symmetrical plane (ground plane) be zero and this cannot occur at odd resonance frequencies.

3. DESIGN OF THE PATCH ANTENNA AND FSS LAYER

3.1. Design of the Probe-fed Patch Antenna

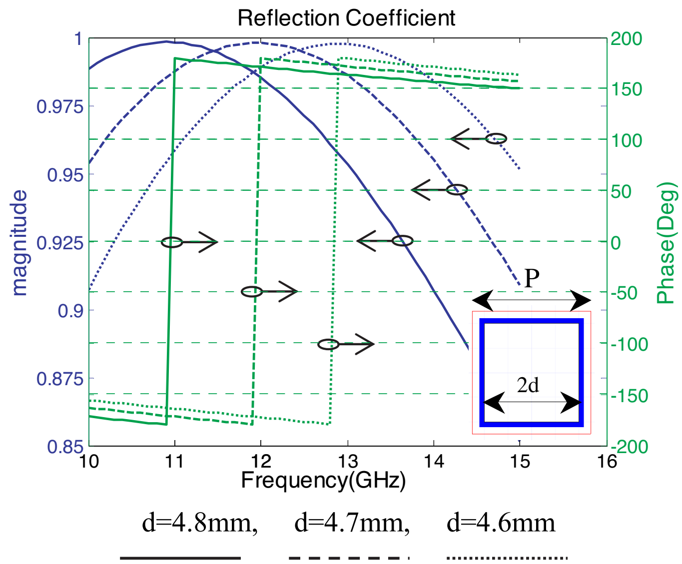
The operating frequency we are considering is 14 GHz. In our design we use a rectangular patch with 6.5 mm side and probe located 1.15 mm from its center. The return loss and directivity of the antenna are shown in Figure 3.

3.2. Design of the FSS Layer

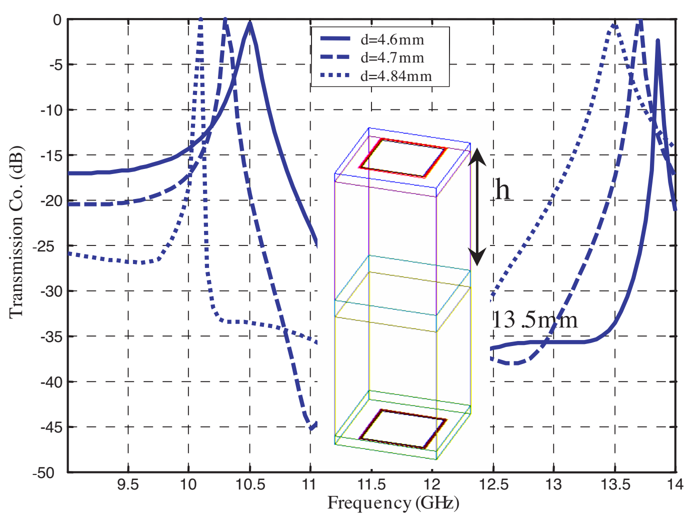
There are different FSS configurations that we can use for designing the high directive antenna, but since we want to achieve good impedance matching beside the directivity enhancement, the choice of the geometry of the FSS elements is important. In this study we examine an FSS structure with loop element geometry and its effect on the return loss of the antenna. Because the FSS superstrate layer and its image in the ground plane are periodic in two dimensions here we analyze, by using periodic boundary condition, only one cell of the structure using the periodic boundary conditions. This can be done by using a suitable numerical method such as periodic method of moment. In our study we use the Ansoft Designer Software based on the Method of Moment (MOM) [22]. This software includes the tool to analyze 2-D planar periodic structures based on the periodic Greens function. In the following we peruse the transmission and reflection coefficients of the structure. A single layer FSS structure operates as an ideal plate with the transmission and reflection coefficients that change with frequency. The changes with frequency can be controlled by adjusting the physical and geometrical parameters of the FSS cells, such as type of elements, cell size and thickness and permittivity of the dielectric of substrate. Here, we use a substrate with low permittivity (RT/duroid 5870) and we consider only the effects of FSS element geometry. Figure 4(a) depicts the magnitude and phase of the transmission and reflection coefficient of a single layer FSS with square loop of different dimensions. By considering the FSS layer and its image in the ground plane and also the dielectric substrate of the patch antenna (Figure 1(b)) we can obtain the reflection and transmission coefficients of the whole structure. Figure 4(b) shows the transmission coefficient of both the FSS structures and its image. As we can see, there are resonance frequencies where the transmission coefficients of the structure are perfect. We use the radiation source imbedded in the superstrate layer to directive its radiation pattern at these frequencies.

4. ANALYSIS OF THE WHOLE STRUCTURE

After determining the resonance frequency of the structure we can use it with a primary radiation source such as patch antenna. Because the effect of the patch antenna, the distance of designed superstrate layer from ground plane, h, needs to be tuned to achieve maximum directivity at the desired resonance frequency. In practice, we cannot use the FSS structure with infinite number of elements, therefore we must limit the number of elements. Also the number of FSS elements only limits the amount of directivity enhancement because the directivity depends on the aperture size of the new structure and this directly depends on the FSS size. We use FSS structure with 5×5 ($\approx \lambda$) elements. There are several parameters that must be adjusted to obtain desired phenomena (Directivity and VSWR). By using the designed patch antenna with superstrate layer at the appropriate distance we can enhance its directivity. Figure 5 depicts the return loss and directivity of the antenna for different values of distance of the superstrate layer from the ground plane.



(a)



(b)

Figure 4. (a) Magnitude and phase of reflection coefficient of one-layer FSS (b) Magnitude of transmission coefficient of two-layer FSS (FSS and its Image in the ground plane.)

5. BANDWIDTH OF THE STRUCTURE

To improve the RL and enhance the bandwidth of the antenna, it must be noticed that the patch antenna is a resonance structure and the superstrate layer is added to it as resonance load. Therefore the circuit model of the structure includes two parallel resonance circuits (Figure 6). In this case we have further parameters that help match the source to free space. The first resonance circuit is tuned by the primary radiation source parameters and the second resonance circuit is tuned by the parameters of superstrate layer. The most important parameters in tuning the input impedance of the structure are the probe location, the superstrate displacement from ground plane and the geometry of the FSS elements. In the following, we examine these parameters and their effects on the directivity and RL of the antenna. At first we tune the probe location and then study the effect of geometrical parameters of the FSS element.

5.1. Effect of Probe Feed Location

As can be seen from Figure 6, although we obtain high directivity, the reflected power is too high and the efficiency of the antenna is low. Figure 7 shows the effect of probe location on the RL of structure. It must be noticed that the probe displacement does not affect the antenna directivity.

5.2. Effect of the FSS Element Size

Another important parameter that affects both the directivity and RL of the EBG resonator antenna is the geometry of the FSS element. The quality factor of total transmission from two layer FSS depends on the FSS reflection coefficient of single layer FSS (Figure 4(b)). In our structure, this parameter can be controlled by the loop diameter, d. To obtain the desired resonance frequency both the distance of the FSS layer from the ground plane and the diameter of loop must be adjusted. But to achieve appropriate impedance matching, it is necessary to fine tune the loop diameter near resonance frequency. Figure 8(a) shows the effect of loop diameter on the RL of the antenna. Because the loop diameter deviations are very little the directivity is not affected seriously. In Figure 8(b) we can see that for the loop diameter 2.1 mm, accepted level for both directivity enhancement and RL is obtained.

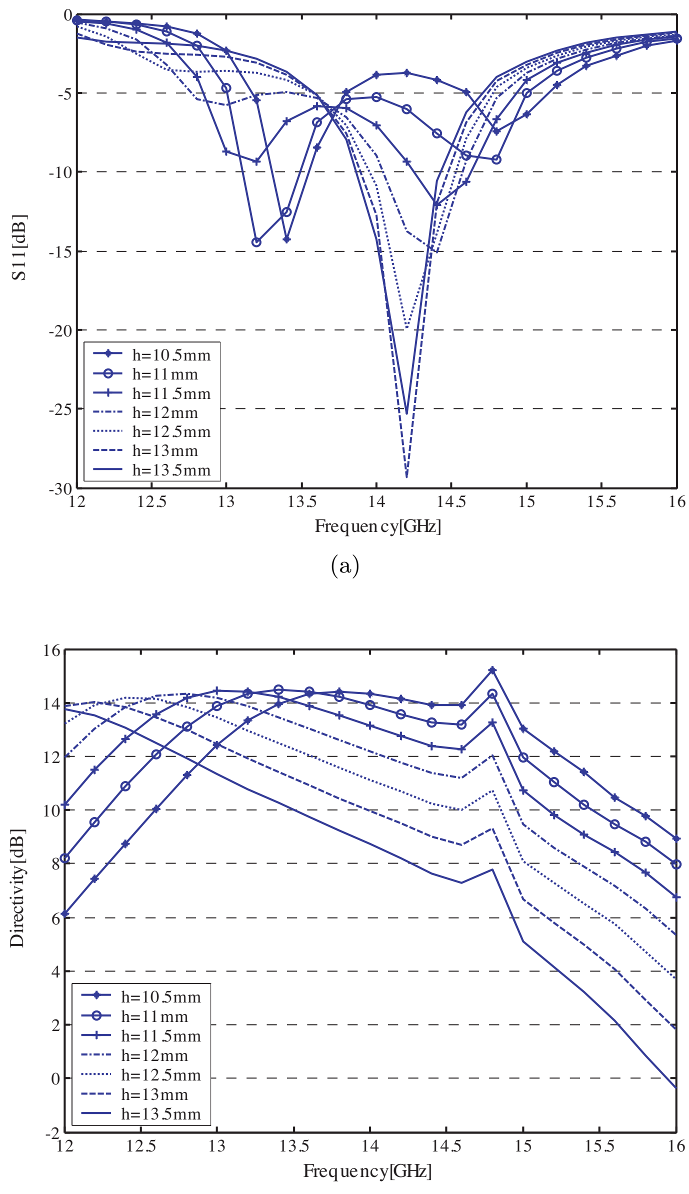


Figure 5. (a) RL of the antenna for different values of h, (b) Directivity of the antenna $(\phi = 0,\ \theta = 0), d1 = 1.15\,\text{mm}$, $d = 2.1\,\text{mm}$.

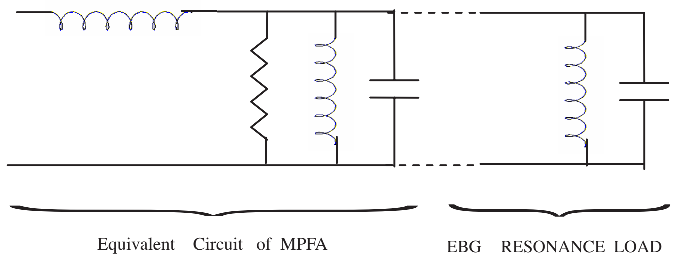


Figure 6. Effect of EBG superstrate as resonance load.

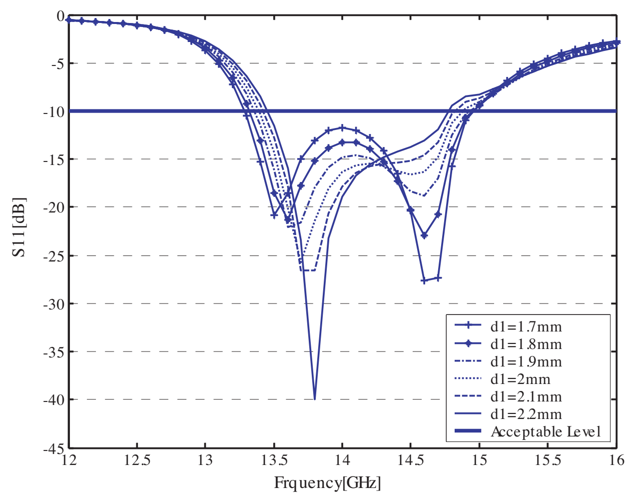
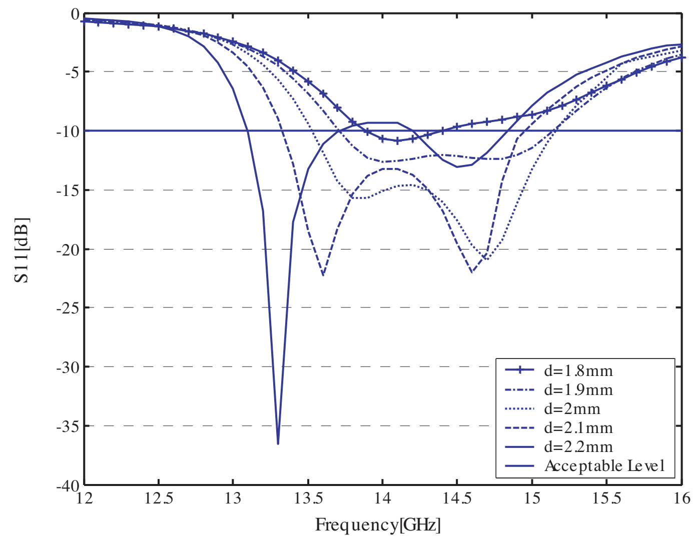


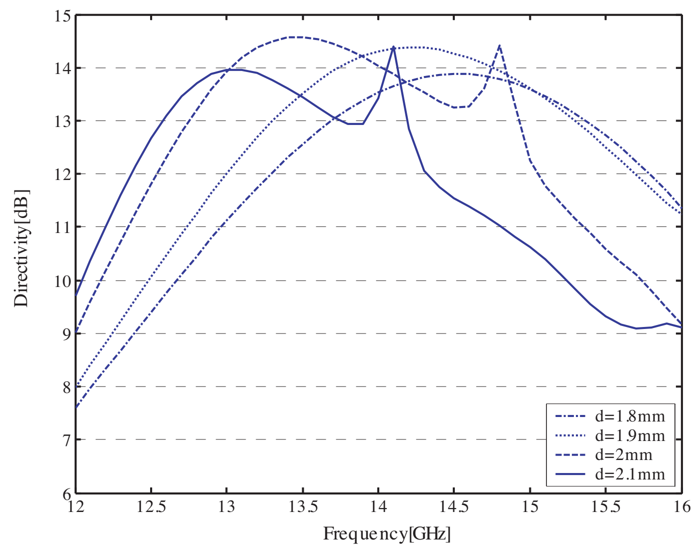
Figure 7. Reflected power coefficient for different probe locations, $h = 11.1\,\text{mm}$, $d = 2.1\,\text{mm}$.

6. FINAL DESIGN

The parametric study of the structure shows that by choosing an appropriate probe feed location, distance of superstrate layer from ground plane and diameter of the loop element of FSS structure leads to good impedance matching besides directivity enhancement of the Microstrip Probe Fed Patch Antenna. Figure 9 shows the RL and directivity of the designed structure with $d = 4.2\,\text{mm}$, $h = 11.1\,\text{mm}$ and probe feed location $= 1.8\,\text{mm}$. We can also see that the bandwidth increases 11.3% while the bandwidth of single patch antenna is about 4%. To confirm our simulation both of Ansoft Designer (based on MOM) [22] and HFSS [23] (based on FEM) results are depicted in Figures 10, 11.

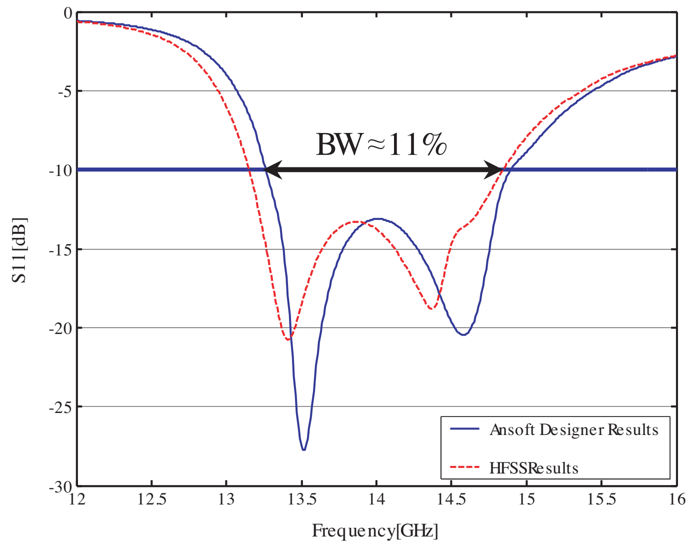


(a)

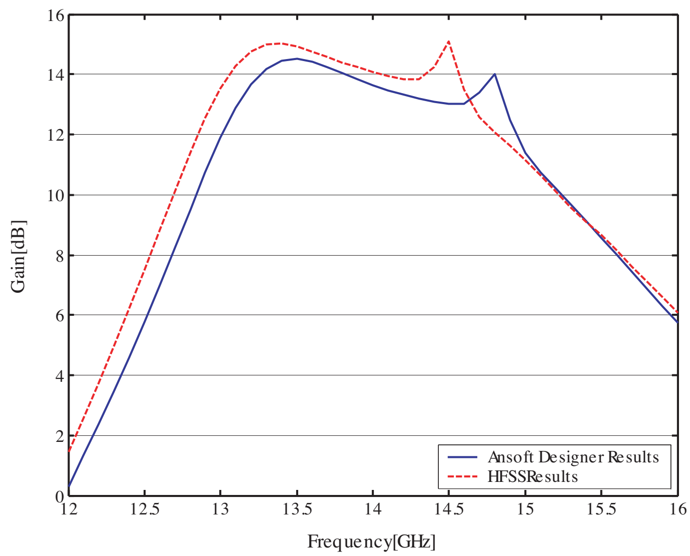


(b)

Figure 8. (a) Effect of loop diameter on the RL for fine tune, (b) Effect of loop diameter on the directivity for fine tune ($\phi = 0,\ \theta = 0$), $h = 11.1$ mm, $d1 = 1.8$ mm.



(a)



(b)

Figure 9. The RL and directivity ($\phi = 0,\ \theta = 0$) of optimum designed structure.

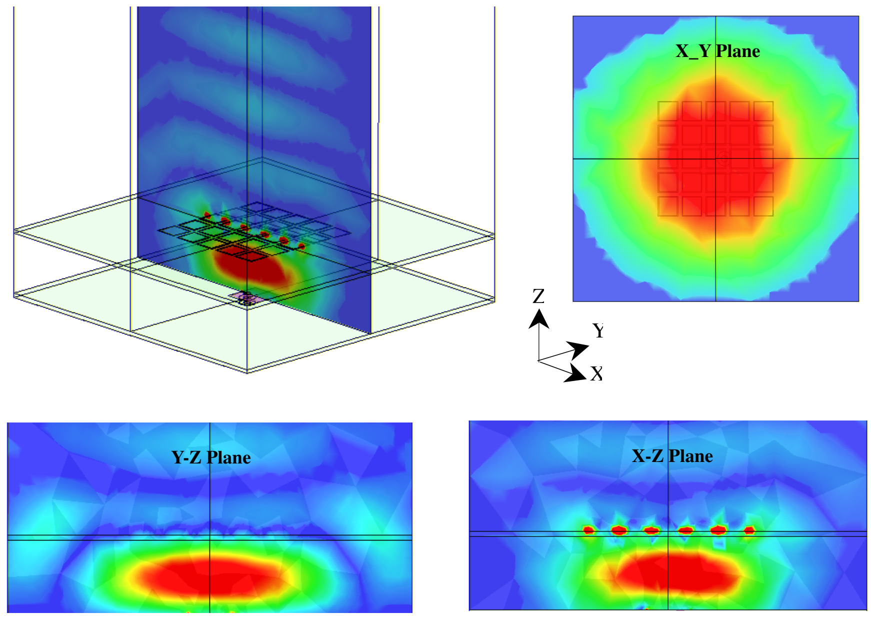


Figure 10. Antenna configuration and electric field distributions at 14 GHz.

In Figure 10, the antenna configuration and electric field distributions at 14 GHz are shown. The E-, H-, and 45°-plane radiation patterns of antenna at 13.5, 14, and 14.8 GHz are shown in Figure 11.

7. CONCLUSIONS

The effect of EBG structures on microstrip antenna performance has been examined. We observe that beside the gain enhancement of the antenna this structure can be used to match the input impedance of antenna because, in fact, the EBG structure acts as a load. This work may be extended to study other types of feeding schemes of the microstrip antenna such as stripline and slot feeding. Also, the process of this paper can be used to design dual band EBG resonator antennas that use two-layer FSS structure as superstrate layer.

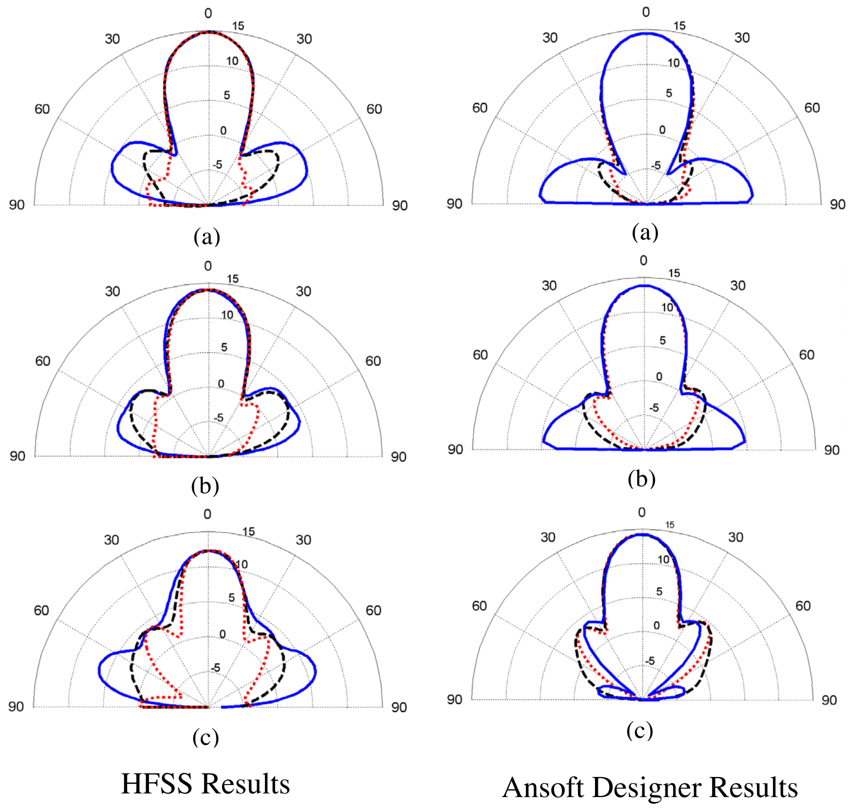


Figure 11. Radiation patterns of antenna (a) $f = 13.5\,\text{GHz}$, (b) $f = 14\,\text{GHz}$, (c) $14.8\,\text{GHz}$. —— $\phi = 0$, - - - - $\phi = 45$, •••• $\phi = 90$.

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REFERENCES

1. Maagt, P. D., R. Gonzalo, Y. C. Vardaxoglou, and J. M. Baracco, "Electromagnetic bandgap antennas and components for microwave and (sub) millimeter wave application," *IEEE Trans. Antennas and Propagation*, Vol. 51, No. 10, 2667–2677, 2003.
2. Chang, C. C., Y. Qian, and T. Itoh, "Analysis and applications

of uniplanar compact photonic bandgap structures," *Progress In Electromagnetics Research*, PIER 41, 211–235, 2003.

3. Agi, K., M. Mojahedi, B. Minhas, and K. J. Malloy, "The effects of an electromagnetic crystal substrate on a microstrip patch antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 50, No. 4, 451–456, April 2002.
4. Yang, H.-Y. D. and J. Wang, "Surface waves of printed antennas on planar artificial periodic dielectric structures," *IEEE Transaction on Antennas and Propagation*, Vol. 49, No. 3, 444–450, March 2001.
5. Broas, R. F. J., D. F. Sievenpiper, and E. Yablonovitch, "An application of high-impedance ground planes to phased array antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 4, 1377–1381, April 2005.
6. Sievenpiper, D., L. Zhang, F. J. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 11, 2059–2074, November 1999.
7. Yang, F. and Y. Rahmat-Samii, "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 10, 2691–2703, October 2003.
8. Mosallaei, H. and K. Sarabandi, "Antenna miniaturization and bandwidth enhancement using a reactive impedance substrate," *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 9, 2403–2414, September 2004.
9. Kern, D. J., D. H. Werner, A. Monorchio, L. Lanuzza, and M. J. Wilhelm, "The design synthesis of multiband artificial magnetic conductors using high impedance frequency selective surfaces," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 1, 8–17, January 2005.
10. Simovski, C. R. and A. A. Sochava, "High-impedance surfaces based on self-resonant grids. Analytical modeling and numerical simulations," *Progress In Electromagnetics Research*, PIER 43, 239–256, 2003.
11. Thevenot, M., C. Cheype, A. Reineix, and B. Jecko, "Directive photonic bandgap antennas," *IEEE, Transaction on Microwave Theory and Techniques*, Vol. 47, No. 11, 2115–2122, Nov. 1999.
12. Akalin, T., J. Danglot, O. Vanbesien, and Lippens, "High directive dipole antenna embedded in a Fabry-Perot type cavity," *IEEE Microwave and Wireless Components*, Vol. 12, No. 2, 48–50,

February 2002.

13. Weily, A. R., L. Horvath, K. P. Esselle, B. C. Sanders, and T. S. Bird, "A planar resonator antenna based on a woodpile EBG material," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 1, 216–223, January 2005.
14. Weily, A. R., K. P. Esselle, B. C. Sanders, and T. S. Bird, "High gain 1-D resonator antenna," *Microwave and Optical Technology Letters*, Vol. 47, No. 2, 107–114, October 2005.
15. Cheype, C., C. Serier, M. Thevenot, A. Reineix, and B. Jecko, "An electromagnetic bandgap resonator antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 50, No. 9, 1285–1290, September 2002.
16. Wu, B.-I., W. Wang, J. Pacheco, X. Chen, T. Grzegorczyk, and J. A. Kong, "A study of using metamaterials as antenna substrate to enhance gain," *Progress In Electromagnetics Research*, PIER 51, 295–328, 2005.
17. Lee, Y. J. U., J. Yeo, K. D. Ko, R. Mittra, Y. Lee, and W. S. Park, "A novel design technique for control of defect frequencies of an electromagnetic bandgap (EBG) superstrate for dual-band directivity enhancement," *Microwave and Optical Technology Letters*, Vol. 42, No. 1, 25–31, July 2005.
18. Lee, Y. J. U., J. Yeo, R. Mittra, Y. Lee, and W. S. Park, "Application of electromagnetic bandgap (EBG) superstrates with controllable defect for a class of patch antennas as spatial angular filters," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 1, 224–235, January 2005.
19. Cheype, C., C. Serier, M. Thevenot, A. Reineix, and B. Jecko, "An electromagnetic bandgap resonator antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 50, No. 9, 1285–1290, September 2002.
20. Enoch, S., G. Tayeb, and B. Gralak, "The richness of dispersion relation of electromagnetic bandgap materials," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 10, 2659–2666, October 2003.
21. Lee, Y. J. U., J. Yeo, K. D. Ko, R. Mittra, Y. Lee, and W. S. Park, "A novel design technique for control of defect frequencies of an electromagnetic bandgap (EBG) superstrate for dual-band directivity enhancement," *Microwave and Optical Technology Letters*, Vol. 42, No. 1, 25–31, July 2005.
22. Ansoft Designer Release 2.0, Ansoft Corp., 2003.
23. HFSS Ansoft Designer Release 9.2, Ansoft Corp., 2003.