Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2012, Article ID 151603, 9 pages
doi:10.1155/2012/151603

Research Article

Investigation of Patch Antenna Based on Photonic Band-Gap Substrate with Heterostructures

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Received 16 February 2011; Accepted 7 September 2011

Academic Editor: Cristian Toma

The characteristics of the patch antenna based on photonic band-gap (PBG) substrate with heterostructures were studied numerically by using the method of finite difference time domain (FDTD). The results indicate that, comparing to the conventional patch antennas, the expansion of working frequency band of the new patch antenna can be realized and its radiation efficiency also can be improved notably with the influence of PBG. In addition, for this new kind of patch antenna, its return loss is much less and there are two minimum values for return loss corresponding to the resonant frequency of the two different photonic crystals made of the substrate. Its physical mechanism lies on the PBG which suppresses the surface waves propagating along the surface of the substrate and reflects most of electromagnetic wave energy radiated to the substrate significantly.

1. Introduction

The concept of "photonic crystal (PC)" was firstly put forward by Yablonovitch [1] and John [2] in the year of 1987. The introduced dielectric periodicity in PCs can modulate the propagation of electromagnetic waves due to the multiple Bragg scatterings and results in the relationship of frequency versus wave-vector characterized by photonic band structure. An electromagnetic wave with frequency falling in the "forbidden band" or "stop band" is forbidden from propagating in any direction in the PC [3, 4]. A nontransmission frequency range will be expected with the complete reflection to those electromagnetic waves falling in the nontransmission range. It has also been known that the PBG is determined by the topology, dielectric constant, and the connectivity [5, 6].

Semiconductor heterostructures have revolutionized optoelectronics and high-speed electronics through their ability to confine electrons of precise kinetic energies in specific devices areas. Photonic crystal heterostructures provide a similar amount of control over the wavelength and localization of light in photonic crystals [7–10]. This is because the strong light-matter interaction in heterostructures of PCs can result in their different positions of the forbidden bands in energy coordination for the different heterogeneity structures of PCs. This also renders an enlargement of non-transmission frequency band in PBG heterostructures in comparison to each single PBG in the heterostructures.

Nowadays, photonic crystals have been found many applications in microwave circuits, antennas [11–14], and so forth. Photonic crystal patch antennas or PBG patch antennas are very useful because the photonic crystals can reduce the substrate absorption compared with conventional patch antennas without PBG substrate due to the existence of non-transmission bands of PCs. The enlargement of non-transmission frequency band in photonic crystal heterostructures will further reduce the substrate absorption and improve the radiation efficiency of antenna.

In the paper, the comparison is carried out to the performance of (1) a conventional patch antenna without PBG substrate, and (2) a patch antenna with PBG heterostructure substrate, by employing the finite difference time domain (FDTD) method. The results show that, comparing to the conventional patch antennas, the working frequency band of the photonic crystal patch antenna with heterostructures can be expanded due to the enlargement of non-transmission frequency band. And its radiation efficiency as well as its return loss can also be improved notably. The physical mechanism lies in the PBG which suppresses the surface waves propagating along the surface of the substrate and reflects most of electromagnetic wave energy radiated to the substrate significantly. Due to such advantages, the use of photonic crystal patch antennas will be extended in many areas, such as, mobile communications, satellite communications as well as communications for aeronautics and astronautics.

2. Calculation Model

The FDTD method [15–18] is frequently employed for calculating the PBG patch antennas due to its advantages in comparison with other algorithms used for the same purposes. Its fundamental principle is that Maxwell's equations are expressed as scalar equations of electric and magnetic field components in Cartesian coordinates first, and then replace differential quotient with difference quotient with second-order precision. Each photonic crystal cell is meshed with the method proposed by Yee [15]; here, Δy are the lattice space increments in the x- and y-coordinate directions, respectively, and Δt is the time increment. By discretizing partial differential Maxwell's equations in the space and time domains in Yell cell, one can obtain the following FDTD approximation as representative relations with respect to TE modes:

$$E_x^{n+1}(i,j) = E_x^n(i,j) + \frac{H_z^{n+1/2}(i,j+1/2) - H_z^{n+1/2}(i,j-1/2)}{\Delta y} \cdot \frac{\Delta t}{\varepsilon(i,j)},$$

$$E_y^{n+1}(i,j) = E_y^n(i,j) + \frac{H_z^{n+1/2}(i+1/2,j) - H_z^{n+1/2}(i-1/2,j)}{\Delta x} \cdot \frac{\Delta t}{\varepsilon(i,j)},$$

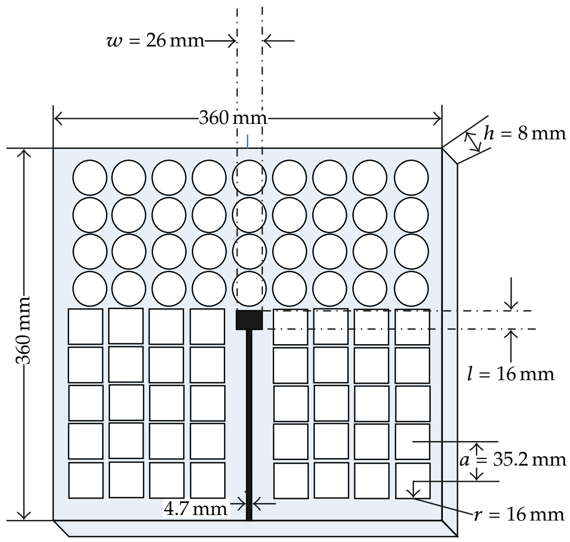

Figure 1: Structural parameters of PBG patch antenna.

$$H_z^{n+1/2}(i,j) = H_z^{n-1/2}(i,j) + \frac{E_x^n(i,j+1/2) - E_x^n(i,j-1/2)}{\Delta y} \cdot \frac{\Delta t}{\mu},$$
$$- \frac{E_x^n(i+1/2,j) - E_x^n(i-1/2,j)}{\Delta x} \cdot \frac{\Delta t}{\mu}. \tag{2.1}$$

To ensure steady results in iteration constringency, $\Delta x, \Delta y, \Delta t$ must satisfy the steady condition [15],

$$\Delta t \leq \frac{1}{c\sqrt{(\Delta x)^{-2} + (\Delta y)^{-2}}}, \tag{2.2}$$

and the calculating formulation for H_x, H_y, E_z for TM mode can be attained in the same way.

In the numerical computation, we divide each photonic crystal cell into 20 × 20 Yell cells and employ Perfectly Matched Layer (PML) as the boundary condition in X, Y directions [16, 17], and numerical solutions to the PBG antenna with source are simulated in 4000 time increments.

It is well known that the relatively subtle confinement mechanism of the photonic crystal heterostructure is very sensitive. If the positions and the sizes of the cylinders inside the supercell unit change, this should cause changes in the resonant frequency and the band gap structures [19]. Therefore, the geometry structure of the drilled PBG antenna is shown in Figure 1, the heterogeneity PBG structure is fabricated by drilling periodic cylinder and square holes in the substrate with relative permittivity 10. The dimension of the substrate is 360 mm × 360 mm × 8 mm. The radii of the cylinder holes are all 16 mm, while the side lengths of the square holes are all 32 mm, and the distance between two neighboring cylinder

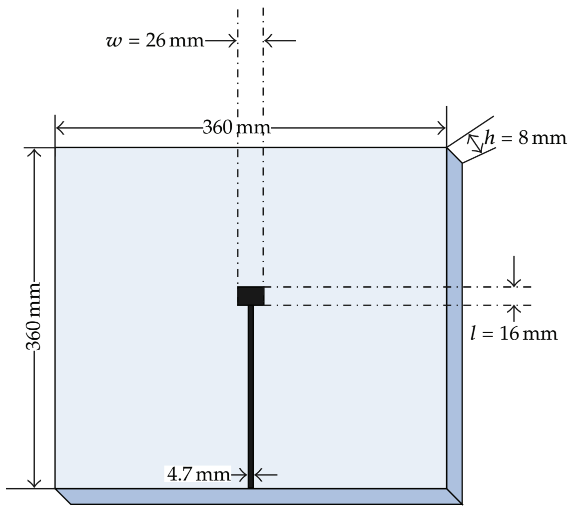

Figure 2: Structural parameters of conventional patch antenna.

or square centers is 35.2 mm. The patch of 26 mm × 16 mm is etched in the top surface of the substrate and is excited by Gaussian discrete source fed by a microstrip. The patch antenna without PBG structure is shown in Figure 2, with structure parameters being the same with those of the PBG antenna.

3. Simulation Results and Analysis

To simulate these two patch antennas with structure parameters shown in Figures 1 and 2, we solve Maxwell's equations by the method of FDTD [20]. Return loss (S11) and gain are shown in Figures 3–6, respectively.

Comparing Figure 3 with Figure 4, one can find out that the return loss ($S11$) of the patch antenna with PBG substrate is improved notably, with minimum return loss about −31 dB at the frequencies of 1.316 GHz and 4.003 GHz corresponding to the resonant frequencies of each PC in the substrate, 10 dB lower than of the conventional patch antenna. It indicates at the same time that the working frequency band patch antenna can be extended. As lower return loss and higher gain from the PBG patch antenna are concerned, they can be analyzed easily from the theoretical point of view. A band gap is formed by adding the PBG structure in the substrate, and EM waves with frequencies falling in the band gap will be suppressed, namely, they cannot be transmitted in any direction in the substrate.

At the same time, according to the antenna radiation patterns as shown in Figures 5 and 6, we can find that the conventional antenna's maximum gain is −3 dB, while that of the PBG one is +5 dB. High gain of the PBG patch antenna results from the effect of electromagnetic waves being highly localized by the aberrance between the PCs, that is to say, the electromagnetic field has enhanced strongly at the interface. It suggests that the PBG structure can improve patch antennas' gain obviously. Therefore, the absorption of EM waves by the substrate is reduced, and their energy is reflected black into the free space, so its return loss and gain are improved greatly.

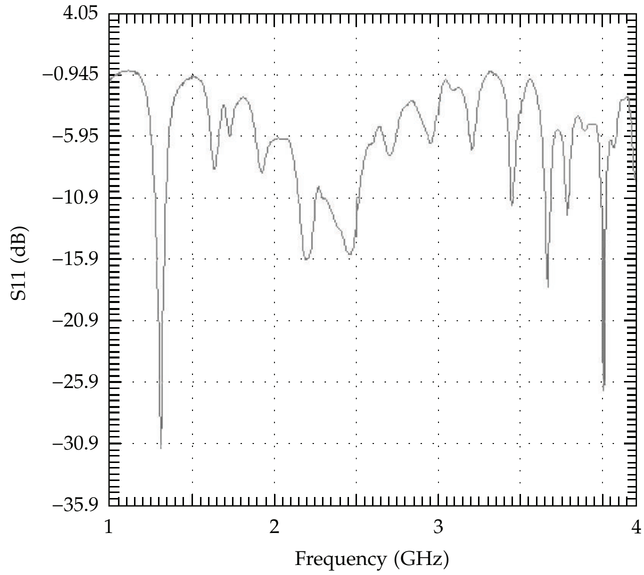

Figure 3: Return loss S11 from the PBG patch antenna.

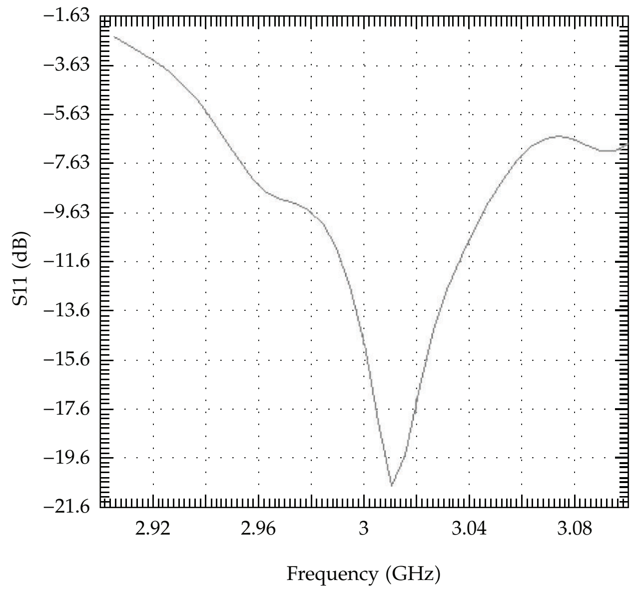

Figure 4: Return loss S11 from the conventional patch antenna.

For the VSWR (voltage standing wave ratio), it is 1.056 for PBG patch antenna, which is very close to the ideal value 1.0, while it is 1.2004 for the conventional antenna. Main characteristic parameters of the patch antennas drawn from the simulation are listed in Table 1. Why the radiation properties of a patch antenna on a photonic crystal substrate are improved is shown schematically in Figure 7 [21].

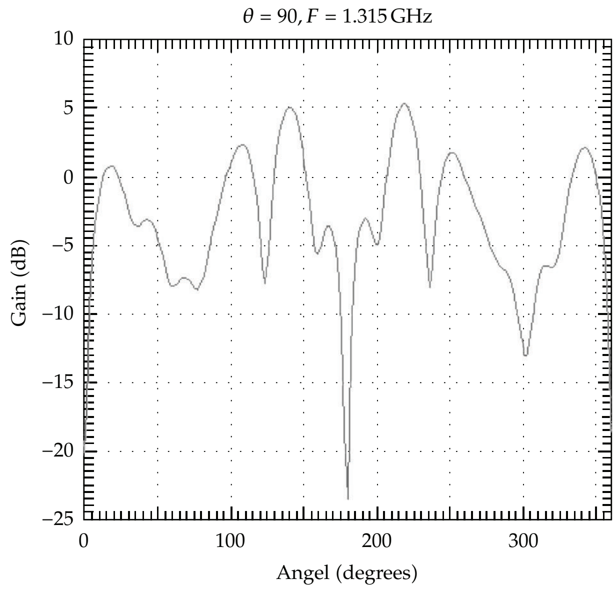

Figure 5: Radiation pattern of the PBG patch antenna.

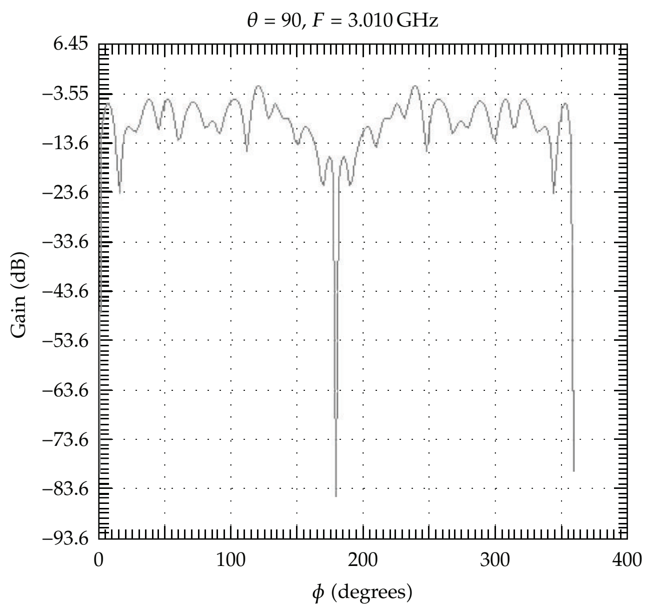

Figure 6: Radiation pattern of the conventional patch antenna.

Table 1: Main characteristic parameters of the patch antennas.

	Return loss	Bandwidth (S11 = −10 dB)	VSWR	Maximum gain
PBG patch antenna	−31 dB (at 1.316 GHz, 4 GHz)	5.64%	1.056	5 dB
Conventional patch antenna	−20 dB (at 3.01 GHz)	1.92%	1.2004	−3 dB

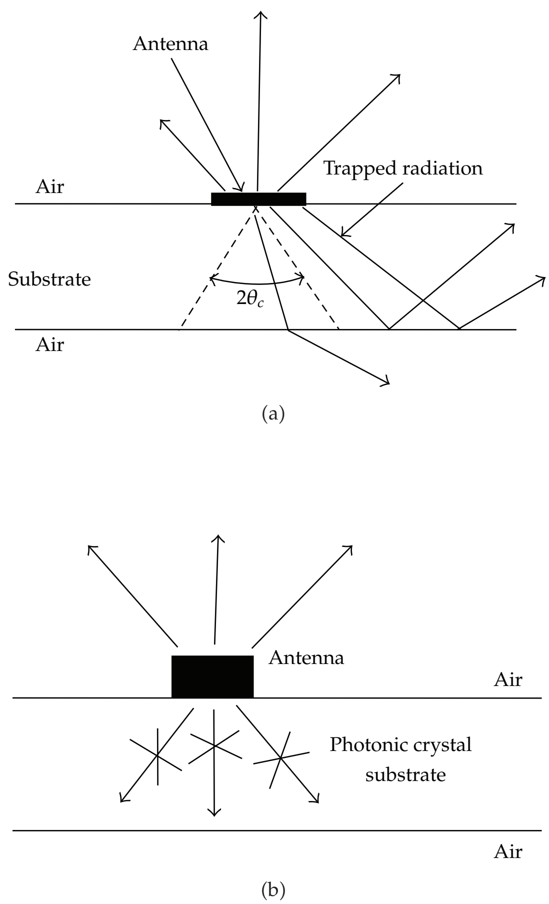

Figure 7: Cross-sectional view of conventional planer antenna on uniform-dielectric substrate (a) and that of conventional planer antenna on a photonic-crystal substrate, showing expulsion of radiation at frequencies in the band gap (b).

4. Conclusion

The contribution from the PBG substrate to the gain of patch antenna can also be illustrated by the distribution of electric field (E_z) for these two antennas, (shown in Figures 8 and 9); here E_z is a component vertical to the patch. Obviously, the electric field energy from surface waves absorbed by conventional antenna is much more than that absorbed by the PBG patch antenna. It shows vividly that surface waves transmitted along the substrate can be suppressed by PBG structure.

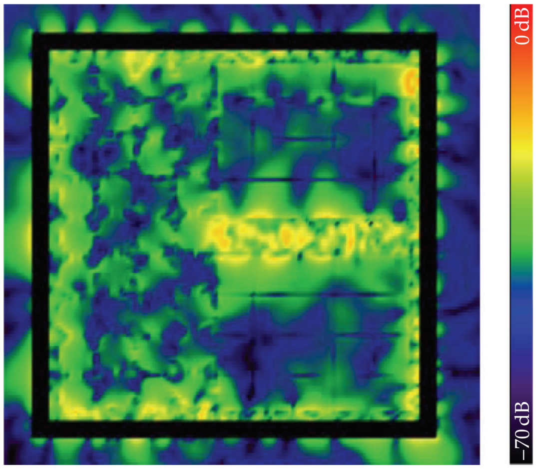

Figure 8: Distribution of electric field component vertical to PBG patch antenna.

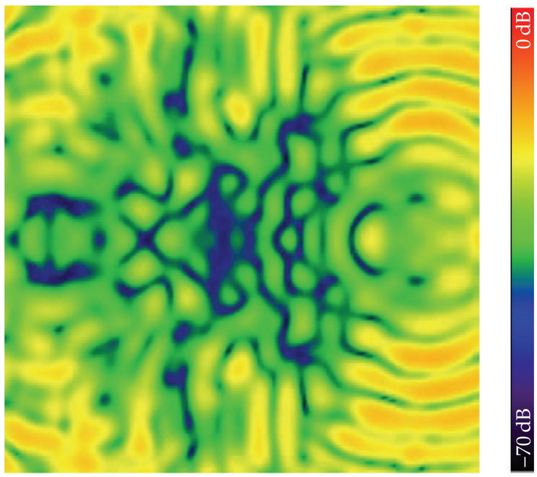

Figure 9: Distribution of electric field component vertical to conventional antenna.

Acknowledgment

This work was financially supported by 973 Key Program from the Ministry of Science and Technology of China (no. 2006CB921100).

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