Simulated Performance of a Microstrip Patch Antenna with both Photonic Crystal Substrate and Cover

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Abstract: - We have simulated the performance of a microstrip patch antenna with a hexagonal low-permittivity photonic crystal used both as substrate and superstrate (cover). The photonic crystal structure was analyzed with the plane wave expansion method. The input return loss, radiation pattern and the directivity of the antenna were calculated using the CST Microwave Studio transient solver based on the finite integration technique (FIT). A comparison between the conventional patch antenna and the proposed antenna is given. It is shown that the presence of the photonic crystal cover is very efficient for improving the radiation directivity.

Key-Words: - Electromagnetic Bandgap (EBG) Materials, Microstrip Patch Antennas, Photonic Crystals, Plane Wave Expansion Method, Finite Integration Technique.

1 Introduction

In recent years, the current trend in commercial and communication systems has been to develop low cost, minimal weight, low profile antennas that are capable of maintaining high performance over a large spectrum of frequencies. This technological trend has focused much effort into the design of microstrip (patch) antennas (MPAs). The conventional MPA is a metallic patch of an arbitrary shape that is placed a certain distance, typically less than 0.01 λ, where λ is the wavelength of the electromagnetic radiation, above a metallic ground plane. It is typically excited using a coaxial probe through the ground plane or by a microstrip line in the plane of the antenna [1].

MPAs are known for their many desirable physical characteristics such as, low profile, low cost, light weight, easy fabrication, and conformability to planar and non-planar surfaces. They have found applications in communication systems, as well as many other systems that require compact antennas structures [2,3]. However, MPA designs have some operational limitations such as restricted bandwidth due to its resonant nature, low gain and poor radiation patterns due to surface wave losses.

Some techniques are explicitly designed to suppress the surface waves. They include optimizing the antenna dimensions so that the surface wave is not excited [4,5], grooving the dielectric or covering the patch by additional dielectric layers [6]. However, these techniques have the fundamental drawback of increasing the weight, thickness and complexity of the microstrip antenna, thus negating many of the advantages of using MPAs.

Photonic Crystal (PC) substrate is a simple solution to the problem of surface waves. Photonic crystals [7], also known as electromagnetic bandgap (EBG) materials, are a new class of periodic metallic, dielectric, or composite structures that when introduced to an electromagnetic signal can exhibit a forbidden band of frequencies (or photonic bandgap: PBG) in which the incident signal destructively interferes and thus is unable to propagate. It is proposed [8,9] that if a 2D-photonic crystal is used as substrate of a MPA, then a broadband response can be obtained from this inherently narrowband antenna. This will result in improvements in the radiation characteristics of the patch antenna, by reducing pattern side-lobes and improving front-to-back pattern ratios and overall efficiency. A MPA with a 2D-PC substrate has been fabricated by Agi *et. al.* [10,11] and Finite-difference time-domain (FDTD) calculations have been employed to determine the effects of the PC substrate.

In this paper, we study the performance of a MPA with a PC structure as substrate and another similar structure as cover (acting as a lens or passive array) [12]. The PC is composed of dielectric rods in a periodic arrangement with hexagonal symmetry. The presence of the ground plane allows the feeding of the antenna by the direct-coupled microstrip method. The plane wave expansion method was used to calculate the photonic band diagram of the designed PC structure. The input return loss, radiation pattern and the directivity of such a patch antenna were simulated using the commercial software package CST Microwave Studio, a time domain field solver based on the finite integration technique (FIT) [13].

The remainder of the paper is organized as follows: In Section 2 the photonic crystal structure used as substrate is presented and the band diagram of the TM propagating modes is used in order to choose the suitable dimensions of the structure. In Section 3, we present simulation results concerning the performance of the MPA with photonic crystal substrate. The performance of a MPA with both a PC substrate and a PC cover is studied in Section 4. We conclude with a summarizing Section 5.

2 Design of the photonic crystal

Although different geometries of PC structures can be used as substrates [14], our proposed structure is a hexagonal 2D-lattice with lattice constant α composed of dielectric rods with radius r and relative dielectric constant ε_r=2.2. The patch is rectangular with 12.5 mm length and 16 mm width. The substrate has size 56.2 mm x 64 mm x 0.8 mm with a ground plane of thickness 2.4 mm. The feeding line is a standard 50 Ω microstrip line of dimensions 2.5 mm x 24 mm. A direct contact feeding method is used and the best impedance match is obtained when the line is displaced 2.1 mm from the patch edge. A schematic diagram of the designed MPA with PC substrate is shown in Fig. 2.

The central working frequency for such a conventional patch antenna (without any PC structure) is 7.48 GHz. The TM_0 mode has no cutoff frequency in such a substrate. The cutoff frequency for the first TE_1 mode is safely away from the working frequency. Thus, one only needs to eliminate the TM_0 mode. So we only have to consider the TM mode band structure.

After defining the basic PC geometry, the dispersion relation for a normal incident plane wave can be calculated. The so called 'gap map' [15] for the structure is obtained by sweeping the ratio r/a and recording the width of the gap. This 'gap map' allows us to choose the ratio r/a that maximizes the available photonic bandgap for the desirable frequency of operation. The dispersion diagram for TM modes of our structure was computed with the plane wave expansion method (PWE) and the result is shown in Fig. 1. It can be seen that a complete band gap exists, which forbid propagation in the normalized frequency ($\omega\alpha/2\pi c$) range from 0.50 to 0.54, regardless the polarization and the direction of wave propagation. From the 'gap map' it is found that the bandgap occurs for the interval $r/a \in$ [0.2, 0.4]. The maximum complete bandgap arises around r/a = 0.28. Together with a central normalized frequency 0.52 this gives a physical lattice period a =20.8 mm and rod radius r =5.82 mm.

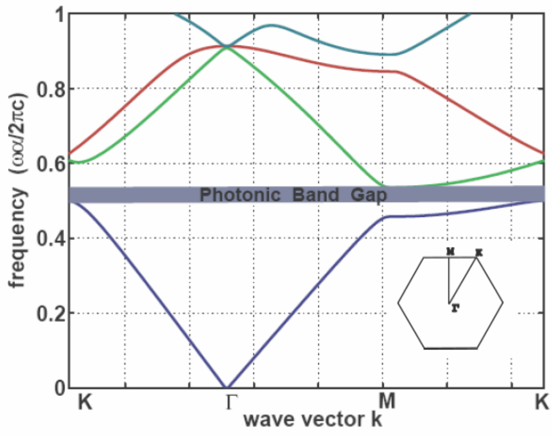

Fig. 1: Photonic band structure of the proposed photonic crystal substrate.

3 Simulation of the MPA with PC substrate

The basic geometry of the designed MPA with PC substrate placed on top of a ground plane as is shown in Fig. 2. The thickness of the substrate is chosen to be equal to the operational wavelength of the conventional patch $\lambda=c_0/f_0$=40 mm. The presence of the ground plane allows the feeding of the antenna by the direct-coupled microstrip method. The goal was to achieve the resonance with optimum characteristics, which was accomplished using a trial-and-error approach to locate the probe excitation point.

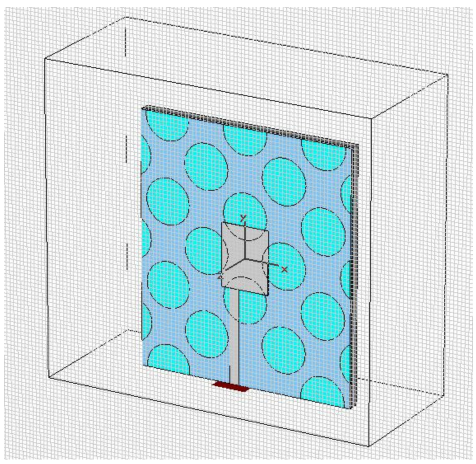

Fig. 2: The MPA designed on a PC substrate.

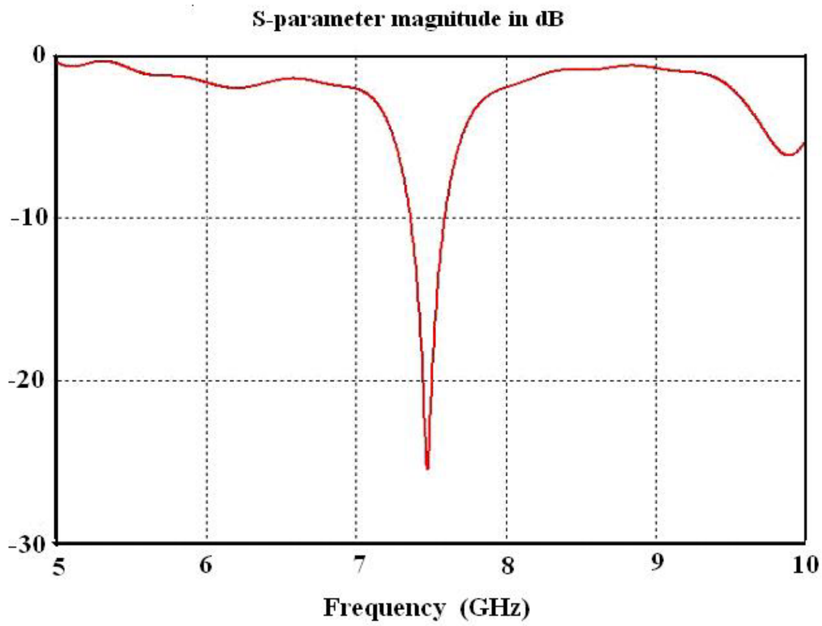

Fig. 3: Simulation results of input return loss S_{11} for the conventional patch antenna versus frequency. The resonant frequency of the antenna is 7.48 GHz.

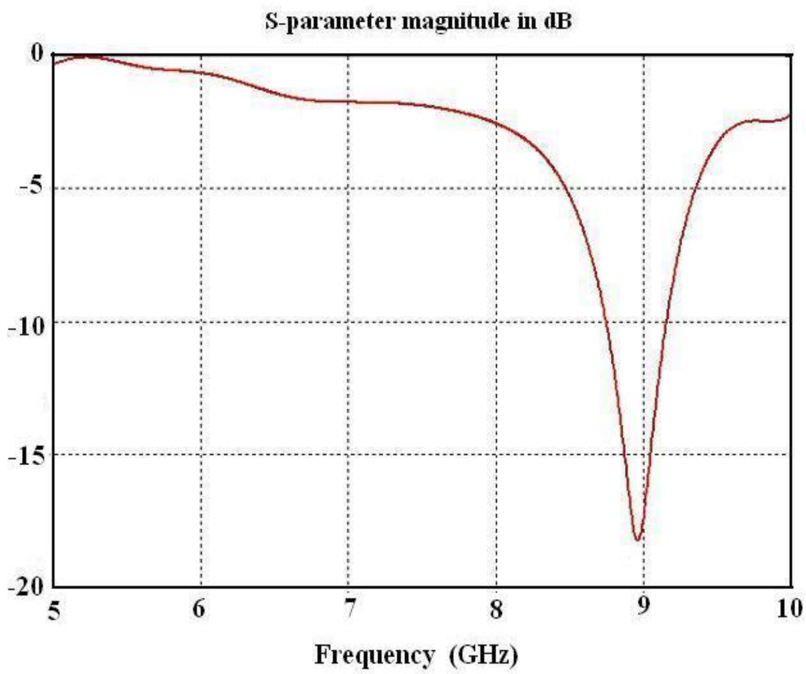

Fig. 4: Simulation results of input return loss S_{11} for the patch antenna with PC substrate versus frequency. The resonant frequency has been shifted to 8.97 GHz.

In the case of a patch antenna, the device is a single-port device, therefore, only the return loss (S_{11}) parameter is calculated. From this calculation, the resonant frequency of the patch can be located by observing the location of the deepest null, that is, the best match between patch and feed. Figures 3 and 4 show the calculated input return loss S_{11} for the conventional MPA and MPA with PC substrate, respectively.

The presence of the PC structure increases the resonant frequency from 7.48 GHz to 8.97 GHz due to lowering of the effective dielectric constant. The suppression of surface waves by the PC substrate leads to a smooth curve (absence of ripples) of the input return loss S_{11}. The improvements concerning the minimum return loss and the operational bandwidth, by using the photonic crystal substrate, are obvious.

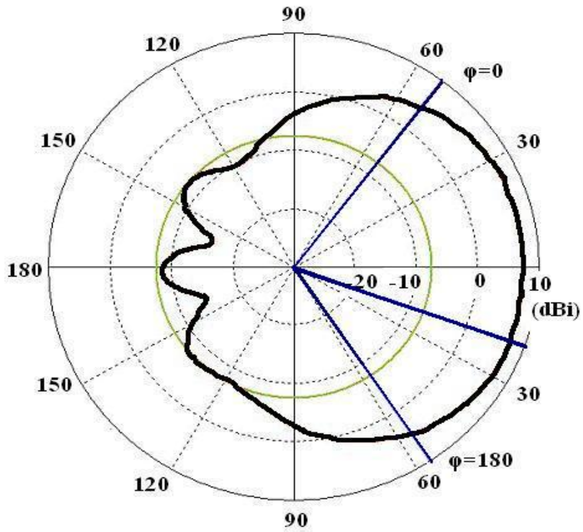

Fig. 5: Far-field radiation pattern from the conventional patch antenna at 7.48 GHz. The main lobe magnitude is 7.4 dBi, the main lobe direction 20 deg., the angular width (3 dB) 109 deg., and the side lobe level -14.9 dB.

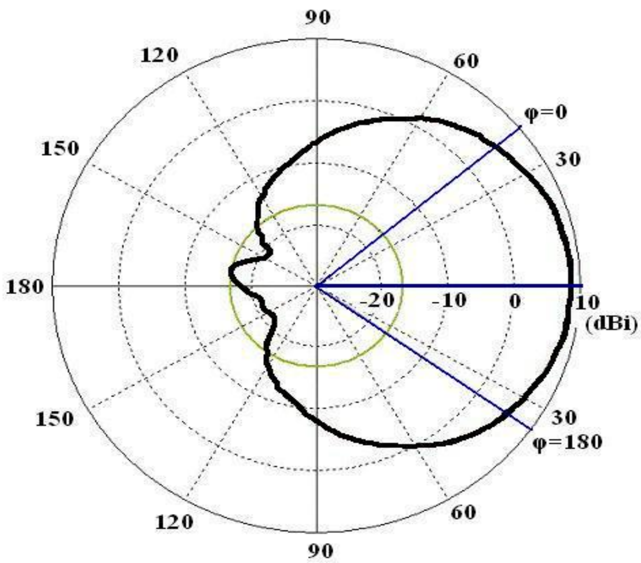

Fig. 6: Far-field radiation pattern from patch antenna with PC substrate at 7.48 GHz. The main lobe magnitude is 8.4 dBi, the main lobe direction 0 deg., the angular width (3 dB) 75.5 deg., and the side lobe level -25.2 dB.

Finally, the radiation patterns at 7.48 GHz for the designed MPA without and with PC structure are presented in Figures 5 and 6 respectively. As it is seen, the gain value is increased, the patterns are smoother and the back and side radiation lobes have been reduced. There is a 1.2 dBi improvement in the directivity when a PC substrate is used. In addition, the frequency dependence of the radiation pattern is reduced while using the PC substrate, indicating that the surface wave mode has been mitigated in the frequency range of operation (about 7.5 to 9 GHz).

4 Simulation of the MPA with both PC-substrate and PC-cover

In this section a photonic crystal is used as substrate as well as superstrate (cover) of the designed MPA with the geometry described in section 2. The PC cover had the same geometrical structure (except for thickness) as the PC substrate (this can make the fabrication of the whole antenna system easier and cheaper). A schematic repre-sentation of the MPA with both PC substrate and cover is given in Fig. 7.

When a PC structure is used as a MPA's cover, it is illuminated by the electromagnetic fields radia-ted from the patch antenna, and almost all of the dielectric elements of the cover are excited so that the field distribution on the cover surface is quite uniform. So the photonic crystal cover is excited to serve as an aperture antenna, and the antenna's directivity is expected to be drastically improved.

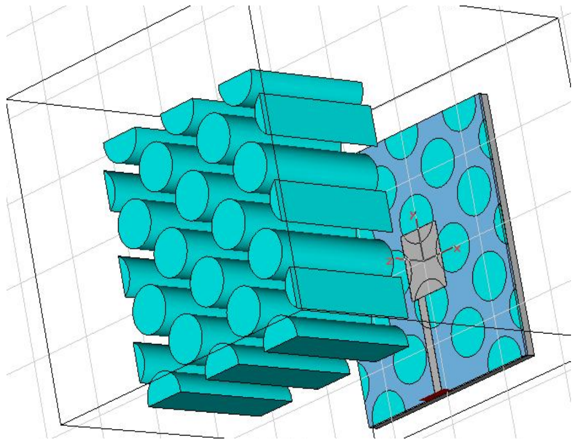

Fig. 7: Schematic representation of the MPA with both PC substrate and cover.

The calculation of the input return loss (S_{11}) indicates that the presence of the cover does not shifts the resonant frequency of the MPA. The maximum improvement in the performance of the antenna was achieved when the thickness of PC cover was chosen to be equal to the operational wavelength λ_0=40 mm and the distance between the substrate and the PC cover has been taken equal to the new operational wavelength d = λ= 33.4 mm. The improvement in the directivity is shown in Fig. 8. The directivity of the MPA has been drastically improved from 7.3 dBi to 15.5 dBi. However, we observe a small increment in the level of the side lobes. The far field three-dimensional pattern of the designed photonic crystal MPA is given in Fig. 9.

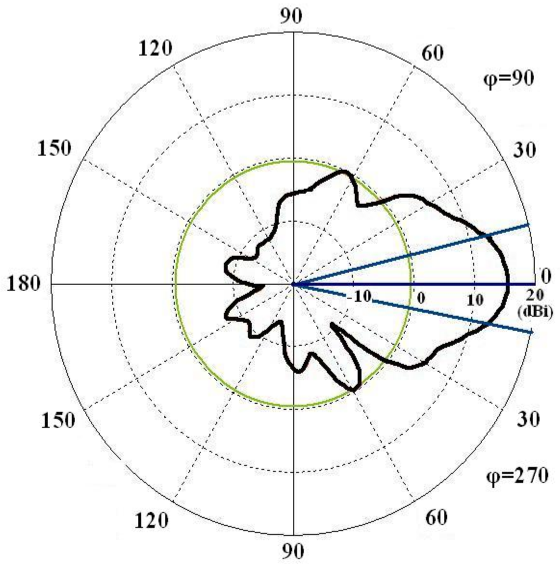

Fig.8: Far-field radiation pattern for patch antenna with both PC substrate and PC cover at 8.97 GHz. The main lobe magnitude is 15.5 dBi, the main lobe direction 0 deg., the angular width (3 dB) 24.8 deg., and the side lobe level -15.9 dB.

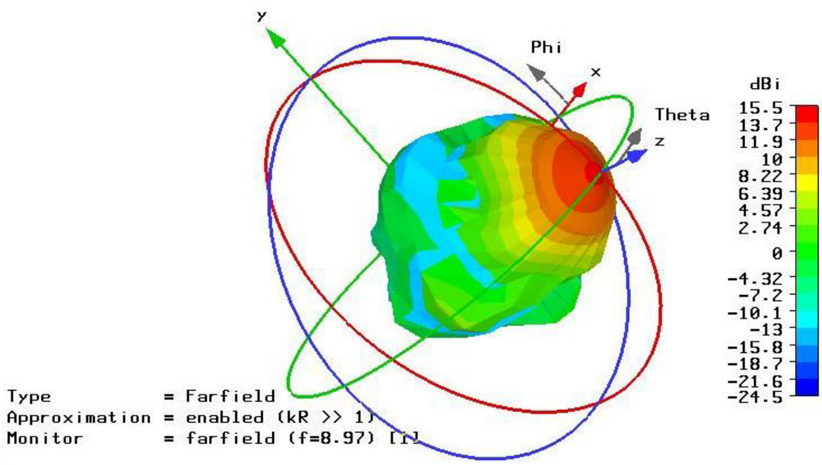

Fig.9: 3D – Far-field radiation pattern from MPA with both PC substrate and cover. The maximum directivity is 15.53 dBi.

5 Conclusion

We have simulated the performance of a MPA with a hexagonal PC used both as substrate and cover. The PC structure is composed of dielectric rods with low relative permittivity ε_r=2.2. The PC structure was analyzed with the plane wave expansion method. The input return loss, radiation pattern, and the directivity of the antenna were calculated using the CST-Microwave Studio time domain field solver.

At the operational frequency, the numerical results showed that the radiation directivity of the designed MPA was improved significantly. The maximum improvement was achieved when the PC cover had a thickness equal to the operational wavelength λ and the distance between the PC-substrate and the PC-cover was chosen to be d = λ. The next stage in this work is to investigate and simulate the performance of an array configuration of the designed MPA.

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