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SIMULATED AND MEASURED PERFORMANCE OF A PATCH ANTENNA ON A 2-DIMENSIONAL PHOTONIC CRYSTALS SUBSTRATE

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Abstract—This paper deals with the use of Photonic Crystal (PC) structures as substrates in patch antenna configurations in order to mitigate the effect of the surface wave mode propagation. The case of a single antenna has been studied. A comparison between a conventional substrate based patch and a patch with a PC as substrate has been performed. The antennas were fabricated and measured. Improvements in all the main parameters of the antenna were obtained when using a PC. The frequency dependence of the radiation patterns is significantly reduced when using a PC as substrate.

1. INTRODUCTION

The microstrip patch has been a popular antenna for many years, as it is low profile, robust, conformable if required and inexpensive to manufacture [1–4]. However, patch antenna designs can have some operational limitations such as restricted bandwidth of operation, low gain and a decrease in radiation efficiency due to surface wave losses.

Thickening the substrate increases the operational bandwidth, but at the same time increases the excitation of substrate modes and a trade-off must be performed. The concept of photonic bandgap materials can have a significant influence on the outcome of such a trade-off.

The photonic bandgap materials introduced in the late eighties allow to control the emission and propagation of electromagnetic waves into a dielectric substrate to an extent that was previously not possible [5–7]. Although many applications have initially been proposed in the field of optics, the scalability of these structures opens up the possibility of using them in the microwave regime. In this frequency range, photonic bandgap materials have attracted a lot of attention as substrates for antennas [8–17]. The basic idea is to match the operational bandwidth of the antenna with the bandgap of the photonic crystal. The utilization of a photonic crystal substrate, instead of the original bulk substrate, has shown to reduce the excitation of surface wave modes, and as a consequence improves the antenna radiation efficiency, reduces the side lobe level and mitigates the problems related to coupling.

In this paper, the design of a photonic crystal as a substrate for patch antennas is discussed. The performance of a single patch on a conventional substrate is compared to that of a patch on a photonic crystal substrate, both theoretically and experimentally.

2. SELECTION AND DESIGN OF THE PHOTONIC CRYSTAL

Although different kinds of PC structures can be used as substrates [18–21], the proposed structure is a square lattice of air columns with a radius r and lattice constant a drilled in a dielectric medium with a dielectric constant $\varepsilon_r = 10$, see Figure 1. The advantage of using this configuration versus other possibilities is a higher number of holes per wavelength [15]. The electromagnetic properties of this type of photonic crystal structure, and the relevant primitive and reciprocal lattice vectors and the corresponding Brillouin zone can be found in [15].

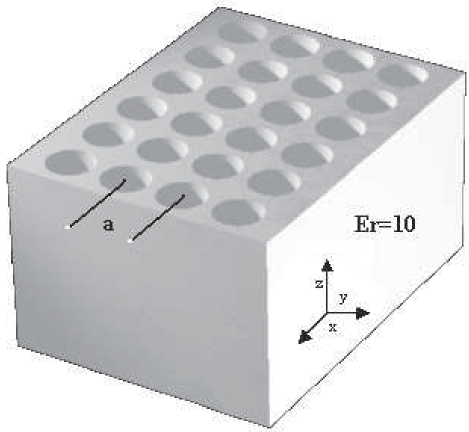


Figure 1. Two-dimensional Photonic Crystal formed by a square array of air columns embedded in a dielectric substrate.

After defining the basic photonic crystal geometry, the dispersion relation for a normal incident plane wave can be calculated. The so-called "gap map" [5] for the structure is obtained by keeping the dielectric constant fixed, sweeping the r/a ratio and recording the width of the gap. This gap map then allows us to choose the r/a value that maximises the available photonic band gap for the desired frequency of operation. Figure 2(a) and (b), shows the TE and TM polarisation gap maps, respectively, for a dielectric constant of 10. Along the horizontal axis of the gap map is the r/a ratio of the air columns; along the vertical axis is the normalised frequency (fa/c). Note at this point that the TE polarisation corresponds with the E field along the axis of the columns and in the TM polarisation, the E field is perpendicular to the columns.

Using these maps and taking a working frequency of 15 GHz, the lattice constant a can be obtained. There are different possibilities, but the selection criteria will be governed by minimising the total device size. By ensuring the only surface mode in propagation will be the TM_0 [22], one only has to focus on the TM polarisation gap-map. With these two premises, a value for r/a of 0.48 was selected. Together with a normalised frequency of 0.3 this gives a physical lattice period of 6 mm and a column radius of 2.88 mm.

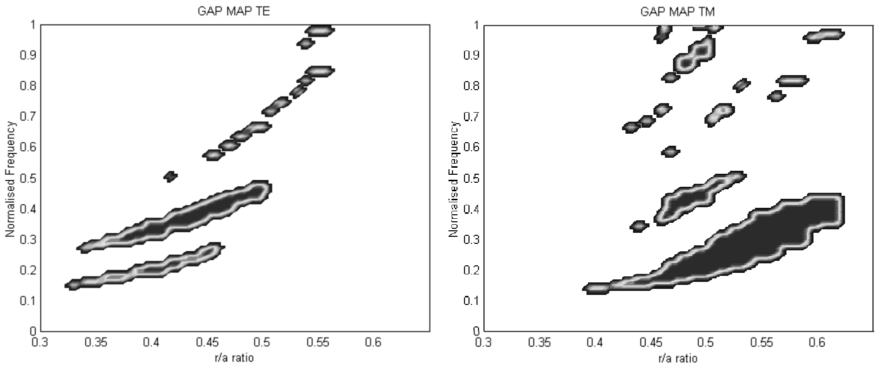


Figure 2. Gap Map for TE (left side) and TM (right side) polarizations in the case of air columns in a dielectric substrate with $\varepsilon_r = 10$.

3. DESIGN OF THE PATCH ANTENNA

The patch antenna configuration was fed using the aperture coupling method. This feeding scheme provides several advantages over other arrangements, primarily due to the physical separation between the radiating region and the feeding network. Aperture coupling provides the freedom of choosing two different substrates, according to practical or technological requirements. With respect to coplanar waveguides feeding, the present solution provides radiation pattern regularity and polarisation purity [1–4].

The geometry of the patch antenna is shown in Figure 3; it has a width W of 4.6 mm and a length L of 1.5 mm. The upper/lower antenna/microstrip substrate is 1.27 mm/0.635 mm thick, respectively. The transmission line designed to feed the patch antenna has a width W_f of 0.635 mm and a stub length L_s of 2.286 mm, measured from the center of the patch antenna, to match the input impedance of the antenna [23]. The slot in the ground plane to couple the power from the transmission line to the patch antenna has an H shape. The dielectric constant is 10.2 ± 0.2 for both substrates and the total substrate size is $60 \times 60 \times 1.27$ mm. The antenna is placed at the central position of the substrate.

According to the design guidelines given in [24], the surface wave excitation becomes noticeable when $h/\lambda > 0.03$ for $\varepsilon_r \approx 10$, with h the height of the dielectric substrate. Following this rule of thumb, there should be significant excitation of surface wave modes for the selected thickness of the antenna substrate.

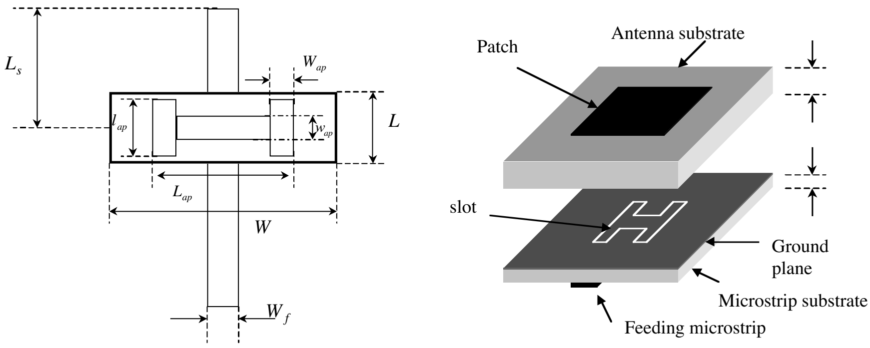


Figure 3. Geometry of the reference aperture coupling fed patch antenna. The feeding line is a standard 50-Ω microstrip line on a dielectric substrate with thickness $t_f = 0.635$ mm and a relative permittivity $\varepsilon_r = 10.2$. Other dimensions are: $W = 4.6$ mm, $L = 1.5$ mm, $L_{ap} = 2.159$ mm, $L_s = 2.286$ mm, $l_{ap} = 1.143$ mm, $W_{ap} = 0.381$ mm, $w_{ap} = 0.381$ mm and $W_f = 0.635$ mm.

4. SIMULATIONS AND MEASUREMENTS

The commercial software package HP-HFSS has been used to simulate the performance of both configurations. Convergence and minimization of errors were obtained in all the studied cases by ensuring that enough iterations were made.

The simulated input return loss is shown in Figure 4. Both curves are quite similar, only a small shift for the Photonic Crystal substrate is observed. The obtained bandwidth, defined for an S_{11} of -7.5 dB, is about 8% for both cases.

The simulated radiation patterns are depicted in Figure 5. These patterns are shown for a frequency of 15.2 GHz for which both antennas have the same S_{11}. The improvements obtained by using the Photonic Crystal substrate are obvious.

The size of the substrate is such that, in theory, the surface wave mode is added in counter-phase for the conventional patch antenna, resulting in a very low value for the gain in boresight direction. This effect of surface waves is nearly completely eliminated by the photonic crystal substrate, leading to a smooth radiation pattern. This gain value in boresight is increased by more than 6 dB, while the back and side radiation has been reduced considerably. The front-back ratio has improved by 6 dB.

The reduction in surface waves as a result of the Photonic Crystal material is also clear from the surface plot of the electric field

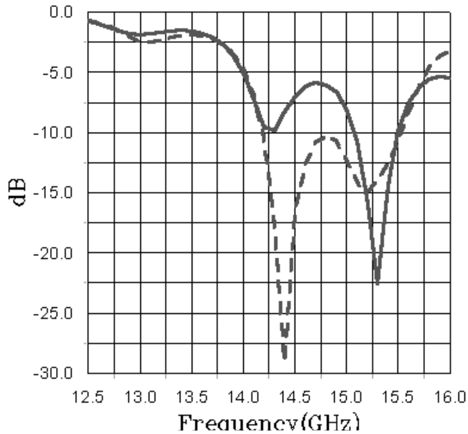
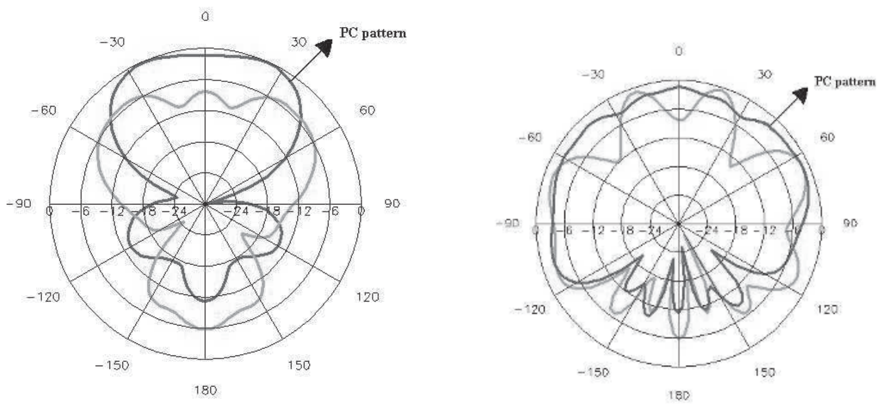


Figure 4. Computed input return loss (S_{11}) for the conventional patch antenna (solid line) and Photonic Crystal antenna (dashed line).



(a) (b)

Figure 5. Comparison of the radiation patterns for the conventional and for the Photonic Crystal substrate patch antenna. (a) H-plane. (b) E-plane.

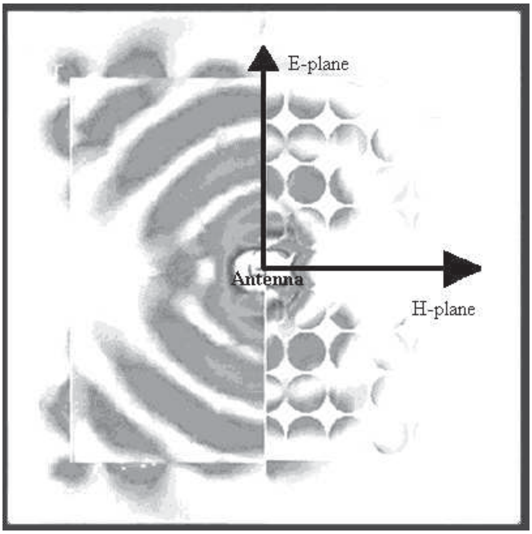


Figure 6. Surface plot of the Electric field magnitude for the conventional and for the Photonic Crystal patch antenna. Dark color corresponds to maximum power and white color to minimum power.

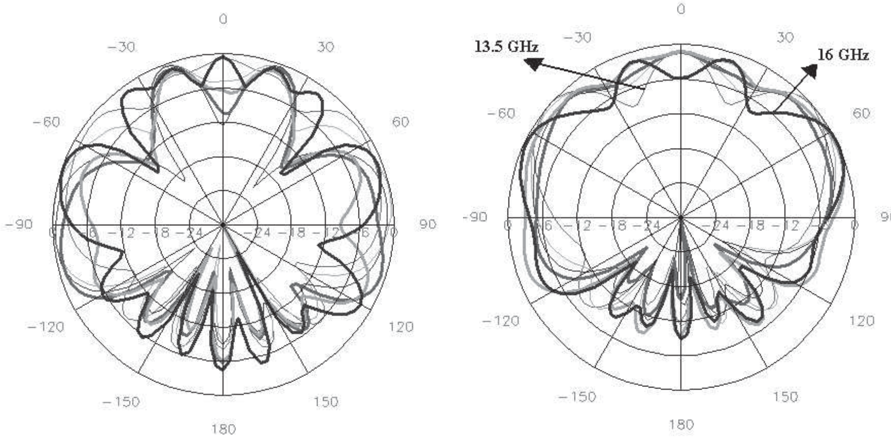
magnitude, as shown in Figure 6.

Finally, the radiation patterns in the E-plane (the plane in which the surface waves are more pronounced) are presented in Figure 7 for several frequencies. The frequencies go from 13.5 GHz to 16 GHz in steps of 0.5 GHz. The pattern for the conventional case (Figure 7(a)) is varying strongly as a function of frequency due to the presence of substrate modes. On the other hand the frequency dependence is reduced while using a photonic crystal substrate, indicating that the surface wave mode has been mitigated in the frequency range of operation (about 13.5 to 15.5 GHz).

It should be noted that the cut at 16 GHz (thick line) shows a deep ripple in both cases because it lies outside the gap of the photonic crystal.

After the simulations, both configurations (see Figure 8) were fabricated using a RO6010 substrate (0.635 mm thickness and $\varepsilon_r = 10 \pm 0.2$) for the back part and a RO3010 substrate (1.27 mm thickness and $\varepsilon_r = 10 \pm 0.2$) for the upper part [25].

The measurements were carried out in the CATR of the ESA-ESTEC in Noordwijk, The Netherlands. The behaviour is similar in both cases showing a resonant frequency of 15.6 GHz, aproximately 2% off from the simulated resonant frequency. This small discrepancy



(a) (b)

Figure 7. E plane radiation patterns for the conventional patch antenna (a) and for the four rows of holes case (b) working at different frequencies (from 13.5 to 16 GHz each 0.5 GHz). Each line shows a different frequency value.

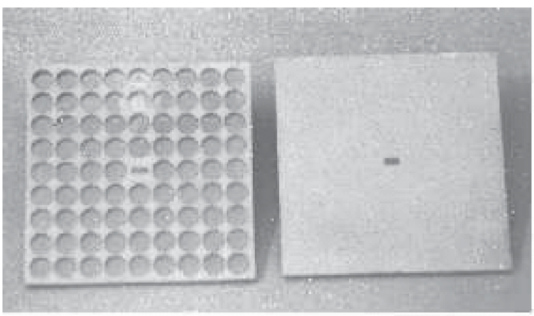


Figure 8. Picture of the fabricated antennas; left with PBG substrate and right with conventional substrate.

observed is probably due to the mechanical tolerances of the fabrication process (for frequencies higher than 14 GHz this tolerance values can be approximately 8%).

The radiation patterns at 15.2 GHz are shown in Figure 9. The improvements by using the Photonic Crystal substrate are considerable. The gain value is increased by almost 10 dB in the boresight direction, the patterns are smoother and the back and side radiations

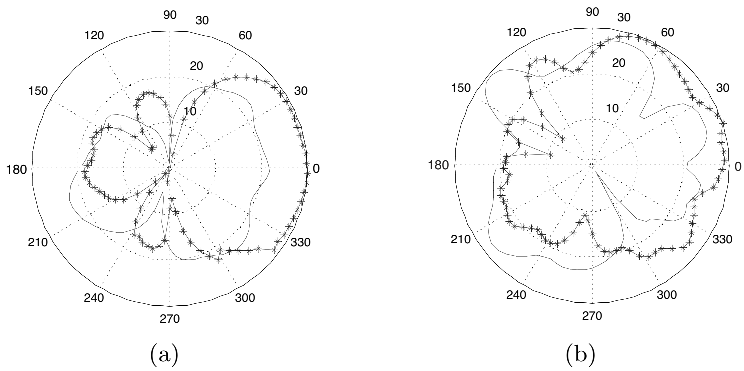


Figure 9. Comparison of the measured radiation patterns for the conventional (solid line) and for the Photonic Crystal substrate (marked line) patch antenna. (a) H-plane. (b) E-plane. Each plot has been normalised to the maximum value. Each division is 10 dB.

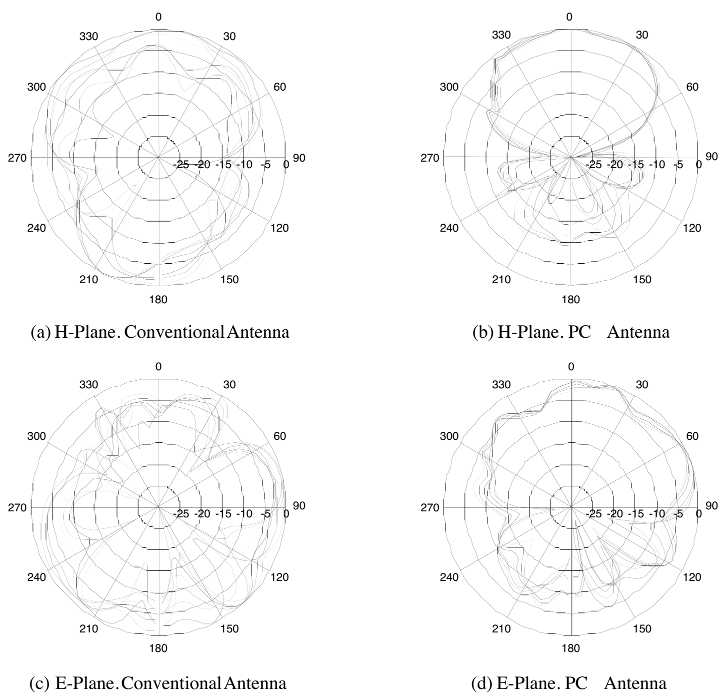


Figure 10. Measured radiation patterns from 14.5 to 16 GHz each 0.25 GHz for the H and E plane for the conventional patch antenna (a) and (c) and for the Photonic Crystal substrate (b) and (d). Each line shows a different value.

have been reduced. In particular, using a Photonic Crystal substrate leads to a front-back ratio of more than 10 dB, while in the case of a conventional substrate it is only around 3 dB.

The E and H planes agree well with the simulations. However, in the angle region 180 to 270 degrees, the E-plane pattern is perturbed by the presence of the connector. Nevertheless, the trends of all measurement agree well with the simulations.

Finally, the radiation patterns within the operational frequency of the gap have been plotted (see Figure 10) for several frequencies. All the patterns are normalised to its maximum value. The radiation patterns in both the E- and H-planes are rather stable using a PC substrate, showing nearly the same radiation pattern. On the other hand, using a conventional substrate, the patterns very due to the surface wave propagation as function of frequency. This behaviour was also predicted by the simulations.

5. CONCLUSIONS

Simulations and measurements of a patch antenna on top of a conventional and a Photonic Crystal substrate have been presented. Substantial improvements by using Photonic Crystal substrates have been obtained.

At the design frequency, the patch antenna on a Photonic Crystal has more directivity, less side and back radiation and a smoother pattern. The gain in the boresight direction increases significantly. The radiation patterns show little dependence with frequency using a PC substrate. On the other hand using a conventional substrate a clear frequency dependence is present.

The ability of the Photonic Crystal substrate to reduce the surface wave mode propagation has been clearly proven. This opens the door to design new devices with thicker substrates and higher dielectric constant without losing performance by the undesired excitation of the surface wave modes.

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