Anisotropic behavior of two-dimensional photonic crystals in the homogenization limit

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This work reports an experimental demonstration of the anisotropy predicted for photonic crystals based on two-dimensional rectangular arrays of dielectric rods (Alumina or FR4) in air. These structures have been studied in the long-wavelength limit (homogenization) by means of a microwave measurement set up. The effective dielectric permittivity ε_{eff} has been analysed along the two perpendicular directions in the lattice for the two cases of interest; E-mode excitation and H-.mode excitation. It is found that ε_{eff} is isotropic for the E-mode case while it is anisotropic for the H-mode case. Data confirm homogenization theories based on plane wave expansions and simulations based on a finite- element method.

Photonic crystals made of arrays of dielectric rods in air have been theoretically studied in the long-wavelength limit (homogenization) because of their possible application as new materials for optical components. Thus, explicit formulas for the effective dielectric constants have been given [1, 2]. More recently, the homogenization of losses have been also studied for rods having the imaginary part of the dielectric constant much lower than the real part. In other words, the imaginary part of the effective dielectric constant has been predicted and it has the same behavior than the real part [3]; it is isotropic for the E-modes an anisotropic for the H-modes.

Experimental demonstration of the previously introduced concepts of isotropy or anisotropy of the effective parameter has been performed by means of a microwave measurement setup. 2D lattices made of alumina (ε_r = 9.4 – i9.4*0.006) or FR4 (ε_r = 4.4 – i 4.4*0.02) rods of diameters ϕ = 4,2 mm and 3.2 mm, respectively, have been fabricated. The lattice period employed is p = 5 mm for the Alumina samples and p= 4 mm for the FR4 samples. According to the lattice periodicity in the propagation direction is 2p = 10 mm (8 mm) for the 0º incidence and p = 5 mm (4 mm) for the 90º incidence. A 2:1 ratio is therefore preserved between both lateral sides of the lattice, giving in practice a filling factor of ff = 0.264 and 0.254 for the Alumina and FR4 samples, respectively. With this geometry and taking into account the operation frequencies (2 – 7 GHz in the experiment), for the Alumina case, the normalized lattice parameter ranges from p/λ_{2GHz} = 3.3% to p/λ_{7GHz} = 11.6%. Thus, the measured arrangement reasonably operates within homogenization conditions. In all cases, total length of the measured sample in the propagation direction is equal (approximately 10 cm), thus giving comparable results in terms of 'bulk' homogenized parameters. Additionally, two broadband horn antennas, covering the whole measured frequency range and with a wide front side lobe, are used to transmit and receive a quasi-plane wave with a vertically polarized **E**-field. In order to guarantee a minimum detectable power for the received signal above the noise floor of the network analyzer, the antennas are closely placed at variable distances between 55 and 125 cm. This range of separations permits to be sufficiently close to the far-field region (for the measured frequency range) when the characterized device is placed equally separated between both antennas.

The real part of the effective dielectric function has been obtained by extracting the refraction index from a measurement of the phase delay $\Delta\phi$ in samples with two different lengths ℓ_1 and ℓ_2,

$$n(\omega) = -\frac{\Delta\phi c_0}{\omega(l_2 - l_1)}$$

where c_0 is light speed. Results for the samples made with FR4 are shown in figures 1 and 2 and are in quantitative agreement with theoretical predictions.

The imaginary part of the effective dielectric function has been analyzed by transmission measurements. Results are depicted in Figs. 3 and 4, where it is shown how the transmittance spectra obtained under E-mode excitation are isotropic in the low frequency region while those obtained under H-mode excitation are anisotropic. Numerical simulations based on a finite-element method (COMSOL multiphysics) are also depicted for comparison purposes.

Acknowledgements

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References

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[2] A. A. Krokhin, P. Halevi, and J. Arriaga, Phys. Rev. B., **65** (2002) 115208.

[3] A. A. Krokhin, L. Gumen, and J. Arriaga (private communication).

Figures 1 and 2:

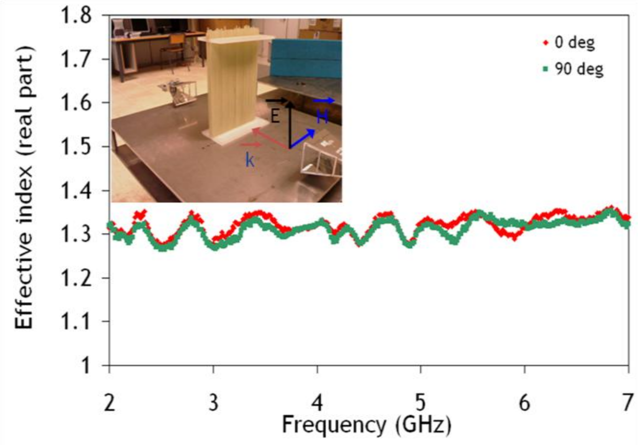

Figure 1.- Effective refractive index extracted from phase delay measurements performed on FR4 samples with lengths ℓ_1=100mm and ℓ_2=52mm. These results correspond to E-mode excitation with two incidence angles (0º and 90º). Inset shows the employed experimental setup with the characterized sample illuminated with an E-polarization.

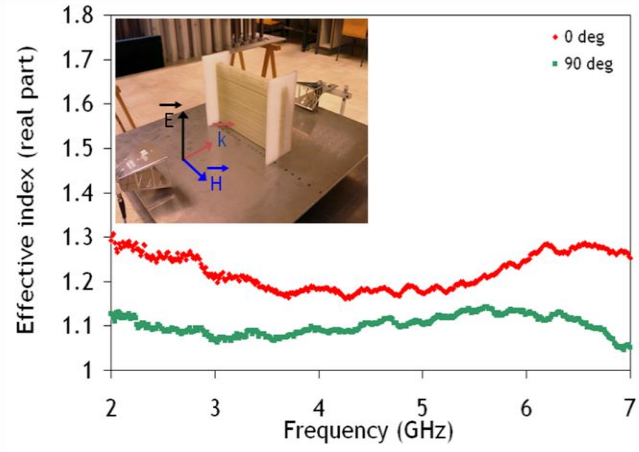

Figure 2.- Effective refractive index extracted from phase delay measurements performed on the FR4 samples. Results correspond to data obtained under H-mode excitation. Inset shows the employed experimental setup.

Figures 3 and 4:

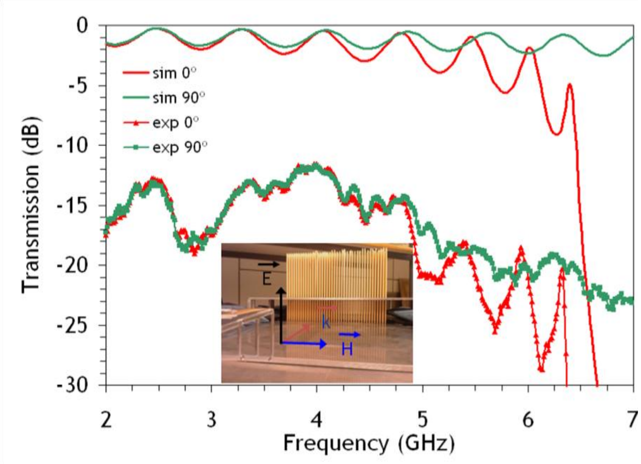

Figure 3.- Measured (symbols) and simulated (lines) transmission for Alumina structures under E-mode excitation wave with two incidence angles (0º and 90º). Inset shows the employed experimental setup with the characterized sample illuminated with an E-polarization.

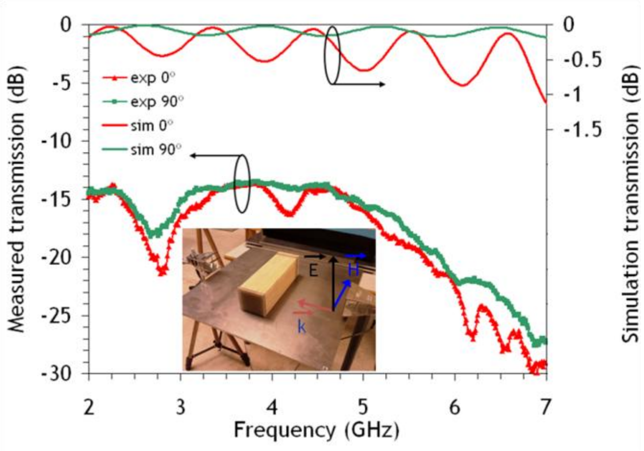

Figure 4 Measured (symbols) and simulated (lines) transmission for Alumina structures under H-mode excitation wave with two incidence angles (0º and 90º). Inset shows the employed experimental setup with the characterized sample illuminated with an H-polarization.