Engineering an achromatic photonic crystal waveplate

D R Solli and J M Hickmann

1 Department of Electrical Engineering, University of California, Los Angeles, CA, USA
2 Instituto de Física, Universidade Federal de Alagoas, Maceió, Alagoas, 57072-970, Brazil
E-mail: jandir.hickmann@loqnl.ufal.br

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Abstract. We have experimentally demonstrated that two-dimensional, dielectric photonic crystals can display large, but non-dispersive, birefringences in the transparent region below the first stopband. This frequency-independent birefringence extends from zero frequency to the band edge. We show that this property can be used to construct achromatic waveplates. Numerical simulations agree very well with our experimental results, and provide further insights into the design of photonic crystal waveplates. Photonic crystal achromatic waveplates may have important practical applications in polarization control.

Photonic crystals have been the focal point of a great deal of interest in contemporary optics. These periodic media exhibit a unique band structure for light owing to interference between Bragg reflections generated at their numerous material interfaces [1]–[3]. Although simple wave optics is the underlying physics, photonic crystals possess a wealth of surprising properties and myriad potential applications ranging from novel waveguides to thresholdless laser cavities [1, 4].

One of the important characteristics of photonic crystals is that they exhibit polarization-dependent effects. For example, the depths, widths and shapes of the band gaps of crystals with two-dimensional (2D) periodicity are known to depend on polarization, even at normal incidence. This situation is further enriched by the size of the non-periodic or extruded dimension. In particular, it has been shown that crystals which are on the order of or smaller than a wavelength
In their non-periodic dimension (slab structures) usually have a small band gap or pseudo-gap for one of the two basis polarizations [5], whereas those much longer than a wavelength in this dimension (bulk structures) usually exhibit well-formed band gaps for both polarizations [6, 7].

In addition to their effects on the amplitudes of reflected and transmitted waves, photonic crystals are also known to impart unique, dispersive phases to these reflected and transmitted fields [8, 9]. These phases are non-trivial and polarization-dependent [10], even in the transparent spectral regions of the crystal. Recently, it has been shown that mode control of a 2D square-lattice laser can be obtained using photonic crystal polarization properties [11].

In this paper, we present an experimental demonstration of achromatic, photonic crystal based, transmission waveplates. We show that 2D, bulk, photonic crystals can be significantly birefringent at frequencies far below their first stopband. At these frequencies, the indices of refraction for the two basis polarizations are weakly dependent on frequency, allowing for compact, zero-order, photonic crystal waveplates, which are useful over a relatively wide bandwidth. Although our experiments were performed at microwave frequencies, the scale-invariance of Maxwell’s equations allows the results to be applied across the electromagnetic spectrum. Using numerical simulations of finite, 2D, hexagonal crystals, we are able to account for the features of our experimental results.

We made transmission measurements with a Hewlett-Packard 8720A vector network analyser (VNA). The crystals were placed between polarization-sensitive transmitter and receiver horns, in a microwave-shielded box with an aperture smaller than the cross-section of the crystals to prevent signal leakage. The box was positioned in the far-field of the transmitter, ensuring that planar wavefronts of a well-defined polarization were incident on the crystals [6].

We compared the birefringence of bulk crystals in two frequency regimes: far below the first stopband and below, but near the first stopband. Because of frequency range limitations of our experimental apparatus, crystals of two different sizes scales were needed to study these two frequency regimes. Both types of crystal consisted of a hexagonal array of acrylic pipes (index of refraction 1.61 [12]) and air-filling fractions (AFFs) of 0.32 (the AFF is defined as the ratio of air volume to total volume in the structure). The first type had a lattice constant of $a = 1/4''$ and first stopband in the vicinity of 18–20 GHz, while the other had a lattice constant of $a = 1/2''$ and first stopband in the neighbourhood of 9–10 GHz (henceforth, we will refer to them as the small and large crystals, respectively). The small crystal was used to characterize the birefringent properties far below the band gap, whereas the larger crystal was used to study the frequency regime just below the band gap. We tested crystals ranging from 2 to 20 layers of pipes. Additional details about our fabrication method can be found in [6]. In summary, our crystals were constructed by stacking pipes in arrays of the desired geometry. The outer and inner diameters (OD and ID) of the acrylic pipes used to construct the small and large crystals were as follows: (i) OD = 1/4" and ID = 1/8"; (ii) OD = 1/2" and ID = 1/4".

A basic schematic of our experimental setup is shown in figure 1. We label the basis polarizations transverse magnetic (TM) and transverse electric (TE) for the electric field parallel and perpendicular to the plane of incidence (the plane perpendicular to the longitudinal direction of the pipes), respectively.

In figures 2(a) and (b), we show representative experimental results for the relative phase retardance (as a fraction of a complete wave) between transmitted TM and TE waves through a small crystal of 20 layers and a large crystal of 14 layers, respectively. We experimentally determined that crystals of the same lattice constant and different numbers of layers exhibit approximately the same birefringences, but different phase retardances owing to the different path
Figure 1. A schematic diagram of the experimental setup used to measure the birefringence in our photonic crystals.

Figure 2. The experimentally measured TE-TM phase retardances for transmission through (blue traces) (a) a 20-layer crystal \( (a = 1/4", \text{ AFF } = 0.32) \) and (b) a 14-layer crystal \( (a = 1/2", \text{ AFF } = 0.32) \). Numerical calculations of the phase retardances for these structure are also shown (green traces). Black dashed lines mark 1/4-wave retardances.

lengths. Clearly, the phases are, overall, nearly linear functions of frequency over the measured intervals, implying that the birefringences \( \Delta n \equiv n_{\text{TE}} - n_{\text{TM}} \) are relatively constant over these ranges \( (n_{\text{TE}} \text{ and } n_{\text{TM}} \text{ are also individually non-dispersive at these wavelengths}) \). The band gap of the large crystal begins just above 9 GHz, while that of the small crystal begins near 17 GHz; these features imposed the frequency ceilings shown in the plots of figure 2(a) and (b). Also in the plots, we show the quarter waveplate condition as horizontal dashed lines, illustrating that these crystals can act as quarter waveplates with a scaled bandwidth comparable to standard, zero-order waveplates for optical wavelengths.
Figure 3. The experimentally measured TE-TM phase retardances for transmission through a 20-layer crystal \((a = 1/4'', \text{AFF} = 0.32)\) below its first stop band (blue line) and a 16-layer crystal \((a = 1/2'', \text{AFF} = 0.32)\) between its first and second stopbands (purple line). The frequencies are normalized to unity at 1/4-wave and full-wave retardances, respectively. Black dashed lines mark 1/4-, 3/4-, full- and 5/4-wave retardances.

To better understand the advantage of using the region below the first stopband, we must compare it with the transparent region between the first and second stopbands. In figure 3, we have plotted the TE-TM relative phase retardance of both our small crystal below its first stopband and another large crystal with 16 layers between its first and second stopbands. In this plot, the frequencies have been normalized so that the two data sets may be easily compared. Clearly, in the region between the band gaps, the crystal is both much more birefringent and much more dispersive; thus, a photonic crystal waveplate designed to operate in this spectral region has a much smaller useful bandwidth than the achromatic waveplates we have described here.

Although the measured retardances shown figures 2(a) and (b) are nearly linear, it is evident from the data that there are local frequency variations or wiggles in the phase, which become more pronounced at larger wavelengths (compared with the lattice spacing). To account for these variations, we have performed 2D numerical studies of our structures using a finite-element, differential equation solver to compute the transmitted fields from normally-incident, monochromatic plane waves. We obtained results (dashed lines), that agreed extremely well with the experimental results and also possess similar wiggles. The crystal thickness was left as a fit parameter in our simulations. Because of small structural errors, the thickness of the crystals used in our experiments were approximately 5.

We also performed additional numerical simulations to study the role of the AFF on photonic crystal birefringence. To create different AFF for our crystal design, we can only change the inner radius of the pipes. In figure 4, we display \(\Delta n(\omega)\) over frequencies below the first stopband for 10-layer, acrylic-air, hexagonal-lattice crystals (hexagonal array of pipes) with AFFs of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8. Each \(\Delta n\) curve is plotted up to the point where the first stopband begin.
These simulations display a number of interesting trends, which may be exploited to engineer photonic crystal waveplates.

Firstly, it is evident that the local frequency wiggles discussed previously become more significant at lower frequencies and smaller AFFs. Furthermore, we have observed that the amplitude of these variations is reduced and the rapidity increased as more layers are added. This feature suggests that these variations are a result of incomplete Bragg interference; for long wavelengths and a small number of layers, the interfering components do not completely reinforce the transmitted component and cancel the reflected component (drawing phasors provides a useful qualitative picture).

Secondly, the average birefringence is clearly dependent on the AFF, reaching a maximum value for an AFF of approximately 0.5. The birefringence appears to decrease fairly symmetrically for AFFs above and below this maximal value.

Because the first stopband of crystals with higher AFF begin at higher frequencies than those with lower AFF, the useful birefringent region below the first band gap is generally larger for crystals of higher AFF. On the other hand, for crystals with very low AFF, the first band gap becomes very small, and the birefringence remains fairly flat up to shorter wavelengths; however, for these low AFFs, the local variations in the birefringence have significant amplitude. It is also worth pointing out that within the local variations in the birefringence, we have frequency regions where the birefringence decreases with frequency. This may make it possible to design a waveplate which has nearly flat phase retardance over a limited frequency interval.

We have repeated these simulations for acrylic-air, square-lattice crystals (square array of pipes) and found similar results, with the birefringence again maximized for an AFF of approximately 0.5.

In conclusion, we have demonstrated that photonic crystals can be used as achromatic, waveplates which are useful over a large bandwidth. Our experiment and numerical simulations have already provided results comparable to standard, optical, zero-order waveplates. We also
presented 2D numerical calculations that reproduced the experimentally observed birefringent characteristics. Furthermore, using numerical simulations, we showed how photonic crystal birefringence can be manipulated and tailored for specific purposes. There is an interplay between the frequency regime, AFF, and number of crystal layers. To obtain overall flat behaviour in the birefringence it is advantageous to go to lower frequencies and lower AFF. However, in this regime, more layers are needed to reduce the local birefringence variations. Alternatively, these variations can be reduced by using high AFFs, but at the expense of less birefringence. We would also like to point out that disordered structures likely possess birefringent characteristics as well because they too have anisotropic boundary conditions for the different basis polarizations. However, additional research is needed to determine the roles of order and disorder for the birefringent characteristics in the different frequency regimes. Introducing disorder may provide yet another way to tailor and improve the characteristics of photonic crystal waveplates for practical applications. We believe that these waveplates may be important for applications where compact, non-dispersive polarization control is desirable, especially in integrated photonic devices.

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