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Slow light in tunable low dispersion wide bandwidth photonic crystal waveguides infiltrated with magnetic fluids

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ABSTRACT

We analyze the properties of a photonic crystal waveguide as a device capable of producing slow light along a wide bandwidth. The proposed structure consists of a square lattice of hollow silicon cylinders rotated 45° immersed on a colloidal suspension of magnetic nanoparticles; this arrangement produces "U-type" group index–frequency curves. The cylinder inner radius is carefully chosen to maximize the normalized delay bandwidth product (NDBP) and the concentration of the magnetic fluid is changed in order to make the device tunable in frequency.

1. Introduction

During recent years, slow light has been the focus of interest of many researches due to its broad field of applications, like optical buffering, all-optical time-domain signal processing and optical switching, key features in next generation optical networks and optical integrated circuits [1,2]. Conventional slow light techniques like electromagnetically induced transparency (EIT) [3] and coherent population scintillation [4] suffer from some penalties such as producing narrow bandwidths and also require bulky systems to be implemented. A more recent approach is to study slow light in dielectric structures, specially coupled ring resonators and photonic crystal waveguides (PCW) [5–7]. The most commonly used device in this kind of structures is the W1 waveguide, created by removing the central row of holes or rods in a perfect PC slab. This structure is however far from optimal, since the large group time delay is obtained only in a narrow bandwith and large group velocity dispersion (GVD) will affect the transmitted pulses, causing signal distortion. These limitations can be overcome by two techniques: dispersion compensation with chirping structures and PC geometry adjustments to achieve nearly-zero dispersion. For many practical applications it is desirable that the slow light properties can be adjusted after the device is fabricated. It has been demonstrated that a broad range of tuning can be achieved by infiltrating the holes in the PC structure with several ionic liquids with different refractive indexes [8,9]. Posterior studies [10,11] with magnetic fluids (MF) confirmed that these colloidal materials are an excellent way to post-engineer the slow light devices without introducing noticeable confinement losses for low concentrations of the MF at a working wavelength of 1550 nm [12]. We present in this paper a novel and flexible way to obtain a low-dispersion slow light tunable PC waveguide with a broad bandwidth.

2. Waveguide design and method

We design a two dimensional PC made of a square silicon rod lattice rotated 45° in which a single line defect waveguide is created by removing a row of cylinders. This structure is then infiltrated with water with different concentrations of magnetic nanoparticles, thus varying the refractive index of the liquid [10]. With the aim of improving the properties of that structure, we want to study the effect in propagation delay and tunability caused by changing the rods in the structure with hollow cylinders (Fig. 1) given the promising results of this kind of geometries [14], which are also capable of lowering coupling losses [13].

The optimal geometry proposed after the simulations presented in this paper can be fabricated by known techniques like electronic beam lithograph etching (EBL) or atomic layer

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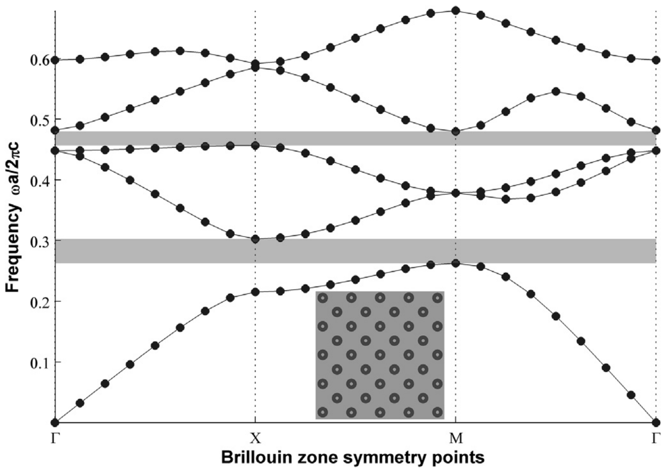

Fig. 1. Diagram band structure for the TE modes of a square lattice of hollow (r=0.35 R) silicon cylinders (n_{Si} = 3.48) rotated 45° and immersed in a 1% $MnFe_2O_4$ magnetic solution (n_{mag} = 1.4155). X-axis represents high-symmetry points at the corners of the irreductible Brillouin zone, while Y-axis corresponds to dimensionless frequency $\omega a/2\pi c$. The photonic bandgaps are highlighted, and an inset diagram of the unit lattice is also shown.

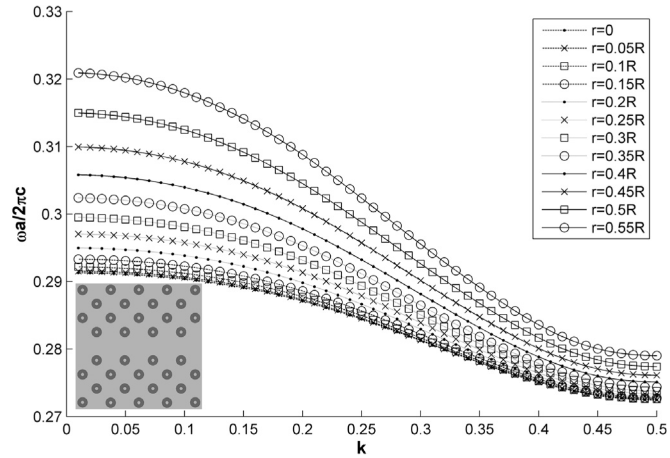

Fig. 3. Projected band dispersion diagrams of the photonic crystal waveguide for different inner radius of the rods. The normalized wave vector $k = k_x a/(\sqrt{2}\pi)$ only component is in the propagation direction. The inset shows a representation of the line defect waveguide.

deposition (ALD) [15,16].

Using the plane-wave expansion method we calculate a band-gap atlas for a chosen external cylinder radius R=0.25 a and a fixed MF concentration of 1% following a previously studied structure [17] while we change the inner radius of the cylinders from r=0 (filled rod) to r=0.95 R in the search for a larger level of light confinement through index contrast. The band gap atlas (Fig. 2) represents the relationship between the hollowness of the cylinders (x-axis) and the normalized gap frequencies – in units of $\omega a/2\pi c = a/\lambda$ – (y-axis). For each value of r, there is a gap delimited by the minimum and maximum values of a/λ. Inspecting Fig. 2 we can see three gaps; we will focus on the one present between gaps 0 and 1, since the other two are narrower and they are restricted to a smaller range of the inner cylinder radius r. It is clear then that there is a gap for the TE mode (electric field perpendicular to the plane of index variation) in the range $0.2453 \le \omega_N \le 0.3009$ with a gap ratio of 20.4%; this gap decreases its width as the values of the free parameter r range from 0 to 5.5 R.

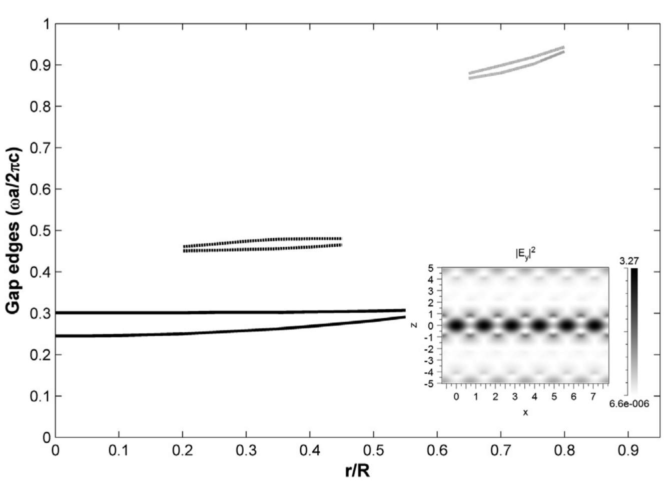

Fig. 2. Photonic gap map (band gap atlas) for a square lattice of hollow silicon cylinders infiltrated with a 1% $MnFe_2O_4$ magnetic solution. Dependence of the PBG width on the radius ratio r/R is depicted for E polarization. Three gaps are found: gap 0 between bands 0 and 1 (solid line), gap 1 between bands 2 and 3 (dashed), and gap 2 between bands 7 and 8 (points). The inset shows the electric field of a mode propagating through a linear defect in the lattice for a frequency $\omega a/2\pi c = 0.287$ belonging to the band gap.

Our aim is to obtain a reduction in light propagation speed, which should remain constant for a wide range of frequencies. Since $v_g = \partial\omega/\partial k$ i.e. the slope of the dispersion curve, this yields that the dispersion diagram shall present a linear zone (constant v_g) called flat band (Fig. 3). Waveguide structures with triangular lattice have been intensively studied in previous works and are known to provide wide flat bands naturally [18,19,4,20,21]; we will employ a 45° rotated square lattice to achieve the same goal.

3. Results and discussion

In order to quantify and compare the slow light properties of different structures, the normalized delay-bandwidth product is employed.

Chromatic dispersion plays an important role in the propagation of optical pulses because its spectral components travel at different velocities (given by $c/n(\omega)$) which produces a deformation of the pulse. In order to account mathematically the effects of dispersion several parameters are defined after expanding the mode propagation constant in a Taylor series [22]:

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c}\left(n + \omega\frac{dn}{d\omega}\right) \tag{1}$$

$$\beta_2 = \frac{d\beta_1}{\omega} = \frac{1}{c}\left(2\frac{dn}{d\omega} + \omega\frac{d^2n}{d\omega^2}\right) \tag{2}$$

where n_g is the group index, v_g is the group velocity and β_2 is the group velocity dispersion (GVD) parameter. The envelope of an optical pulse will travel at the group velocity $v_g = c/n_g$ and β_2 is the dispersion of that measurement, responsible for the pulse broadening. Constant v_g requires constant n_g, or the GVD β_2 will be zero when n_g is constant (Eqs. (1) and (2)), so it is clear from the previous statements that the design objective is to obtain a so-called U-shaped n_g curve.

We performed our study in two steps:

- First we took a fixed MF concentration of 1% and calculated the projected band dispersion diagrams for different inner radius of the rods, looking for the optimal ring thickness.
- Given the optimal ring, a new set of simulations is performed, sweeping along different MF concentrations and testing the tunability characteristics of the structure.