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Tunable flat band slow light in reconfigurable photonic crystal waveguides based on magnetic fluids

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ABSTRACT

A kind of two-dimensional photonic crystal line-defect waveguide with 45°-rotated square lattice is proposed to present slow light phenomena. Infiltrating the photonic crystal waveguide with appropriate magnetic fluids can generate very wide flat bands of guided modes, which give rise to the excellent slow light properties. The bandwidth centered at $\lambda_0=1550$ nm of the designed W1 waveguide is considerably large (around 54 nm). The obtained group velocity dispersion β_2 within the bandwidth is ultralow (varying from $-2118a/2\pi c^2$ to $1845a/2\pi c^2$, where a and c are the period of the lattice and the light speed in vacuum, respectively). Simultaneously, the normalized delay-bandwidth product is relatively large compared with other works. Reconfiguring the photonic crystal waveguide with magnetic fluids of different concentrations can remarkably tune the slow light parameters and the trade-off between them, while the type of magnetic nanoparticles constituting the magnetic fluids negligibly affect the slow light properties. The explicit linear variation of the slow light parameters with the magnetic fluid concentration is convenient for the practical tuning.

1. Introduction

Slow light can be exploited for the fundamental physics research and a broad range of optical applications, such as optical delay lines or buffers, signal processing, optical switch, and light–matter interaction [1–6]. The conventional slow light techniques based on the electromagnetically induced transparency (EIT) effect in atomic systems and coherent population oscillation (CPO) effect in solid-state systems have the intrinsic disadvantages of operation at specific wavelengths, very narrow bandwidths, and cumbersome systems [7–11]. In view of the booming development and versatility of photonic crystals (PCs), a lot of work have contributed to slowing light with PC structures, which have the advantages of easily changing the desirable operation wavelengths and enabling the on-chip photonic integration [1,4,12–16].

To increase the bandwidth and decrease the group velocity dispersion (GVD) of slow light within the PC dispersive microstructures, chirping and adjusting the structures are employed. Chirping structures may incur the fabrication complexity and accuracy reduction [17,18]. Therefore, much work have focused on trimming the structures, such as changing the hole/rod sizes, positions or shapes (e.g. annular rings, sandglass-shaped holes) near the waveguide region [19–24]. The ultimate aim is to achieve the relatively flat bands of the line-defect modes through dispersion engineering. This technique requires fabricating out different devices to present different slow light performance. If liquids are utilized as the constitutive materials of the PC structures, changing slow light performance with a single device can be realized by replacing the liquids. This one-device technique based on the reconfigurable PC structures is favorable for pragmatic applications from the fabrication and online tunability point of view. It is also significant to the microfluidic PC devices and circuits [25,26].

Casas-Bedoya et al. have successfully demonstrated optimizing and tuning the slow light properties by selectively and controllably infiltrating the holes near the PC line-defect waveguide with different liquids in 2012 [27–29]. Recently, magnetic fluids (MFs) as plain colloidal materials in magnetics get renewed and extensive interests in optics with the increasing development of optical communications, optical sensing and nanoscience and technology [30–39]. We have proposed to achieve the extremely large bandwidth and ultralow-dispersion slow light in PC waveguides with MFs as the background [40]. The magnetic-field-dependent refractive indices of MFs are used to finely tune the slow light properties. In this work, MFs with different concentrations and magnetic nanoparticle types are proposed as the infiltration

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liquids for the reconfigurable PC waveguides. The MFs infiltrate across the whole structures, so it avoids needing elaborate positioning in submicron precision for the selective and controllable infiltration technique. Flat bands are found with the designed structures and excellent and tunable slow light properties can be obtained.

2. Model and waveguide design

To design the slow light structures through simulations, the magnetic-nanoparticle-type- and concentration-dependent refractive indices of MFs are extracted from Ref. [41] and listed in Table 1 (ambient temperature T=24.3 °C). Herein, the magnetic nanoparticles within the MFs are $CoFe_2O_4$, $MnFe_2O_4$, and Fe_3O_4, respectively. The carrier liquid is water. The magnetic nanoparticle volume fraction concentrations within the MFs are 0.25%, 0.5%, 1%, 1.5%, and 1.75%, respectively.

To effectively confine the line-defect modes in the waveguide region, it is desirable to design a corresponding perfect PC structure with a relatively large bandgap. A kind of two-dimensional PC with arrayed silicon columns in square lattice and MFs infiltrated into the interstitial regions is designed (see the inset of Fig. 1). Using the standard plane-wave expansion method, we find that the perfect PC have a considerable bandgap for TE modes (electrical field parallels the silicon columns) when $r=0.25a$ (where r and a are the radius and period of the arrayed columns, respectively). Fig. 1 shows the typical band diagram for the TE modes when $r=0.25a$ and the refractive index of MF (n_{MF}) set at a moderate value (1.4155 for $MnFe_2O_4$ MF with magnetic nanoparticle volume faction of 1%).

Table 1
Refractive indices of three kinds of magnetic fluids with magnetic nanoparticles of $CoFe_2O_4$, $MnFe_2O_4$, and Fe_3O_4, respectively [41]. The concentrations of magnetic nanoparticle in volume faction are: 0.25%, 0.5%, 1%, 1.5%, and 1.75%, respectively.

Type of magnetic nanoparticle	Concentration (magnetic nanoparticle in volume fraction)				
	0.25%	0.5%	1%	1.5%	1.75%
$CoFe_2O_4$	1.3506	1.3725	1.4164	1.4603	1.4822
$MnFe_2O_4$	1.3496	1.3721	1.4155	1.4594	1.4804
Fe_3O_4	1.3477	1.3697	1.4136	1.4575	1.4794

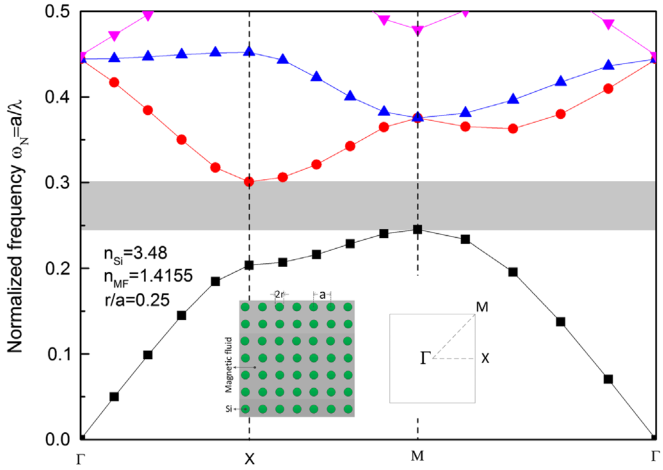

Fig. 1. Band structures for the TE modes of the designed perfect photonic crystal when $r=0.25a$ and $n_{MF}=1.4155$ ($MnFe_2O_4$ magnetic fluid with 1% magnetic nanoparticle volume fraction). The shadow region denotes the forbidden band and the insets show schematically the structure in the real space and the first Brillouin zone in the wave-vector space.

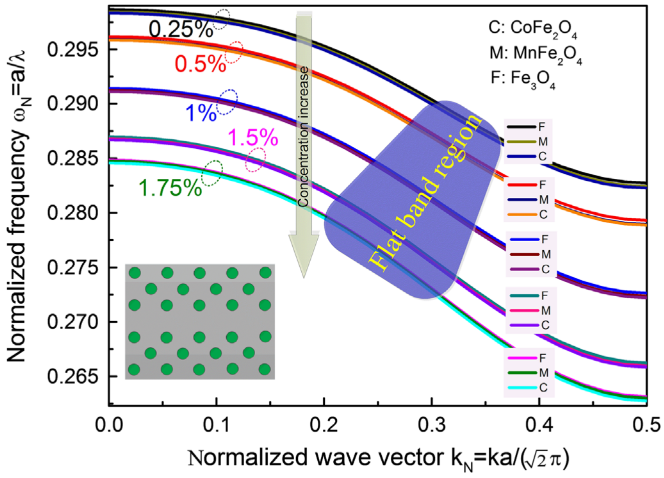

Fig. 2. Projected band dispersion diagrams of the photonic crystal waveguide infiltrated with MFs of different magnetic nanoparticles and volume fractions. The inset shows schematically the line-defect waveguide within the two-dimensional photonic crystal with 45°-rotated square lattice.

Therein, the refractive index of integrated-photonics-compatible silicon is set at $n_{Si}=3.48$. The ordinate in Fig. 1 denotes frequency, which has been normalized to $2\pi c/a$ (c is the light speed in vacuum) and equals a/λ, i.e. $\omega_N=\omega a/(2\pi c)=a/\lambda$. The solid lines in Fig. 1 are the bands of PC bulk modes and the shaded region is the bandgap. It is clear from Fig. 1 that the designed PC exhibits a large TE bandgap in the range $0.2453<\omega_N<0.3009$ with a gap ratio (defined as the width of the full forbidden band to its central frequency) of 20.4%.

Removing a row of columns along the propagation direction will form the PC line-defect waveguide (also called W1 waveguide). The line-defect state modes created within the bandgap of the corresponding perfect PC may present the slow light phenomena. Comparing with the intensively investigated PC waveguide structures with triangular lattice, we use 45°-rotated square lattice to support the PC waveguide (see the inset of Fig. 2), which is found to be capable of producing wide flat bands naturally (without needing further trimming the structures). Reconfiguring the slow light structures through infiltration with MFs of different magnetic nanoparticle types and volume fractions may change the guided modes of the line-defect waveguide and then the slow light properties.

3. Results and discussion

The projected band dispersion diagrams of the designed PC waveguide infiltrated with MFs of different magnetic nanoparticles and volume fractions are calculated using the data in Table 1. The results are depicted in Fig. 2, where the wave vector has been normalized to $\sqrt{2}\pi/a$, i.e. $k_N=ka/(\sqrt{2}\pi)$. It is obvious from Fig. 2 that there are wide regions of nearly constant slope of the waveguide mode dispersion curves, which is called the flat band as indicated in Fig. 2. In the flat band regions, the GVD of the waveguide modes will be very low and then gives rise to the ultralow-dispersion slow light.

Fig. 2 implies that the dispersion curves shift to low frequency with the increasing magnetic nanoparticle concentration, which is contributed to the increased refractive index of MF with the magnetic nanoparticle concentration. However, the type of magnetic nanoparticle has very slight influence on the dispersion curves. This is due to the refractive index of MF having much weaker dependence on magnetic nanoparticle type than on the concentration.