Slow light in a dielectric waveguide with negative-refractive-index photonic crystal cladding

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Abstract: A slow light waveguide made of a dielectric slab inserted in a two-dimensional photonic crystal with a negative effective refractive index is proposed and numerically studied. The waveguide may possess modes with zero group velocity, and its frequency varies with the thickness of the waveguide. A linearly tapered left-handed photonic crystal waveguide is also proposed and studied. It is shown that the so-called 'trapped rainbow' proposed by Tsakmakidis, Boardman, and Hess [1] is difficult to realize due to a coupling of forward- and backward-propagating modes near zero group velocity. However, different frequency components of a broadband excitation can still be separated through partial accumulation at waveguide sections of different thicknesses.

OCIS codes: (260.2110) Physical optics; (230.7400) Waveguides, slab; (130.2790) Guided waves

References and links

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#96652 - $15.00 USD Received 27 May 2008; revised 3 Jul 2008; accepted 4 Jul 2008; published 9 Jul 2008

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1. Introduction

Slow light structures have attracted much attention recently since they may offer solutions to many potential applications such as optical delay lines, enhanced light-matter interaction, etc. Various methods/structures such as electromagnetically induced transparency [2], direct-coupled resonators [3] and photonic crystal waveguides [4-6] have been proposed to slow down the group velocity of light. Recently, slow light waveguides composed of left-handed materials (LHMs; with simultaneously negative permittivity and permeability) and normal dielectric medium have been proposed [7-9]. In these waveguides, the time average power in the LHM layer flows in an opposite direction of that in the normal dielectric layer. For the case when they are almost equal, slow light can be achieved. The frequency of the slow light regime varies with the thickness of the LHM layer. In our previous work [8], we have proposed an LHM waveguide to slow down and even trap the light. A similar structure is used to achieve a so-called ‘trapped rainbow’ [1] (as different frequency components of light may be trapped at waveguide sections of different thicknesses). However, the LHMs used in these waveguides are always lossy [10] and it is very difficult to fabricate an isotropic LHM at a given optical frequency. The attenuation of the slow light will be much larger because of the enhancement of the interaction between the guided light and the lossy materials. Surface roughness issues are common for both LHMs [11] or photonic crystal structures [12] and they may increase the scattering losses.

A dielectric photonic crystal (PC) may also be left-handed and can have an isotropic negative effective index (see e.g. [13]). For a beam launched obliquely on the interface of a left-handed PC, the energy in the PC may flow backward along the surface [14]. In the present paper, we will show that slow light can also be achieved in a waveguide composed of a dielectric layer and some left-handed photonic crystal (LHPC). In this way we can avoid the problems of loss and fabrication difficulty of the LHM. To the best of our knowledge, this is the first time report on a slow light waveguide based on an LH PC.

2. Design and analysis of slow light waveguides

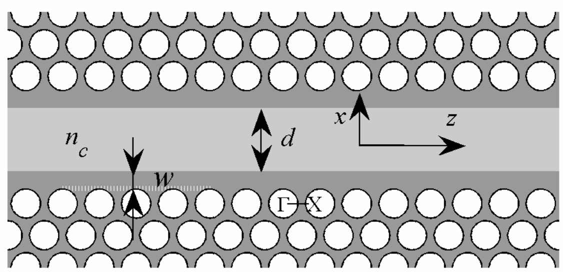

Fig. 1 Schematic diagram of the proposed left-handed photonic crystal waveguide.

The two-dimensional LHPC waveguide structure we consider in the present paper is illustrated in Fig. 1. In our simulation, the waveguide consists of a dielectric (n_c=1.5, a typical value for e.g. polymer) slab (with width d) inserted along the Γ-X direction in a hexagonal air-hole dielectric PC structure. The dielectric has refractive index n=3.6, a typical value for, e.g. GaAs. The radius of air holes of the PC is 0.4a (a is the lattice constant). The width of each flat margin from the air hole edges to the dielectric slab surface is w. In all our numerical examples, we choose (for convenience) the total thickness of the waveguides as $d+2w=2.464a$, which corresponds to the removal of 3 rows of air holes in the PC structure before the insertion of a dielectric slab of lower index. For TE polarization (i.e., the electric field is perpendicular to the 2D plane), the PC structure is similar to an isotropic medium with a negative effective index n_{eff} varying from –1.2 to –0.2 in a frequency window ranging

#96652 - $15.00 USD Received 27 May 2008; revised 3 Jul 2008; accepted 4 Jul 2008; published 9 Jul 2008

from 0.29(2πc/*a*) to 0.345(2πc/*a*), as shown in [13]. For the reflection (at a PC boundary) of a plane wave with a frequency above 0.333(2πc/*a*), the PC boundary is more like a grating than a uniform medium. This is because more than one plane wave can be diffracted back into the core layer. Thus, for simplicity we only study below the guided modes with frequencies between 0.29(2πc/*a*) to 0.33 (2πc/*a*).

We analyze the LHPC waveguide using some interface boundary conditions [15]. Assuming a plane wave in the core layer has a propagation constant β in z direction, the transverse propagation constant in the core can be calculated by $\kappa_x = [(n_c\omega/c)^2 - \beta^2]^{1/2}$. For a guide mode, the following self-consistent condition must be satisfied:

$$r_1 r_2 e^{2i\kappa_x d} = 1, \tag{1}$$

where r_1 and r_2 are the reflection coefficients for the two core-PC interfaces and they are calculated by the layer-KKR method [16]. By solving Eq. (1), we can obtain the dispersion curves for the LHPC waveguide.

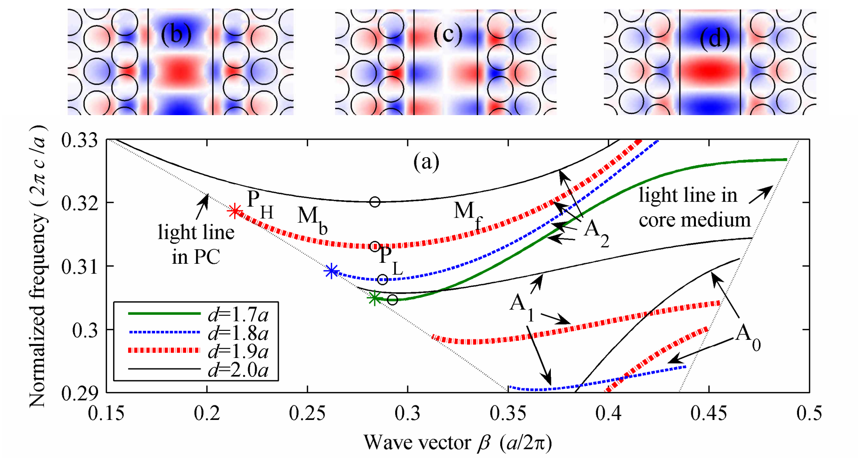

Fig. 2. (a). Dispersion curves for oscillatory modes in LHPC waveguides of different thickness *d*. The total thickness of the waveguide is fixed as *d*+2*w* =2.464*a*. The two dotted lines correspond to the light line in the PC and the light line in the core medium. Backward modes and forward modes of A_2 are denoted by M_b and M_f, respectively. Circle point P_L indicates the low cut-off frequency of mode A_2, and asterisk point P_H indicates the high cut-off frequency of backward mode on A_2. (b)-(d) Distributions of electric field for modes A_2, A_1 and A_0, respectively, when *d*=1.9*a*.

Figure 2(a) shows the dispersion curves of some oscillatory modes ($\beta < n_c\omega/c$) in LHPC waveguides with *d*=1.7*a*, 1.8*a*, 1.9*a* and 2.0*a*. We put these modes into different mode categories of A_0, A_1 and A_2. Backward modes and forward modes of A_2 are denoted by M_b and M_f, respectively. The circle point P_L in Fig. 2(a) corresponds to the low cut-off frequency of mode A_2, and the asterisk point P_H corresponds to the high cut-off frequency. For *d*=1.7*a*, the waveguide is of single mode (only mode A_2 exists) within the considered frequency window from 0.29(2πc/*a*) to 0.33(2πc/*a*). As the core thickness d increases, the mode A_2 blue-shifts and a new low order mode A_1 already appears when *d*=1.8*a*. For *d*=1.9*a* and 2.0*a*, three modes A_2, A_1 and A_0 exist in the LHPC waveguide.

Figures 2(b)-2(d) show the field patterns for modes A_2-A_0, respectively, when d = 1.9*a*. Modes A_0 are even modes and exhibit similar field pattern in the core layer as that of the fundamental mode in a standard dielectric waveguide, but have large group velocities. Modes A_1 are odd modes, which means they are difficult to couple to a single mode dielectric waveguide due to the symmetry mismatch. Therefore, we concentrate on even modes A_2.

#96652 - $15.00 USD Received 27 May 2008; revised 3 Jul 2008; accepted 4 Jul 2008; published 9 Jul 2008

The group velocity of a guided mode can be calculated by $v_g = \partial\omega/\partial\beta \approx \Delta\omega/\Delta\beta$. Figure 3(a) shows the group velocities of the corresponding modes A_2 in Fig. 2(a). When the energy of a guided mode mainly flows in the LHPC regions [see the field intensity distribution of mode M_b in Fig. 3(b) for d= 1.9a], the group velocity (i.e., the total time average energy flux of the guided mode) is antiparallel to the phase velocity of the guided mode. The group velocity is thus negative (assuming the phase velocity is positive) and the guided wave has been called backward wave. While for forward modes M_f, the energy mainly flows in the core layer [see the field intensity distribution of mode M_f in Fig. 3(c)], and the total time average energy flux in the waveguide is parallel to the phase velocity. As a result, the mode has a positive group velocity. Backward modes and forward modes are degenerated at the low cut-off frequency point P_L [see Fig. 2(a) and Fig. 3(a)]. Close to such a cut-off condition, the time average energy flux of modes in the core layer almost equals that in the claddings. Thus, the group velocities of these modes are very small. The mode (M_s) at the low cut-off frequency point has a zero group velocity.

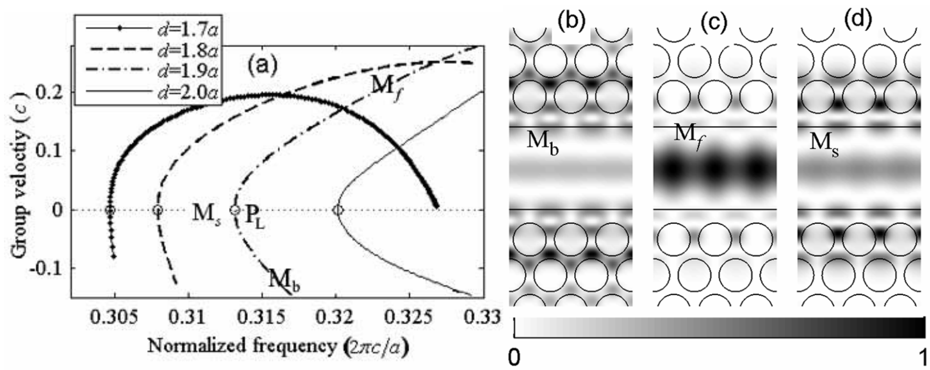

Fig. 3(a) Group velocities for modes A_2 for the four waveguides in Fig. 2(a). Circle point P_L corresponds to the low cut-off frequency. Modes at P_L have a zero group velocity, and are denoted by M_s. Backward modes and forward modes are denoted by M_b and M_f, respectively. (b)-(d) Light intensity patterns of modes (b) M_b, (c) M_f and (d) M_s for the LHPC waveguide with d= 1.9a.

3. Analysis of the tapered waveguide

From Fig. 3(a), one can see that the frequency of the guided mode with zero group velocity varies with thickness d of the LHPC waveguide. Below we study a core-tapered waveguide structure illustrated in Fig. 4(a) (the total thickness is fixed to $d + 2w = 2.464a$). The length of the linearly tapered waveguide is L=31a. The width of the dielectric core at two ports P_a and P_b are d=1.8a and d=2.0a. Two uniform normal waveguides W_1 and W_2 are used as the input and output waveguides; see Fig. 4(a). For waves with a normalized frequency above 0.31(2πc/a) (launched from W_1), only forward mode A_2 can be excited in entrance P_a since the LHPC waveguide with d=1.8a supports single-mode operation when the frequency is above the high cut-off frequency [about 0.309(2πc/a)] for backward modes [see Fig. 2(a) and Fig. 3(a)].

We study the slow propagation of a pulse in the above core-tapered structure by using 2D finite difference time domain (FDTD) method. The spatial increment of the computation is 0.01a. A Gaussian pulse (pulse width $c\Delta t$=100a) with center normalized frequency f_c=0.315(2πc/a) has been launched from input waveguide W_1. The spatial distributions of light intensity ($|E_y|^2$) in the waveguide at different times (frames) are shown in Fig. 4(b). The time interval between every two frames is Δt=40a/c. The pulse is gradually slowed down and compressed when it propagates along the tapered structure. As it approaches the critical thickness, the pulse is localized (stopped). However, the pulse begins to propagate backward after standing for a while [a few time frames; see Fig. 4(b)] instead of being trapped forever in

#96652 - $15.00 USD Received 27 May 2008; revised 3 Jul 2008; accepted 4 Jul 2008; published 9 Jul 2008

the tapered structure as described in Ref. [1]. We attribute such a “bounce back” phenomenon to the coupling between the backward modes and forward modes near the low cut-off frequency point, where the two modes have similar phase velocities and mode profiles (and are thus easy to couple to each other) but opposite group velocities. At the position with critical thickness, the forward wave gradually couples back and becomes a backward wave. Thus, the pulse propagates backward until it reaches the high cut-off frequency point P_H of the backward mode. Then the backward pulse is partly reflected to the forward direction and in the mean time some energy lost to radiation leakage into the cladding region, because the total internal reflection condition is no longer satisfied above this cut-off frequency point P_H. This reflected pulse couples back again at the position with critical thickness, and such a process repeats and gives the pattern of time frames in Fig. 4(b). This shows that it is not easy to realize the so-called ‘trapped rainbow’ [1] due to the above “gradual back coupling” phenomenon.

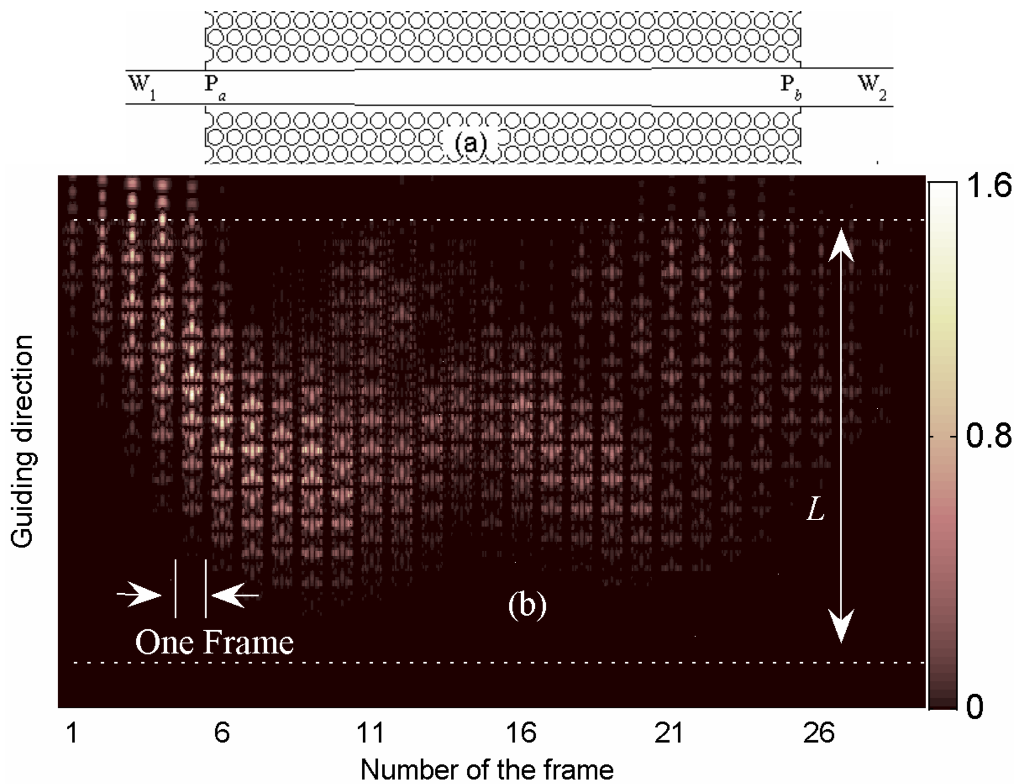

Fig. 4. (a). Schematic diagram of a tapered LHPC structure with length L=31a. The width of the dielectric core is d=1.8a at entrance P_a and d=2.0a at exit P_b. The light is launched from the uniform input waveguide W_1. (b) Spatial distributions of light intensity for a pulse propagating in the tapered LHPC structure. Time interval for every two frames is Δt=40a/c.

Nevertheless, interestingly we found that different frequency components of light can still be partially accumulated at waveguide sections of different thicknesses. Figures 5(a)-5(d) show the FEM (finite element method) simulation results for the electric field distributions in the tapered structure when light is launched from input waveguide W_1 at normalized frequency of 0.312(2πc/a), 0.314(2πc/a), 0.316(2πc/a) and 0.318(2πc/a), respectively. Around the critical thickness, the amplitudes of the light are about 3-4 times larger than those in the input waveguide W_1. They may be higher if the radiation leakage could be reduced. In

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other words, the tapered structure can still separate the light of different frequencies with their centers of distribution at different positions, however, with low efficiency.

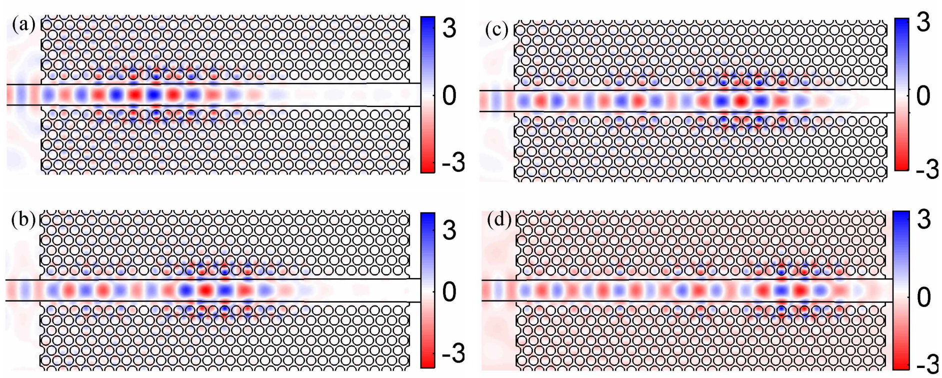

Fig. 5. Spatial field distributions in the tapered structure for light launched from W_1 at normalized frequency of (a) f=0.312(2πc/a), (b) f=0.314(2πc/a), (c) f=0.316(2πc/a) and (d) f=0.318(2πc/a).

4. Conclusion

In the present paper, we have analyzed a two-dimensional slow light waveguide of a normal dielectric slab cladded with a left-handed photonic crystal. The physical mechanism for the slow light in the LHPC waveguide relies on the exchange of power between the core and cladding layers (unlike slow light waveguides of photonic bandgap type [4-6]). The dispersion relationship of the guided modes has been numerically studied. The frequency for the mode with zero group velocity varies with the thickness of the waveguide. A linearly tapered LHPC waveguide has also been proposed and studied. Our numerical analysis has shown that the propagation of the light in the tapered structure will be coupled to a backward wave when it reaches the critical thickness due to the degeneration of the backward and forward modes at the critical thickness. Thus, it is not easy to realize the so-called 'trapped rainbow' 1 due to the "gradual back coupling" phenomenon. Our additional numerical analyses have shown that a similar phenomenon can also been observed in an LHM tapered waveguide. Nevertheless, one can still separate the light of different frequencies with their centers of distribution partially accumulated at different positions. Like a conventional dielectric waveguide, the guide modes in the present LHPC waveguide are confined by the total internal reflection between two media with isotropic effective indices (instead of photonic bandgap in other PC waveguides). Consequently, the present LHPC waveguide can have similar mode profiles as conventional dielectric waveguides and are easier to couple to a dielectric waveguide. The present slow light waveguide can also avoid the serious problems of loss and fabrication difficulty that an LHM waveguide has.

Acknowledgments

This work is partially supported by grants from the Provincial Education Office of Zhejiang, from Jiliang University, the National Basic Research Program (No.2004CB719800) and the Natural Science Foundation of China (No. 60576042).