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2003 J. Phys.: Condens. Matter 15 6731

(http://iopscience.iop.org/0953-8984/15/40/010)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **15** (2003) 6731–6737 PII: S0953-8984(03)65470-6

Tunability of photonic crystals based on the Faraday effect

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Received 30 June 2003
Published 26 September 2003
Online at stacks.iop.org/JPhysCM/15/6731

Abstract

We show theoretically that the photonic band structures of photonic crystals (PhCs) with constituent materials containing free carriers can be tuned by an external magnetic field in the frequency range below the far infrared region. We take one-dimensional PhCs consisting of an intrinsic InSb layer and an air layer stacked alternately as an example in studying photonic band structures and transmissive properties within the magnetic field.

1. Introduction

In the past decade, there has been a great deal of interest in photonic crystals (PhCs) in which the dielectric constituents are periodically arranged [1, 2]. Due to the introduced periodicity, multiple Bragg scatterings from each unit cell may open a photonic bandgap (PBG), analogous to the electronic bandgap in semiconductors, within which the propagation of electromagnetic (EM) waves is completely forbidden. PhCs are optical materials of a new kind, which have important applications.

For conventional PhCs, the photonic band structures (PBSs) remain fixed once the PhCs have been fabricated. Recently, there has been considerable interest in tunable PhCs, whose PBSs can be tuned by some external parameters [3–14]. The possibility of tuning PBSs externally will significantly enhance the range of applications of PhCs. It has been demonstrated theoretically and experimentally that PhCs with liquid crystal infiltration exhibit tunability on applying an external electric field [3–5] or changing the temperature [8, 9, 14]. If the constituent materials of PhCs have magnetic permeabilities dependent on the external magnetic field, the PBSs can then be altered by changing the magnetic field [6, 7]. PBSs can be also tuned by means of the temperature for PhCs with semiconductor constituents [10, 11]

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0953-8984/03/406731+07$30.00

or by means of the strain for ones with piezoelectric constituents [12]. One of the advantages of using an electric or magnetic field to tune PBSs is that the response is much faster than that induced by changing the temperature or strain.

In this paper, we will demonstrate another possibility: that of tuning the PBSs of PhCs with semiconductor constituents by using an external magnetic field. The situation is different from the case where the constituent material has magnetic permeability dependent on a magnetic field [6, 7]. The idea is based on the fact that when a material with free carriers is placed in the magnetic field, its dielectric constant will be modified [15, 16]. We take 1D PhCs as an example in showing that PBSs can be tuned by using the external magnetic field.

The outline of this paper is as follows. In section 2, we will discuss the dielectric constant for semiconductors in a magnetic field. Results and discussion are given in section 3. Finally we summarize our results in section 4.

2. Dielectric constants of semiconductors in a magnetic field

As a first approximation, neglecting absorption (to be discussed later on), for frequencies below the far infrared resonance region, the dielectric constant of a semiconductor is given by [17]

$$\varepsilon(\omega) = \varepsilon_0\left(1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2}\right), \tag{1}$$

where ε_0 is the static (background) dielectric constant and ω_{p} is the screened plasma frequency. The plasma frequency depends on the densities n and effective masses m^* of the free carriers, given by [17]

$$\omega_{\mathrm{p}}^2 = \sum_i \frac{4\pi n_i e^2}{m_i^* \varepsilon_0}, \tag{2}$$

where the subscript i stands for the relevant conducting or valence band of free electrons and holes and e is the charge. For frequencies substantially above the phonon resonance, ε_0 in the above equations should be replaced by the optical dielectric constant ε_∞.

As a semiconductor with free carriers is placed in an external magnetic field, its dielectric constant will be modified owing to the magneto-optic effects [16]. In this paper we consider the Faraday configuration only; i.e., the external magnetic field is parallel to the propagation direction. For this configuration, the eigenstates are either left- or right-circularly polarized EM waves. For the two counter-rotating modes, they have different responses to the external magnetic field, leading to different dielectric constants, given by [16]

$$\varepsilon_\pm(\omega) = \varepsilon_0\left(1 - \frac{\omega_{\mathrm{p}}^2}{\omega(\omega \mp \omega_{\mathrm{c}})}\right), \tag{3}$$

where the subscripts + and − stand for right-circular polarization (RCP) and left-circular polarization (LCP), respectively. $\omega_{\mathrm{c}} = eB/m^*c$ is the cyclotron frequency in CGS units, where B is the magnetic field and c is the speed of light in vacuum.

The dielectric constant for semiconductors within a magnetic field is given in figure 1. In the displayed frequency range, for a given frequency, the dielectric constant for RCP (LCP) is smaller (larger) than that without the magnetic field. For a given frequency, the dielectric constant for RCP (LCP) decreases (increases) with the cyclotron frequency—in other words, with the magnetic field, since the cyclotron frequency is linearly proportional to the magnetic field. Just above the plasma frequency the modification of the dielectric constants for RCP and LCP by the magnetic field is considerable. Well above ω_{p}, however, the modification is small. It is known that in the optical and near infrared regime the modification of the

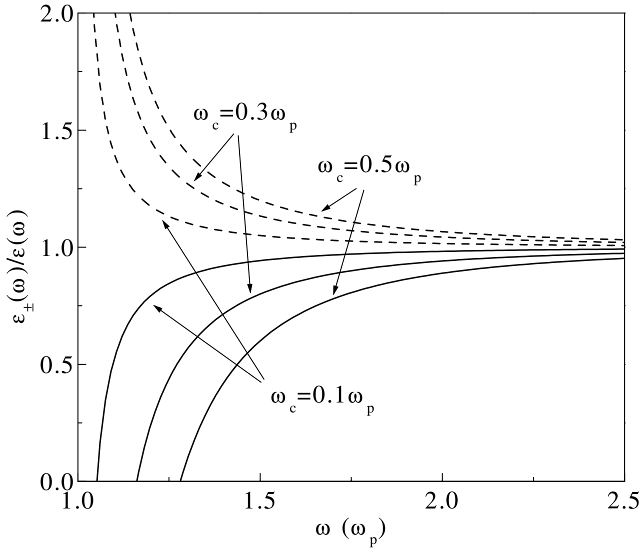

Figure 1. Ratios of the dielectric constants for RCP (solid curves) and LCP (dashed curves) to that without the magnetic field.

dielectric constant by the magnetic field is rather weak. However, below the far infrared, the modification is significant. If one of the constituents of the PhCs is semiconductor, their PBSs are expected to be tunable since the dielectric constant varies with the magnetic field. Although our discussions in this paper are devoted to 1D PhCs, the idea of tuning PBSs by using the magnetic field can be also applied to 2D and 3D PhCs.

3. Results and discussion

In order to illustrate the ideas discussed above, we consider 1D PhCs consisting of two layers stacked alternately. The first constituent layer is an intrinsic semiconductor, specifically InSb, and the second layer is air. The static dielectric constant and effective mass of InSb are taken to be $\varepsilon_0 = 17.7$ and $m^*/m = 0.015$ [17]. For InSb, the narrow bandgap gives rise to the plasma frequency $\omega_\mathrm{p} = 1.6 \times 10^{13}$ Hz at room temperature [10]. The transfer matrix method [18, 19] is used in the present work to calculate the PBSs and the transmission of 1D PhCs.

Figure 2 shows the PBSs of a 1D PhC placed in an external magnetic field, calculated by the transfer matrix method. Without the magnetic field the PBSs for LCP and RCP should be degenerate. When the magnetic field is applied, the dielectric constants for LCP and RCP in the InSb layer will be modified differently, as can be seen from equation (3). As a result, the degeneracy for LCP and RCP will be lifted upon applying the magnetic field.

With increasing magnetic field, the PBS of RCP is found to be shifted systematically upwards with respect to that without a magnetic field. Low frequency modes are affected more strongly than higher ones. This can be understood from the fact that the dielectric constant of the InSb layer is less modified for higher frequencies for both LCP and RCP. On the other hand, the PBS for LCP is shifted systematically downwards. It can be seen from equation (3) that for frequencies well above the plasma frequency, the dielectric constants of LCP and RCP are almost equal. Consequently, at high frequencies, the PBSs for LCP and RCP are expected to coincide with each other.

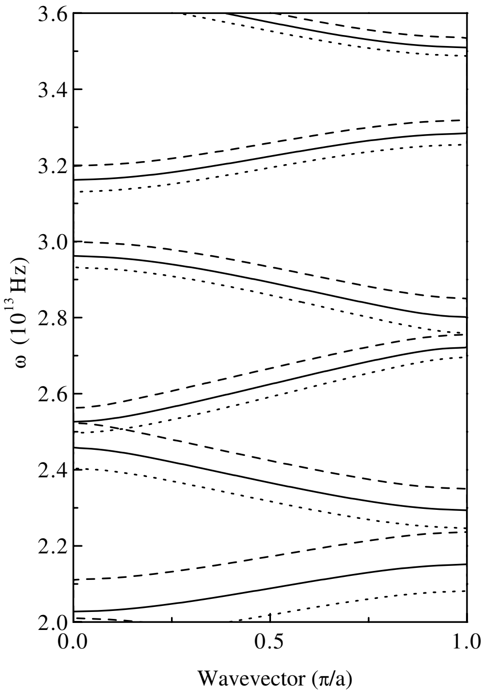

Figure 2. Calculated PBSs for the 1D PhC consisting of air and InSb layers repeating alternately. The lattice constant of the 1D PhC is $d = 120\ \mu$m. The thicknesses of the InSb and air layers are $d_{\mathrm{InSb}} = 0.4d$ and $d_{\mathrm{air}} = 0.6d$. Solid curves stand for the case without the external magnetic field. Dashed and dotted curves stand for the PBSs of RCP and LCP, in the presence of the external magnetic field of $B = 0.27$ T, respectively.

In figure 3 the variations of photonic band edges versus the magnetic field are shown. It can be seen that photonic band edges for LCP are shifted downwards almost linearly with the magnetic field, while those for RCP are shifted upwards almost linearly. Note that a linearly polarized EM wave can be decoupled as a superposition of a LCP and a RCP wave. For a linear EM wave passing through such a system, PBGs are determined by the overlapping regions of PBGs for LCP and RCP. As the magnetic field increases, the PBGs for linear EM waves decrease since the PBGs for LCP and RCP shift with the magnetic field oppositely. Consequently, a PBG for linear EM waves will finally close when the magnetic field reaches a critical value. Hence, the PBGs for LCP, RCP, and linear polarization can be tuned by adjusting the external magnetic field.

It is interesting to note the frequency range between the PBGs of LCP and RCP which are located just inside the PBG without a magnetic field. For linear EM waves within this frequency window, propagation is forbidden in the case without a magnetic field. However, when the magnetic field is applied, EM waves can be transmitted. Switching the magnetic field on or off, EM waves can pass through or are blocked. A potential application of this property is in a switching device.

When passing through the PhC within the magnetic field, waves with LCP and RCP experience different values of the dielectric constant. Therefore, EM waves with LCP and RCP emerge from the PhC with different phases and amplitudes. For a linearly polarized incident EM wave, the outgoing wave is a superposition of the two emergent circular polarization states.

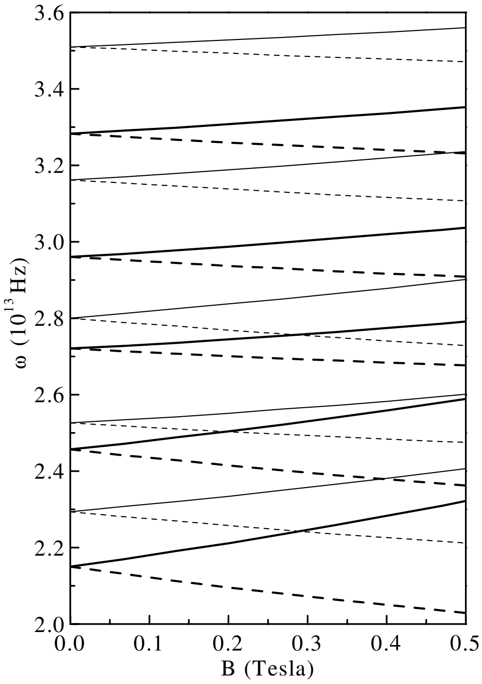

Figure 3. Calculated variations of the photonic band edges of the same 1D PhC as in figure 2 versus the magnetic field. Solid and dashed curves stand for RCP and LCP, respectively. Thick and thin curves define the lower and upper edges, respectively.

Consequently, the outgoing wave is, in general, elliptically polarized. The ellipticity η of the outgoing wave is determined by $\eta = (a_+ - a_-)/(a_+ + a_-)$, where a_+ and a_- are the amplitudes of the outgoing waves with RCP and LCP, respectively. The values of $\eta = \pm 1$ stand for the circular polarization and $\eta = 0$ for linear polarization. The other values imply elliptic polarization.

In figure 4 the transmission and the ellipticity of the outgoing EM wave for a linearly polarized incident EM wave after passing through a PhC consisting of 20 periods are given. Without the magnetic field, the transmission does not depend on the polarization of the incident EM waves. Transmissive properties, however, are dependent on the polarization when the magnetic field is applied, which can be clearly seen from the figure. Within the PBG for RCP (LCP), propagation of EM waves with RCP (LCP) is forbidden. However, EM waves with LCP (RCP) can propagate within the PBG for RCP (LCP). The PBG window for LCP (RCP) can be used to generate EM waves with RCP (LCP). Therefore, such a system can be used as circular polarizer.

As is well known, in the far infrared regime and below, absorption effects are important. The losses due to absorption can be attributed to the finite lifetimes of electrons, holes, and phonons. For frequencies well below the phonon resonance, the contribution from electrons for intrinsic InSb is dominant [10]. Therefore, the dielectric constant has a damping term due to the finite lifetime of electrons, given by

$$\varepsilon_{\pm}(\omega) = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega(\omega \mp \omega_c - i/\tau)}\right), \tag{4}$$

where τ is the scattering time for the electrons. This time can be estimated from the mobility

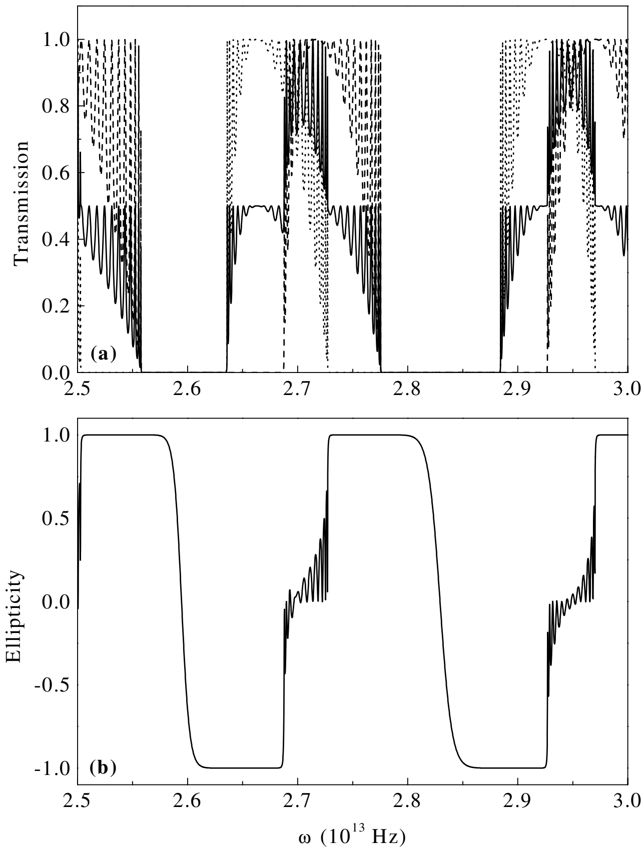

Figure 4. (a) Calculated transmission for an incident EM wave with linear polarization (solid curve), LCP (dashed curve), and RCP (dotted curve) and (b) the calculated ellipticity of the outgoing EM wave for a linearly polarized incident EM wave after passing through a InSb/air PhC consisting of 20 periods. The lattice constant of the PhC is $d = 120\ \mu$m. The thicknesses of the InSb and air layers are $d_{\mathrm{InSb}} = 0.6d$ and $d_{\mathrm{air}} = 0.4d$. The external magnetic field is $B = 0.14$ T.

of the electrons $\mu = e\tau/m^*$. For InSb the mobility is $\mu = 7.7$ m^2 V^{-1} s^{-1} [17], leading to the scattering time $\tau = 6.6 \times 10^{-13}$ s. The ratio of the imaginary part to the real part of the dielectric constant can be used as a measure of the absorption. Near the plasma frequency, this ratio is very large, indicating a strong absorption. For frequencies varying from 2.4 to 3.5×10^{13} Hz, the ratio decreases approximately from 0.05 to 0.01 in the case without a magnetic field. Therefore, in this frequency range, absorption should be small, as indicated in [10]. When the magnetic field is applied, the above conclusion is still valid since the frequencies of interest are well above the cyclotron resonance.

While the semiconductor constituent in this study is an intrinsic semiconductor, one can also use doped semiconductors. In order to suppress absorption, the mobility of the electrons of the doped semiconductor should be large.

4. Conclusions

We have shown theoretically that the PBSs of 1D PhCs with constituent materials containing free carriers can be tuned by adjusting the external magnetic field in the frequency range below the far infrared. Propagation properties are considerably modified by the magnetic field. Although the discussion given above is for 1D PhCs, we expect the PBSs of 2D [20] and 3D PhCs to also be tunable by means of an external magnetic field in a similar way, as long as one constituent contains free carriers.

Acknowledgments

This work was supported mostly by the Chinese National Key Basic Research Special Fund of the Ministry of Science and Technology. Partial support from the NSF, from the Ministry of Education, and from Shanghai Science and Technology Commission, China, is acknowledged. We thank Professor J Z Y Chen for a critical reading of the manuscript. We are grateful to Dr H Chen and Dr W Lu for interesting discussions.

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