Electromagnetic Bloch oscillation in one-dimensional multiple microcavities composed of metamaterials*

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We propose a photonic structure stacked sequentially by one-dimensional photonic crystals and cavities. The whole structure is composed of single-negative and double-negative materials. The optical Wannier–Stark ladder (WSL) can be obtained in a low frequency region by modulating the widths of the cavities in order. We simulate the dynamical behavior of the electromagnetic wave passing through the proposed photonic structure. Due to the dispersive characteristics of the metamaterials, a very narrow WSL can be obtained. The long-period electromagnetic Bloch oscillation is demonstrated theoretically to have a period on a microsecond time scale.

Keywords: Bloch oscillation, metamaterial

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1. Introduction

Bloch oscillations, which were first discussed by Zener[1] in 1934, are periodic motions of electrons that are driven by a high electric field sweeping through a Bloch band.[2] Due to the fact that the coherence time of an electronic wavepacket is much shorter than the period of the Bloch oscillation, this phenomenon was not observed until the experimental fabrication of a semiconductor superlattice in 1992.[3] Compared with the electron, the photon has many natural advantages in studying optical Bloch oscillations, such as no interactions between photons, and a much longer interference time and so on. Because of the potential application in generating a terahertz source, optical Bloch oscillations have attracted much attention both experimentally and theoretically in recent years.[4–13]

The electromagnetic Bloch oscillation was first observed in an optical superlattice based on porous silicon microcavity superlattices in 2004.[6] The experimental observation of photonic Bloch oscillations was reported in two-dimensional periodic systems two years later.[7] The photonic Bloch oscillations can also occur in curved coupled optical waveguide arrays.[14–17] Having the ability to overcome the diffraction limit, surface plasmons polaritons, which can control light in subwavelength, have made great progress in the past decade.[18,19] Researchers have also paid much attention to the plasmonic Bloch oscillations in many kinds of structures.[20–23] In addition, because a phonon has similar particle characteristics to those of an electron and photon, phonon acoustic Bloch oscillations have also been extensively studied.[24–26]

Metamaterials have received much attention recently because of their fascinating properties.[27–32] They can basically be divided into two types: one is a single-negative (SNG) material with negative permittivity or permeability, the other is a double-negative (DNG) material with negative permittivity and permeability. There are two types of SNG materials, the one with negative permittivity ($\varepsilon < 0$, $\mu > 0$) is called an epsilon-negative (ENG) material, and the one with negative permeability ($\mu < 0$, $\varepsilon > 0$) is called an mu-negative (MNG) material. Owing to their novel optical properties, plenty of one-dimensional (1D) photonic structures composed of metamaterials have been studied.[33–41]

Researchers also studied the optical Bloch oscillations in a 1D photonic structure containing SNG numerically.[42] We have proposed a 1D coupled multiple microcavities (MMCs) containing DNG material.[43] The optical WSL appears by properly modulating the widths of the cavities in the omnidirectional gap.[43] The electromagnetic Bloch oscillations have been discussed in detail. The periods of electromagnetic Bloch oscillations in Refs. [42] and [43] are on a nanosecond time scale. The periods of the photonic Bloch oscillations have been on a femtosecond,[20,22] picosecond,[4,5] and nanosecond[42,43] time scale. In this paper, we propose another 1D photonic MMCs structure which is composed of MNG and DNG materials. By increasing the widths of the cavities sequentially, photonic WSL can be obtained. An electromagnetic Bloch oscillation with a period of about several microseconds can be achieved when a Gaussian pulse passes

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through the MMC structure.

2. Theoretical model

Figure 1 shows the diagram of the photonic MMCs, which are simply stacked in sequence by 1D photonic crystals (PCs) and cavities. The PCs are alternately composed of SNG and DNG materials, respectively. The cavities are made of DNG materials. As is well known, PCs can form band gaps; and when the cavities are introduced into the PCs, there would be some transmission peaks in the gaps. The number of the peaks depends on the number of the cavities. If the intervals of the cavities are not too large, the neighboring transmission peaks can couple with each other, and a miniband (MB) appears in the band gap.

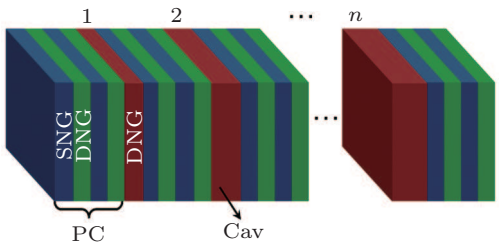


Fig. 1. (color online) Schematic representation of the photonic MMC structure. PC and Cav denote the photonic crystal and cavity, respectively. The PCs are made of SNG and DNG materials, and the cavities are composed of DNG materials.

In this study, the SNG and DNG materials are assumed to be isotropic and dispersive. Generally, they can be described by the periodically LC loaded transmission lines, and the effective permittivity ε and permeability μ are given by[34]

$$\varepsilon_{\rm A} = 3.0, \quad \mu_{\rm A} = \mu_{\rm a} - \frac{\beta}{\omega^2}, \tag{1}$$

$$\varepsilon_{\rm B} = \varepsilon_{\rm b} - \frac{\alpha}{\omega^2}, \quad \mu_{\rm B} = \mu_{\rm b} - \frac{\beta}{\omega^2}, \tag{2}$$

the frequency $f = \omega/2\pi$ is in units of gigahertz. The parameters of these materials are selected to be $\mu_{\rm a} = 1.0$, $\varepsilon_{\rm b} = 1.21$, $\mu_{\rm b} = 1.0$, and $\alpha = \beta = 100$. Figure 2 shows the optical parameters of materials versus the frequency. It can be seen that in the low frequency region, materials A and B exhibit MNG and DNG properties, respectively. Their optical parameters change rapidly in the low frequency region due to their dispersion characteristics. Therefore, these materials can produce a narrow photonic band gap in low frequency region.

In order to obtain a long-period Bloch oscillation, the frequency interval between neighboring peaks in an MB should be very small. Therefore, in order to create a narrow MB with more transmission peaks, the above dispersive metamaterials were selected as the components of the proposed photonic structure. It is necessary to obtain the optical Wannier–Stark ladder (WSL) if one wants to obtain the electromagnetic Bloch oscillation. Therefore, we should investigate the band structure first for such a photonic MMCs structure. In the following, we must tilt the band to obtain the photonic WSL. The band structures each as a function of the number of cavities is shown in Fig. 3 by the transfer matrix method.[44] The allowed and forbidden bands are denoted in white and gray areas, respectively. In Fig. 3(a), all the cavities have the same widths, and there is an MB in the band gap. The band structure does not change as the cavities number increases, and the WSL does not exist. Generally, increasing or decreasing the widths of the cavities sequentially can shift the band; here we select to increase the cavity widths in order. When the widths of the cavities are modulated properly with an index $\delta = 1.002$, i.e., $d_{n+1} = \delta d_n$, the MB moves towards the higher frequency in Fig. 3(b). It is observed that the band tilts and a WSL appears clearly.

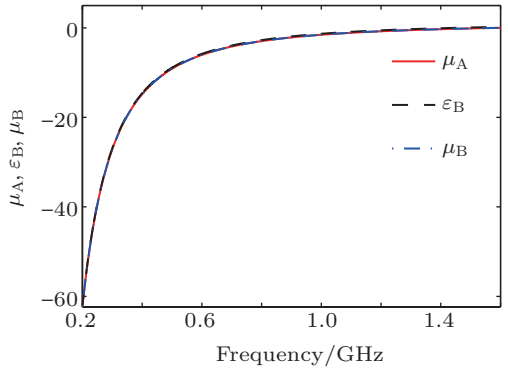


Fig. 2. (color online) Physical parameters of SNG and DNG materials each as a function of frequency. The red solid, black dashed, and blue dotted lines are $\mu_{\rm A}$, $\varepsilon_{\rm B}$, and $\mu_{\rm B}$, respectively.

As long as the WSL is obtained, the electromagnetic wave with the frequency located in the WSL can propagate. The wave within gaps would be reflected, indicating that the electromagnetic wave would oscillate in the WSL region. In order to obtain an intuitive impression, we display the spatiotemporal dynamical behavior of a Gaussian pulse rather than a monochromatic light passing through the MMCs structure. Therefore, the electromagnetic fields must be transferred from the frequency domain to the time domain. The time-dependent electric field $E(z,t)$ in the MMC structure is described in the following form:[4,5]

$$E(z,t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} {\rm e}^{-{\rm i}\omega t} E(z,\omega) g(\omega)\,{\rm d}\omega, \tag{3}$$

where $E(z,\omega)$ is the scattering state, which can also be obtained by the transfer matrix method, and $g(\omega)$ is a spectral function of the incident electromagnetic pulse, which can be written as

$$g(\omega) = \frac{1}{\sqrt{\pi}\Delta\omega}\exp\left[-\left(\frac{\omega-\omega_0}{\Delta\omega}\right)^2\right], \tag{4}$$

where $\Delta\omega$ and ω_0 are the frequency width and central frequency of the incident electromagnetic pulse, respectively. Then, the spatiotemporal evolutions of the electromagnetic waves in the MMCs can be easily obtained from Eq. (3), which is similar to the performance of Fourier transformation.

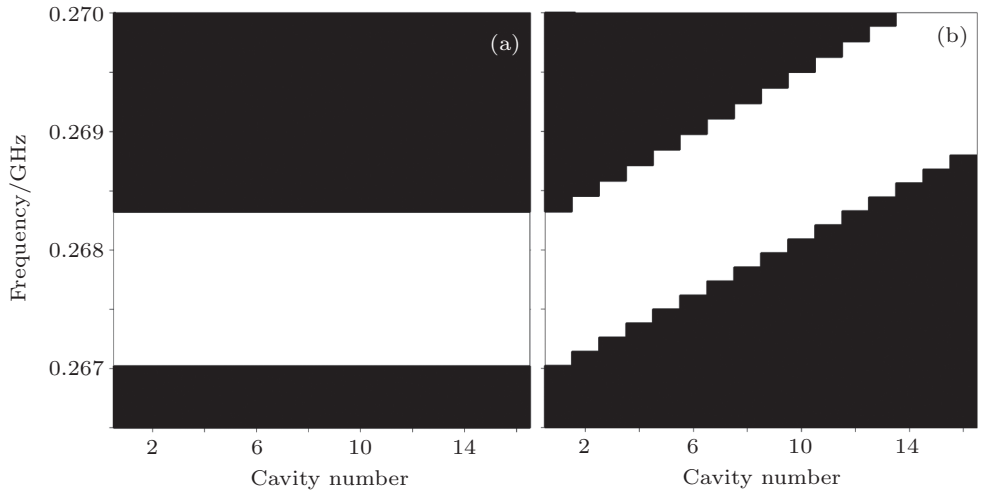


Fig. 3. Band structures of the MMCs versus the cavity number for different modulation indices: $\delta = 1.0$ (a) and 1.002 (b). The white and gray areas represent the allowed and the forbidden band, respectively.

3. Results

We concentrate on the low frequency region and materials A and B that exhibit SNG and DNG characteristics, respectively, as discussed in Section 2. In our calculation, the widths of materials A and B in PCs are 6 mm and 12 mm, respectively. The number of cavities is 16, the width of the first cavity $d_{C_1} = 12$ mm, and the widths of the other cavities can be modulated by the relation $d_{C_n} = \delta d_{C_{n-1}}$, where δ is a constant, i.e., $\delta = 1.002$.

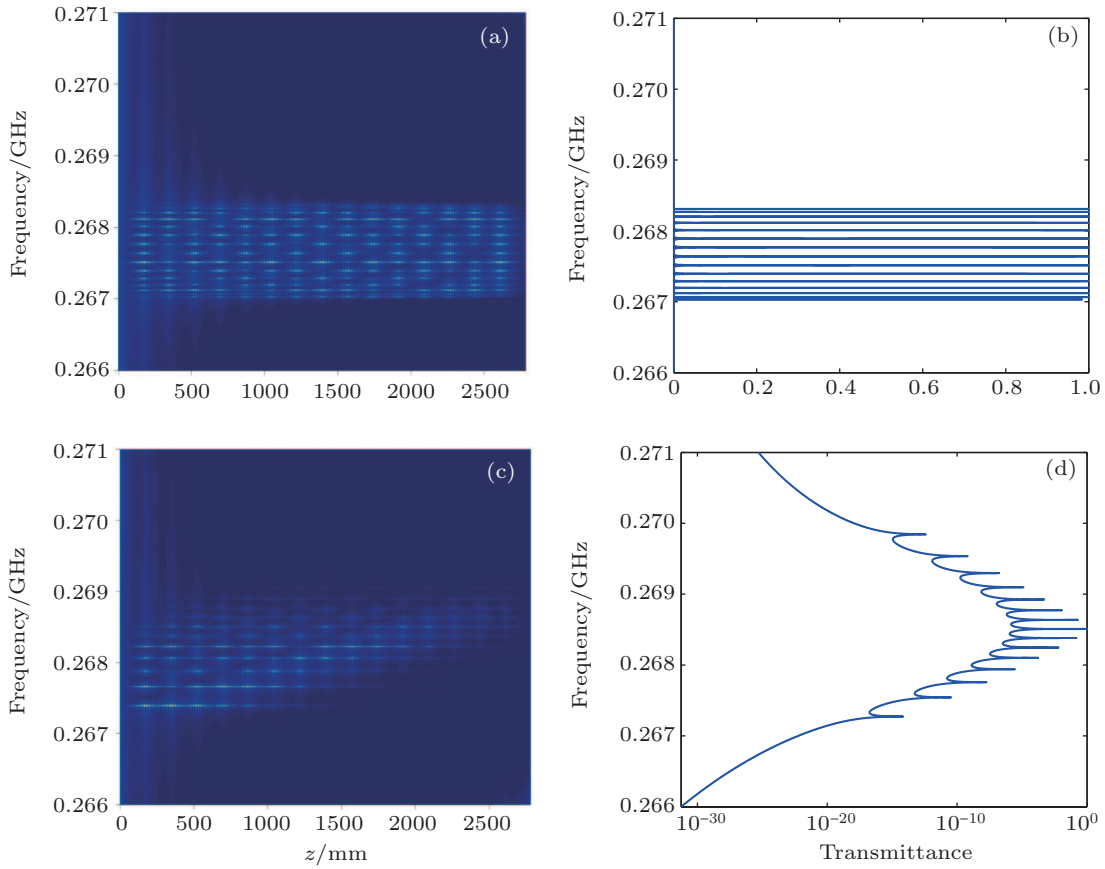


Fig. 4. (color online) Electric field intensity distributions and transmission spectra of the photonic MMCs made of SNG and DNG materials. Panels (a) and (b) show the scattering state map and transmission for modulation index $\delta = 1.0$; panels (c) and (d) display the scattering state map and transmission for modulation index $\delta = 1.002$.

Firstly, we display the scattering states in Figs. 4(a) and 4(c) with modulation indices 1.0 and 1.002, respectively. The scattering states describe the electric field distributions as a function of the frequency and the coordinate. The light and dark areas correspond to the allowed bands and band gaps, respectively. In Fig. 4(a), the allowed band whose frequency is in a range from 0.2673 GHz to 0.2681 GHz is the MB that we need. The MB contains a serial of discrete states. In Fig. 4(c), the discrete states shift towards a higher frequency, and their energies in a lower frequency region are sharply defined. The transmission spectra are shown in Figs. 4(b) and 4(d), corresponding to the scattering states. There is an MB containing 16 transmission peaks, which is equal to the number of cavities in Fig. 4(b). The interval frequency between two neighboring peaks is about 10^{-4} GHz. When the widths of cavities are modulated, the transmission spectrum in Fig. 4(d) has an apparent change compared with that in Fig. 4(b). It can be seen that the position of the MB moves towards a higher frequency. The values of side transmission peaks decrease very rapidly, while the value of the central peak almost does not change. Therefore, we can see that the MB in Fig. 4(b) becomes the WSL in Fig. 4(d). Each cell composed of a PC and a cavity contributes to the band structure. Owing to the increase of the cavity width, the band formed by each cell shifts towards a higher frequency, causing the formation of the WSL.

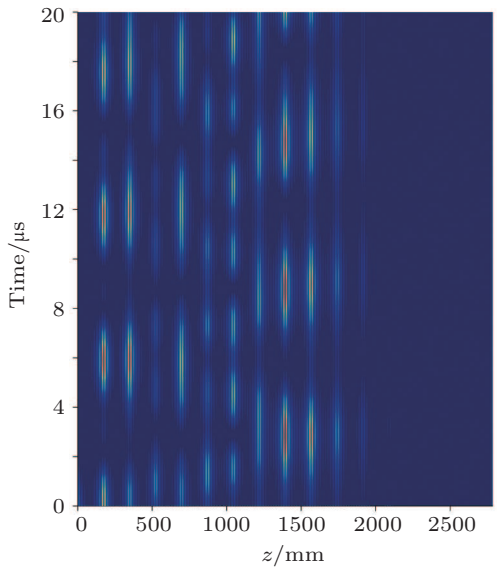


Fig. 5. (color online) Electromagnetic Bloch oscillation in the MMC structure made of DNG and SNG materials. The frequency of the incident Gaussian pulse is centered at $f_0 = 0.26815$ GHz and the width of the pulse is $\Delta f = 0.00023$ GHz. The brightness is proportional to the intensity of the electric field.

As long as we obtain the scattering states, the behavior of the spatiotemporal evolution can be easily calculated from Eq. (3). The electrical field distribution as a function of coordinate and time is plotted in Fig. 5. The electromagnetic wave is incident at the origin of the coordinate and propagates rightwards, then is reflected strongly in the MMCs after propagating through about eleven cells and propagates leftwards. The electric fields are located in the cavities rather than in the PCs regions. So we can clearly see that the electric field exhibits a periodic oscillation with a period of about 6 μs, meaning that the electromagnetic Bloch oscillation occurs. We have assumed that all the materials have no damping, thus the oscillation almost does not decay. Therefore, a long-period electromagnetic Bloch oscillation is achieved in the multiple microcavities composed of SNG and DNG materials.

Finally, due to the fact that the losses in man-made metamaterials are inevitable, we give a quantitative discussion on the influence of the losses on the electromagnetic Bloch oscillation. As is well known, the existence of losses in metamaterials will reduce the transmittance of PCs, while they do not influence the positions of transmission peaks. Therefore, the losses have no effects on the peak position nor on the width of an MB nor on the width of a WSL. The period of the electromagnetic Bloch oscillation which is determined by the width of the WSL will not change. However, the energy of the electromagnetic waves in the MMC structure would decay due to the losses, and the electromagnetic Bloch oscillation would also decay in such MMCs made of metamaterials.

4. Conclusion

In this paper, we proposed a photonic multiple microcavity structure composed of SNG and DNG materials to study the propagation behavior of electromagnetic waves. The optical WSL is obtained by modulating the widths of the cavities. The WSL can be very narrow and the frequency interval is very small for such a structure. The spatiotemporal evolution behavior of an electromagnetic wave has been simulated. Selecting the parameters of the MMCs structure properly, we first demonstrate that the period of electromagnetic Bloch oscillation can be achieved on a μs scale in theory.

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