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The Optical Bloch oscillation in chirped one-dimensional superconducting photonic crystal

Zhengren Zhang[a], Yang Long[b], Liwei Zhang[c], Pengfei Yin[a,*], Chunhua Xue[d]

[a] *School of Materials Science and Engineering, Chongqing Jiaotong University, Chongqing 400074, China*
[b] *School of Physics Sciences and Engineering, Tongji University, Shanghai 200092, China*
[c] *School of Physics and Chemistry, Henan Polytechnic University, Jiaozuo 454000, China*
[d] *School of Computer Science and Communication Engineering, Guangxi University of Science and Technology, Liuzhou, Guangxi 545006, China*

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ABSTRACT

We exploit theoretically the propagation properties of electromagnetic waves in nanoscale one-dimensional superconducting photonic crystal. The Wannier Stark ladders can be formed in the photonic crystal by varying the thickness of the dielectric layers linearly across the structure. The dynamics behavior of a Gaussian pulse transmitting through the structure is simulated theoretically. We find that photons undergo Bloch oscillations inside tilted photonic bands and the Bloch oscillations are sensitive to the change of temperature in the range of 3–8 K. It is demonstrated that our structure is possible to realize tunable optical Bloch oscillations by controlling the temperature of superconducting material.

1. Introduction

Bloch oscillations (BOs), which were proposed by Bloch in 1928, are one of the fascinating fundamental wave behaviors of quantum particles in periodic media under the action of a constant external force [1]. Due to the coherence time of electric wave packets being much shorter than the period of the BO, this fascinating physical phenomenon was not observed in conventional crystals until 1992 when it was detected experimentally in semiconductor superlattices [2]. Comparing with electrons, photons possess many advantages in studying BO, such as no interaction and longer coherence time. Hence, the research for the optical BOs has been drawn a good deal of attention in the recent years. Optical BOs have been predicted theoretically and demonstrated experimentally in many different dielectric systems [3–7], and also various applications of optical BOs have been proposed by researchers [8,9]. With respect to applications to optical devices, on the other hand, it is advantageous to obtain an optical BO in nanoscale systems. However, this phenomenon is hard to establish in nanoscale systems due to the limitation of optical diffraction effect. Therefore, some scientists begin to search some methods to overcome this problem. Excitingly, some scientists have used the metallic structure to realize the Optical BOs in nanoscale systems in the recent years, for example, W. Lin and G. Wang realized the optical BOs in a nanoscale metal heterowaveguide superlattices [10].

Nevertheless, in application of a metallic structure, it may be inevitable to face the inherent loss issue arising from the metallic extinction coefficient. To remedy this loss problem, it is possible to use superconducting materials in place of the metals. Indeed, the structures composed of superconductors and dielectric materials have started to attract research interest [11–16]. In addition to reducing the loss, compared with the normal metals, the superconductors also have other some advantages, such as lower dispersions, and wide bandwidths.

Motivated by the above researches, in the present paper, we design one kind of nanoscale chirped superconducting photonic crystals to realize optical BOs. We investigate the dynamics behavior of Gaussian pulse passing through the one dimensional chirped superconducting photonic crystals. The Wannier-Stark ladders (WSLs) can appear in the energy band. We theoretically demonstrate the existence of optical BOs in the designed photonic crystal structure containing superconducting materials. Meanwhile, we study the effect of temperature on optical BOs. We find that the optical BOs are sensitive to the change of temperature in the range of 3–8 K. This property may give us a way to achieve tunable optical BOs. The rest of this paper is organized as follows. In Section 2, the theoretical model is described in detail. Subsequently, in Section 3, we study the optical BOs in our model. The results obtained are summarized in Section 4.

2. Physical structure

The structure of one-dimensional chirped superconducting photo-

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[*] Corresponding author.
E-mail address: boyle629@126.com (P. Yin).

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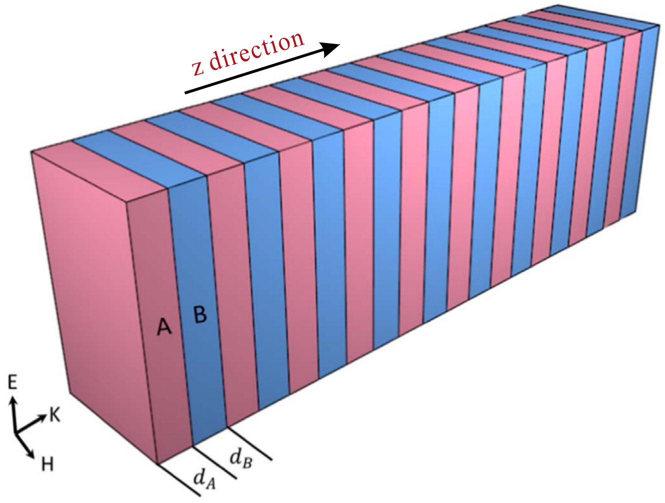

Fig. 1. Schematic representation of the superconducting photonic crystal structure. The A layers denote superconducting material layer and the enclosed B_n layers are dielectric. There is a gradient in the dielectric layer thickness. Electromagnetic waves impinge from the left side of the structure normally.

nic crystal considered in this paper is composed by alternately stratified dielectric and superconducting material. As shown in Fig. 1, the whole structure is $AB_1AB_2\ldots AB_n\ AB_{n+1}\ldots AB_{10}$. The layer of B_n is the nth dielectric layer, which thicknesses obey the following rule: $d_{B(n+1)} = \delta d_{Bn}$ (δ is thickness gradient). All A layers are composed by superconducting material with a thickness $d_A = 50$ nm. All the electromagnetic waves considered in this paper impinge from the left-side of the structure and transmit along the direction $B_1 - B_{10}$.

The corresponding permittivity of the B_n layers is $\epsilon_B = 2$, $\mu_B = 1$. The superconducting material A, we adopt the Gorter-Casimir two-fluid model [17] to describe the material properties of it in the absence of external magnetic field. Based on the two-fluid model, the permittivity of lossless superconducting materials is given by [15,18]

$$\epsilon_A = 1 - \omega_{th}^2/\omega^2,\ \mu_A = 1 \tag{1}$$

where ω_{th} is the threshold frequency of the bulk superconducting material,

$$\omega_{th}^2 = c^2/\lambda_L^2 \tag{2}$$

where c is the speed of light in vacuum, λ_L is the temperature-dependent London penetration depth, which is described by

$$\lambda_L = \lambda_0/\sqrt{1 - G(T)} \tag{3}$$

Here λ_0 is the London penetration length at T = 0 K, and $G(T) = (T/T_c)^p$, where T_c is the critical temperature of a superconducting material. In this paper, the typical superconducting material Nb is taken, and $p = 4$, $T_c = 9.2$ K, $\lambda_0 = 40$ nm are chosen in the following numerical simulations. Through analyzing the Eq. (1)–(3), we can easily obtain the following conclusions. First, when the $\omega > \omega_{th}$, ϵ_A is positive, then the refractive-index is real, hence the superconducting material behaves as a typical dielectric and the electromagnetic wave can transmit in the superconducting material. Second, when the $\omega < \omega_{th}$, ϵ_A is negative, then the refractive-index becomes imaginary, hence the superconducting material behaves as an ε-negative material [4,5] and the electromagnetic wave transmission is prohibited in the superconducting material. Obviously, in the one-dimensional superconducting photonic crystal, a sequence of optical micro-cavities (MCs) can be formed by a dielectric layer sandwiched between two superconducting material layers at the case of $\omega < \omega_{th}$. The MCs array with properly modulated resonant frequencies is well analogue to the quantum wells array subjected to dc electric field [19]. In the typical realizations of electron BO in the semiconductor superlattices, a sequence of quantum wells subjected to dc electric was used, such as in Ref [20]. Therefore, we can infer that the optical BO should occur in our designed structure.

3. Results and discussions

3.1. The optical BOs in the one-dimensional chirped superconducting photonic crystal

Let a wave be incident from the vacuum at an angle $\theta = \pi/2$ onto the one-dimensional chirped superconducting photonic crystal long z direction in the frequency range of 200–900 THz, as shown in Fig. 1. Generally, the electric and magnetic fields at any two positions z and $z + \Delta z$ in the same layer can be related via a transfer matrix [15,18,21,22],

$$M(\Delta z, \omega) = \begin{bmatrix} \cos(k_{jz}\Delta z) & -\frac{i}{q_{jz}}\sin(k_{jz}\Delta z) \\ -iq_{jz}\sin(k_{jz}\Delta z) & \cos(k_{jz}\Delta z) \end{bmatrix} \tag{4}$$

where j denotes different layers, $k_{jz} = (\omega/c)\sqrt{\epsilon_j}\sqrt{\mu_j}\sqrt{1 - \sin^2\theta\epsilon_j\mu_j}$ is the wave vector along the z axis, $q_{jz} = \sqrt{\epsilon_j}/\sqrt{\mu_j}\sqrt{1 - \sin^2\theta\epsilon_j\mu_j}$ for the TE polarization, and $q_{jz} = \sqrt{\mu_j}/\sqrt{\epsilon_j}\sqrt{1 - \sin^2\theta\epsilon_j\mu_j}$ for the TM polarization. For the multilayer structures, the total transfer matrix can be gotten by multiplying all individual transfer matrices of the each layer medium. Therefore, the total transfer matrix in our structure can be written as,

$$X_N(\omega) = \prod_{j=1}^{N} M_j(\Delta z, \omega) = \begin{bmatrix} x_{11}(\omega) & x_{12}(\omega) \\ x_{21}(\omega) & x_{22}(\omega) \end{bmatrix} \tag{5}$$

Then the transmission coefficient can be written as,

$$a(f) = \frac{2q_0}{(x_{11} + x_{12}q_l)q_0 + (x_{21} + x_{22}q_l)} \tag{6}$$

$q_0 = q_l$=$\cos\theta$, $x_{k,m}$ $(k, m = 1,2)$ are the matrix elements of $X_N(\omega)$.

First of all, we study the superconducting photonic crystal at the case of $T = 6\ K$, $d_{B1} = 150$ nm and $\delta = 1$ by using the transfer matrix method. From the thickness expression of dielectric layer B, we can find that there is no thickness gradient for it. Meanwhile, by calculating Eq. (1), we also find that ϵ_A is always negative in the frequency range of 200–900 THz when $T = 6$ K. Thus, a sequence of identical MCs is formed in the photonic crystal. In Fig. 2a, we plot the scattering states map of the superconducting photonic crystal. In the scattering states map, the field distribution is represented by the brightness. From Fig. 2a, we can clearly find that there is no field localization among the cavities in the superconducting photonic crystal. Composed by some delocalized states in space, each bright band is the optical analogue to an electronic energy band of a periodic potential. Corresponding to the scattering state map (Fig. 2a), the transmission spectrum is shown in Fig. 2b. The reason for generating the delocalized states is that the optical thickness of MC in the photonic crystal is a constant, optical energy in each MC is identical. As we know, BOs become possible due to beating of the localized eigenmodes of the structure corresponding to the equidistant tilted eigenstates of the spectrum known as the WSLs [23]. However, from the above analysis we know that the minibands and minigaps show delocalization and no tilting when δ=1, and hence the WSLs do not appear at this case. Thus, in order to realize optical BOs in periodic electromagnetic system, one needs to construct electromagnetic WSLs in frequency domain.

In order to obtain the WSLs, the energy in each MC should be different from that of others; such a cavity energy difference can be gotten by introducing an optical thickness gradient in the MCs [21]. Thus, in the next step, we introduce the thickness gradient $\delta = 1.1$ for the dielectric layer B. Fig. 2c shows the scattering states map of a structure in this case. Comparing with the Fig. 2a and 2c, one can find that the energy bands of the structure undergo critical change. Fig. 2c