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Optical Tamm states in photonic structures made of inhomogeneous material

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ABSTRACT

We demonstrate a tunable optical Tamm state at the interface between a photonic crystal (PC) and a film with non-uniformly varying refractive index. The optical Tamm state is associated with a sharp transmission peak and strong localization of the electric field. It is spectrally located inside the overlapping band gaps. The shift of the optical Tamm state is sensitive to the lattice constant of the inhomogeneous material. Our results provide an approach to tailor interface states in a controllable manner.

1. Introduction

There has long been an interest in surface state which is electron state in the energy band gap of crystals predicted by Tamm in 1932 [1]. Since in many regards photonic crystal (PC) spectra are similar to electronic spectra of crystals [2,3], e.g. photonic band gaps, and localization effects, surface states may exist at the PCs surface. An optical analog of electronic Tamm states has been theoretically and experimentally studied at the interface of different photonic crystals. Such states are often called Optical Tamm States (OTSs) [4–14]. Unlike electronic Tamm state, OTS cannot be formed at the surface, but at the interface between two single-negative mediums (e.g. metals). OTS is formed inside the "light cone" limited by a $k = \omega/c$. The mode does extend into the single-negative mediums because of their pure imaginary wave number. For the frequency within the photonic band gaps, PCs can play the role of single-negative mediums [6]. Thereby, OTS may appear at the interface between two different photonic structures having overlapping band gaps, and lies in the optical stop bands of both parts of the structure. OTS causes strong enhancement of the transmittance. Light with the wavelength OTS occurring is strongly coupled to another adjoining PC. OTS can be used for fabrication of polariton lasers without cavities [15].

The structure composed of two one-dimensional (1D) PC is the most typical one to obtain OTS [10,14]. Besides, similar interface modes were found at the interface between an isotropic single-negative medium and a PC [4,7], whose lifetime has been measured experimentally recently [17]. The states were also observed at the interface between a magneto-photonic crystal and a nonmagnetic crystal [5,6]. Backward nonlinear and linear surface Tamm states have also been demonstrated [12,13]. Moreover, OTSs have recently been found to appear at the interface between a PC and a dielectric slab with arrayed nanoholes. Such OTS will cause a giant asymmetry of the light transmission [18]. By utilizing the metal–insulator–metal Bragg reflector, researchers have proposed a plasmonic Tamm state. They have obtained enhancement of both the electric field and magnetic field intensities with three orders of magnitude [19]. By introducing a WSe_2 monolayer into Tamm-plasmon structure, exciton-polaritons at room temperature have been obtained [20]. Optical Tamm states can also appear in three-dimensional photonic crystals coated by thin metal films [21].

However, most of the previous studies focus on OTSs in structures whose refractive index is homogeneous or varied periodically and discretely. However, in organism or some military equipment, there are lots of gradient materials with continuous varied refractive index. Even the variation of refractive index is not strictly periodic. Can OTS be formed in such materials? To answer this question, we investigate the conditions for the appearance of OTSs at an interface between a PC and a film with gradient refractive index changing in the form of damped sine function. We find that the OTSs can also be obtained at such interface by employing the transfer matrix method (TMM). What is more, the wavelength of the optical Tamm state is sensitive to the lattice constant.

2. Theoretical analysis

We consider a 1D heterostructure composed of a dielectric PC and an inhomogeneous film, as illustrated in Fig. 1. The PC is formed by

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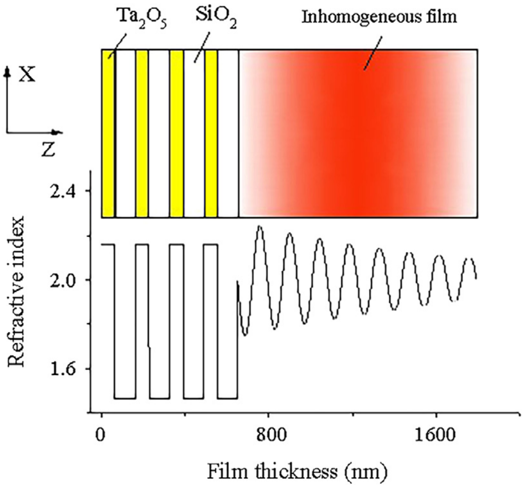

Fig. 1. 1D structure composed of a dielectric PC and an inhomogeneous film. The yellow regions stand for Ta_2O_5 layers, the white regions show SiO_2 layers, and the red region represents the inhomogeneous film.

periodic stack of Ta_2O_5 and SiO_2. The thin film with a continuous sinusoidal variation of the refractive index have been experimentally studied by using glancing angle deposition [16]. These gradient index optical thin films can display the optical effects. Here, the refractive index of the inhomogeneous film varies in the form of damped sine function.

The 1D heterostructure is placed along the z direction. The TMM is used to calculate the optical properties of the heterostructure shown. Here we discuss the TE-polarized waves (with the electric field in the $y$direction) which propagate along z axis. Now we define the state vector $\psi(z) = \left(E_x, H_y\right)^T$ at the surface of each layer. Through the TMM, we can get

$$\psi(z+d) = \begin{bmatrix} \cos x & (iu/v)\sin x \\ (iv/u)\sin x & \cos x \end{bmatrix} \psi(z) = P(d)\,\psi(z), \tag{1}$$

where $x = uv\omega d/c$, $v = \sqrt{\varepsilon}$, and $u = \sqrt{\mu}$, where ε and μ are the permittivity and permeability of each layer. ω $(= 2\pi c/\lambda_0)$ is the angular frequency. c is the velocity of light in vacuum. λ_0 is the wavelength of light in free space. d is the thickness of each layer. What is more, in our implementation, we involve approximating the continuously varying refractive index profile by a series of linear, isotropic, and homogeneous layers of 1 nm thick [11,13]. The light propagates from the periodic dielectric PC to the gradient index thin film.

The OTS is formed at the interface between the PC and the inhomogeneous material, if

$$r_P r_I = 1, \tag{2}$$

where r_P and r_I represent the reflection coefficients of the PC and the inhomogeneous film respectively for light incident from the vacuum. We are interested in the first band gap of the PC. For a wave with frequency ω sufficiently close to the Bragg frequency ω_0 of the PC, reflection coefficient of the PC can be expressed as

$$r_P = \exp(i\varphi) = \pm\exp\left[i\beta\left(\omega-\omega_0\right)/\omega_0\right], \tag{3}$$

where the positive (negative) sign in Eq. (3) corresponds to the case $n_L > n_R$ $(n_L < n_R)$. n_L and n_R respectively represent the refractive index of left layer and right layer of a unit cell of the PC. If the wave is incident from a medium with refractive index n_0, then we have

$$\beta = \frac{\pi n_0}{\left|n_L - n_R\right|}. \tag{4}$$

In our proposed PC, the refractive index of Ta_2O_5 is greater than of SiO_2, and the working frequency ω is in the band gap of the inhomogeneous media. Then, Eq. (2) becomes

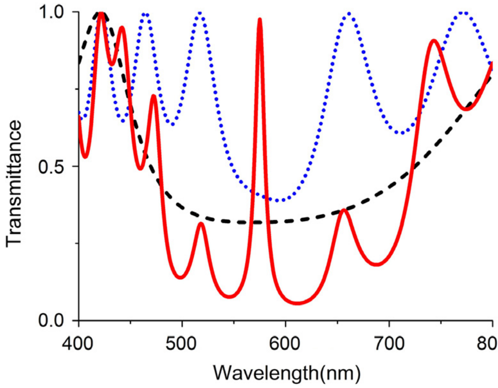

Fig. 2. (a) The dispersion relationship of the PC. (b) Transmission spectra of the $(Ta_2O_5/SiO_2)^3$ multilayer, the inhomogeneous film and the paired structure are denoted by the black dashed line, blue dotted line, and the red solid line, respectively.

$$\left|r_I\right|\exp\left[i\left(\beta_1\frac{\omega-\omega_0}{\omega_0}+\varphi_I\right)\right] = \exp(2m\pi i), \tag{5}$$

where $\beta 1 = \pi n_I/\left|n_L - n_R\right| .\varphi_I$ and n_I respectively represent the phase and the refractive index of the inhomogeneous film at the interface between the PC and the inhomogeneous film. We choose some suitable parameters to make sure that the frequency of incident wave ω is close to the Bragg frequency. As a result, the term of $\beta_1\left(\omega-\omega_0\right)/\omega_0$ in Eq. (5) is negligible. Eq. (5) indicates that we can find a solution for m $(m = 1)$, if $\varphi_I = 0$ and $\left|r_I\right| = 1$. In order to achieve OTS at the interface between the PC and the inhomogeneous film, the inhomogeneous film should have high reflectivity, and the angle of the reflection wave should be zero. To satisfy these conditions, an inhomogeneous film with damped sinusoidal varying refractive index is proposed.

3. Numerical simulations

The PC is a dielectric multilayer composed of 3 pairs of Ta_2O_5/SiO_2 film with a SiO_2 film at the end. The thicknesses of films are 97.6 nm (SiO_2) and 65.97 nm (Ta_2O_5). And the refractive indices of SiO_2 and Ta_2O_5 are 1.46 and 2.16, respectively. It can be seen from Fig. 2 (the black dashed line) that there is a photonic band gap (PBG) in the displayed wavelength range, from 450 nm to 790 nm. The inhomogeneous film is attached at the right side of the PC. We consider the inhomogeneous film with a continuously damped sinusoidal varying index as follows:

$$n(z) = n_a - \frac{n_p}{2}\times\sin\left(\frac{2\pi z}{a}\right)\times\exp\left(-\frac{z}{8a}\right), \tag{6}$$

where a $(= \lambda_0/4)$ is the lattice constant of the inhomogeneous film, n_a is the average refractive index on which the oscillation occurs, n_p is the peak-to-peak amplitude of the index variation, and λ_0 is the free space wavelength where the reflectance stop band will be centered. Here $n_a = 2.0$, $n_p = 0.52$, and the thickness of the inhomogeneous film is 8a. The transmission spectrum of the inhomogeneous film is shown in Fig. 2 (blue dotted line). We can see that, the PBG is from 500 nm to 660 nm. It is worth noting that the PC and the inhomogeneous film have the overlapping band gap. We can combine the PC and the inhomogeneous film to form a heterostructure in which the OTS may be obtained.

The optical transmittance of our sample is calculated using the TMM, and band structures and the transmittance are shown in Fig. 2 (the red solid line). One can see that, inside the overlapping stop band of the dielectric PC and the inhomogeneous film, there is a transmittance peak at about 567 nm. That is to say, the OTS occurs at the wavelength of 567 nm. Why can this happen? Due to the resonance tunneling of an electromagnetic wave through the Tamm state, a narrow peak appears

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