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Optimizing the spectral efficiency of photonic quantum well structures

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Abstract

One can construct photonic single quantum well structures by sandwiching a homogeneous medium slab as a defect between two symmetrical photonic crystals (PCs). It is shown that the number of observed resonant peaks increases with increasing slab thickness. It is found that while the slab is composed of alternatively stacked step-index films, the frequencies of these resonant peaks can be adjusted finely by changing the film thickness properly. In this case, the frequency and frequency interval of confined states can be tuned accurately, and the spectral efficiency can be greatly enhanced without increasing the volume of optical devices. Numerical simulation is based on the finite-difference time-domain (FDTD) method.

Keywords: Spectral efficiency; Confined states; Finite-difference time-domain method; Photonic quantum well

1. Introduction

Since the pioneering work of Yablonovitch [1] and John [2], interest in photonic crystals (PCs) has grown enormously. PCs can exhibit a photonic band gap (PBG) where light possessing certain values of wave vector is not allowed to propagate in the material. Usually, it is hoped that the band-gap material has a wide band-gap width. Previous studies indicate that the band-gap width is influenced not only by the lattice parameters but also by the refractive index contrast and the filling factor between the high-index and the low-index materials. If the periodicity of the PC is broken, the defect modes could appear inside the PBG due to the photonic confinement effects. Physically, the defect modes represent the confined states that correspond to isolated optical wavelengths one-to-one. In these systems, it is expected that the conversion efficiency might be increased considerably.

In spite of a large number of papers that have appeared in the literature on the application of defect modes in optical and microwave communication systems [3–6], very few considerations have been carried out to investigate spectral efficiency. Usually, the number of confined states located in a certain region of frequencies is only a few with extremely low spectral efficiency when some defects are introduced into a PC, leading to a great waste of spectral resources. This kind of characteristic is not suitable especially for improving the information capacity of the optical communication system and the optical integration in the situation, which is lack of spectral resource. These structures may be easily fabricated by the standard semiconductor growth techniques or the film growth techniques.

The purpose of this letter is to report the studies of how to improve spectral efficiency. It is found that

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frequencies of the confined states can be tuned finely as desired. In this case, multiple defect modes could be generated in a certain PBG without increasing the volume of the device. Thus, the spectral efficiency can be highly improved. It may also have high technological significance in photon control and optical integration.

2. Physical model and theoretical method

The structural configuration researched in this work may be expressed by $(HL)^f(D)(LH)^f$, where H and L stand for the different dielectric slabs with high and low refractive index, and f is the number of the HL layers. In this work, TiO_2 and SiO_2 are chosen, their refractive indices and thicknesses are $n_H = 2.2$, $n_L = 1.44$ and $d_H = 0.4a$, $d_L = 0.6a$, respectively, where the parameter a is the lattice constant. D is a dielectric slab as a defect consisting of alternating A/B films (denoted as $(AB)^M A$, in which the B film is sandwiched between two A films with small refractive index contract. M represents the number of AB layers). The refractive indices and the thickness of these two films are as follows: $n_A = 2.2$, $n_B = 2.05$ (corresponding to AgCl) and $d_A = d_B = d_D/(2M+1)$, d_D is the total thickness of the D slab. If the D slab is made up of only a film (apparently $d_B = 0$), we label this situation as $M = 0$. In terms of these notations, the structure can be shown as what we express in Fig. 1, where the value of the X-coordinate takes a as its unit.

Our numerical simulation is based on the finite-difference time-domain (FDTD) [7] technique with perfectly matched layer absorbing boundary condition [8]. There are many books and papers on the topic of the FDTD method; for a detailed and exhaustive description, see Refs. [9,10]. By using this technique, photon propagation problems can be formulated systematically in terms of the well-known Maxwell's equations without using special mathematical knowledge. Only the normal incidence situation was discussed. In this case, the TM and the TE polarizations are degenerate. Therefore, TM and TE waves are quite similar, and are no longer differentiated. In what follows, only essential steps are outlined.

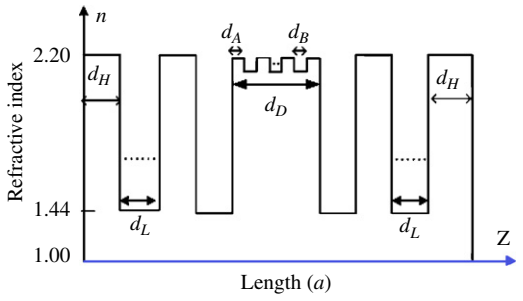

Fig. 1. Refractive index profile of PC with defect slabs made of step-index films.

The basic research work is to compile precise and effective FDTD computational procedures. The difference formulas used in programming are as follows:

$$E_z^{N+1}(k) = E_z^N(k) + \frac{\Delta t}{\varepsilon(k)\Delta s}\left[H_y^{N+1/2}\left(k+\frac{1}{2}\right) - H_y^{N+1/2}\left(k-\frac{1}{2}\right)\right], \tag{1}$$

$$H_y^{N+1/2}\left(k+\frac{1}{2}\right) = H_y^{N-1/2}\left(k-\frac{1}{2}\right) + \frac{\Delta t}{\mu(k)\Delta s}[E^N(k+1) - E_z^N(k)], \tag{2}$$

where k indicates the position of the grid in the z direction, N indicates the discrete time step, $E_z^{N+1}(k)$ represents the electric field E_z at the corresponding position z and time step $N+1$. The physical meaning of other field components can be analogized. $\varepsilon(k)$ and $\mu(k)$ are the position-dependent dielectric constant and magnetic conductivity of the material, respectively. In the following text, only the nonmagnetic materials are studied. Thus $\mu(k)$ can be substituted by μ_0. Δt is the time increment and Δs is the spatial increment in the neighboring grid points. From the stability criterion, the duration of one time step should be satisfied with $\Delta t \leqslant \Delta s/(c\sqrt{2})$. These difference formulas are simple and easy to be programmed. Some time-dependent problems, such as pulse propagation, can be solved, because the electro-magnetic fields are computed at each time step. The time-varying electric fields of observation point are recorded in a digit group. We then take the fast Fourier transform of these recorded fields. Thus, the transmission spectra can be obtained at a large range of frequencies in a single run.

In order to ensure the accuracy and usefulness of our automated computer codes, we chose some structures that are frequently reported in the literature [11,12]. With different calculated algorithms but the same geometric parameters and refractive indices, those numerical results are in good agreement. Thus, the reliability and accuracy of our computer codes are guaranteed. According to the portability of FDTD computational procedures, the reliable bases for the subsequent research works are provided. The total field and the scattered field technologies are used during the calculation. The modulation Gaussian pulse is chosen as the incident light source, and is given by

$$E_z(t) = \exp\left[-4\pi\frac{(t-t_0)^2}{T^2}\right], \tag{3}$$

where t_0 is the center position of Gaussian pulse and T is a time constant. This incident light source is a wideband source that can be used to analyze the forbidden band and the localization characteristic of PCs conveniently.