Study of the photonic crystal waveguide based on 2D compound lattice structure*

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By employing 2D plane wave expansion (PWE) and finite difference time domain (FDTD) methods, a photonic crystal waveguide (PCW) based on the compound square lattice structure is presented. Band-gap can be observed for TM polarization and compared with the simple lattice structure based on the same material, the band-gap is increased by 62.7%. By optimizing the parameters we get the PCW with the propagation only near the wavelength of 1.55 μm and a flat group index curve in a wide wavelength range of 40 nm. And the group velocity dispersion compensation can be realized by the structure optimization. The results provide a reference for the study and application of photonic crystal waveguide based on the compound lattice structure.

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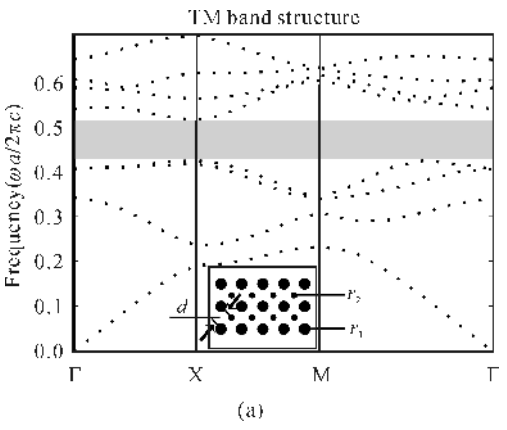
A photonic crystal waveguide (PCW) can be created by introducing line-defect in the photonic crystals (PCs) and localizing certain frequency within the photonic band gap (PBG). Different kinds of line defect structures have been adopted to obtain different propagation properties[1-8], but there are few researches about the compound lattice strusture.

In this paper, we focus on a compound square lattice dielectric rod structure to design a novel PCW using 2D PWE and FDTD methods, and find a much wider band gap in the proposed structure than the usual simple dielectric rod structure. By optimizing the parameters, we get the PCW with only one defect-mode propagation near the wavelength of 1.55 μm and a flat group index curve in a wide wavelength range of 40 nm. At the same time it is likely to be used to realize the group velocity dispersion compensation and good rise-fall effect at the edge of pass-band.

The proposed structure is a 2D compound lattice structure composed of two square lattices of dielectric rods based on the silicon-on-insulator (SOI) with the same lattice constant a, the cladding index n_0=1.45, the core index n_1=3.5, and y direction is parallel with the cylinders. And the two simple square lattices shift the distance of $d = \sqrt{2}/2a$ along ΓM direction with different normalized rod radii of r_1= 0.28a and r_2=0.15a. The design parameters are chosen to obtain a maximum range of photonic band gap. The photonic band diagram for transverse magnetic (TM) polarization of PBG structure by using PWE method is shown in Fig.1(a), which exhibits the PBG with normalized frequency range of $0.4227 \leqslant a/\lambda \leqslant 0.5127$, and normalized band-gap width of 0.09. But for a simple square rod structure with the same dielectric constant, there is the maximum band-gap when the radius of the cylinder is $r = 0.23a$, the normalized frequency range is $0.2523 \leqslant a/\lambda \leqslant 0.3076$ and normalized band-gap width is 0.0553 as displayed in Fig.1(b). So, compared with the simple lattice, the normalized band-gap of the compound lattice is increased by 62.7%, which is much more useful and convenient for designing devices with high performance.



(a)

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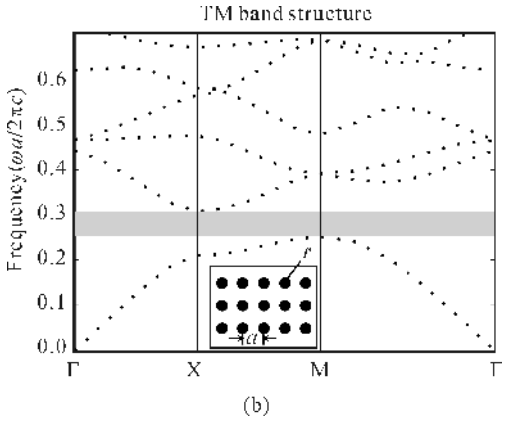

Fig.1(a) Band diagram of PBG structure of dielectric rods with two simple square lattices nested each other for TM polarization. (b) Band diagram of PBG structure of simple square lattice for TM polarization.

Now, the PCW is formed by creating line defect waveguide through removing three rows of dielectric rods along x direction, including the middle row with the radius r_1 and the others with the radius r_2. In addition, the first row rods (r_1) aside the line-defect are moved inward by $d_1 = 0.3a$ and the second row rods (r_2) are moved inward by $d_2 = 0.2a$, ensuring that the PCW supports only one guided mode in PBG. Fig.2 shows the schematic diagram of the PCW, and the arrows represent the moving direction.

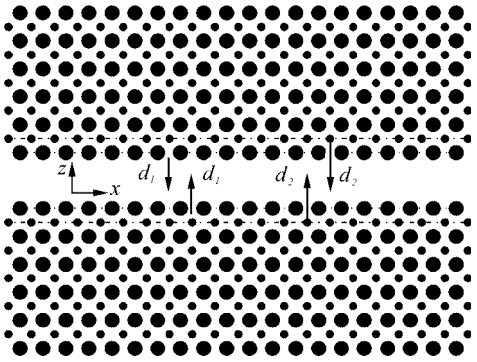

Fig.2 Schematic view of the PCW

Using the 2D PWE method, the dispersion curve for TM polarized light-wave in PCW can be numerically simulated and analyzed, as shown in Fig.3. There is only one defect mode in the range of the normalized frequency of $0.4357 \leqslant a/\lambda \leqslant 0.4513$, and the curve of such mode is considerably flat in a large wave-vector region of $0 \leqslant 2\pi/a \leqslant 0.3$. To satisfy the wavelength condition of optical communication, the lattice constant a is tailored to be 0.69 μm, and thus the guided wavelength range is $1.53\ \mu m \leqslant \lambda \leqslant 1.59\ \mu m$.

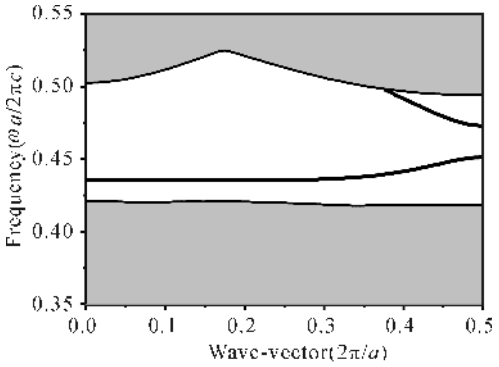

Fig.3 Dispersion diagram of the waveguide for TM polarization

The group index of the PBG mode can be obtained from the slope of the dispersion curve, $n_g = c/v_g = n + \omega dn/d\omega$, where c is the light velocity in vacuum, v_g is the group velocity, ω is the angular frequency, and n is the equivalent refractive index of the guided mode of the PCW. The relation between n_g and the wavelength λ is plotted in Fig.4. For the wavelengths between 1.54 μm and 1.57 μm, the curve is very flat and the group index is small with the minimum $n_g \approx 8$ at λ=1.55 μm. For the longer and shorter wavelengths, the properties of the defect mode are influenced by photonic crystal structure more strongly, and the group index is increased sharply. So the light velocity in the PCW approaches the maximum value $v_g \approx 0.12c$ at the wavelength of $\lambda = 1.55$ μm. What's more, the light velocity near $\lambda = 1.55$ μm is smaller than $0.12c$, with the opposite dispersion property between the longer and shorter wavelengths, and the dispersion curve varies slowly, which can be used for dispersion compensation.

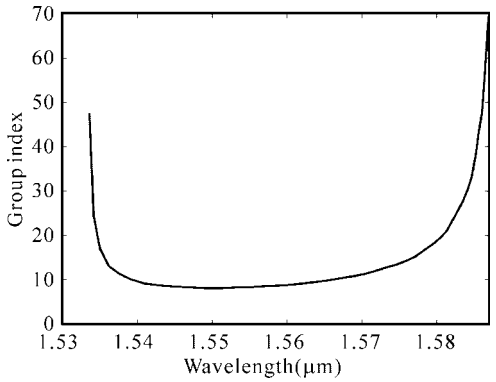

Fig.4 Group index for the defect mode

Furthermore, the FDTD method has been used to simulate the transmission properties in the proposed PCW. The transmission spectrum launched by Gaussian pulse and the electric field distribution of the light propagation launched by continuous wave (CW) are displayed in Fig.5 (a) and Fig.

5 (b) respectively. The spectrum features two obvious pass-bands with the ranges of 1.41 μm-1.47 μm and 1.53 μm-1.59 μm, which is in accordance with the results by PWE method (Fig.3). The range of 1.53 μm-1.59 μm is what we expect for optical communications. And the intensity of the other one is very weak and not wanted. At the same time, as plotted in Fig.5 (a), the defect mode between 1.53 μm and 1.59 μm has extremely sharp turn-on and turn-off performance at the edge of the pass-band, which is useful for wavelength-selection and noise-filtering to enhance the communication quality. Fig.5 (b) describes the stable electric field intensity distribution after being excited by the continuous wave at the wavelength of 1.55 μm for TM polarization in the input waveguide. In the simulation, the space increment is defined as $\Delta x=\Delta z=0.01$ μm and the time increment $\Delta t = 2.22 \times 10^{-17}$ s, which satisfies the stable condition of FDTD.

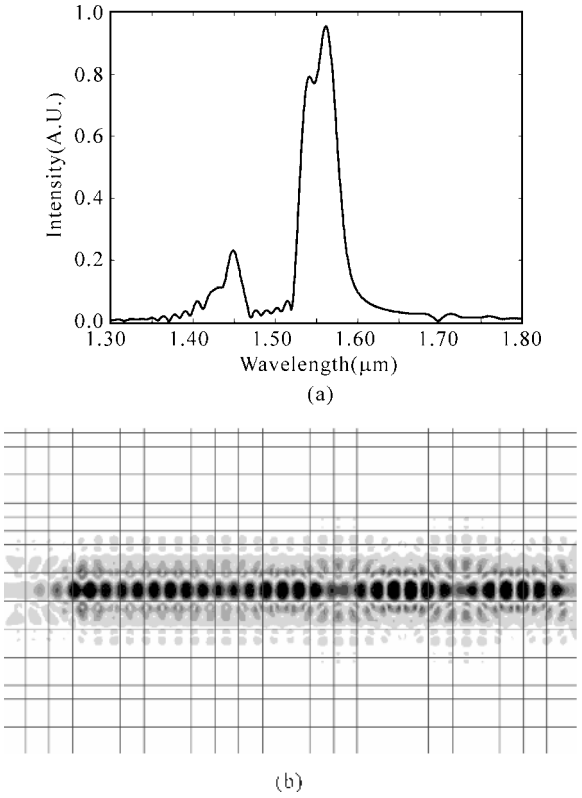

Fig.5 (a) Transmission spectrum for compound lattice PCW (by FDTD). (b) Electric field intensity distribution of the PCW at λ=1.55 μm.

Using 2D PWE and FDTD methods, we have explored the existence of PBG with compound square lattice of dielectric rods, and the normalized band-gap is wider by about 62.7% than that of the simple lattice structure with the same dielectric material, which improves the performance of the PC structure. By further optimizing the structure and parameters of the line-defect, we design the single-mode PCW operating near the wavelength of 1.55 μm with a flat group index curve in a wide range and good rise-fall characteristic at the edge of pass-band. Group velocity dispersion compensation can also be realized by further optimization to meet the demand of optical communication.

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