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Design of ultra-compact wavelength splitter based on lithium niobate nanowire optical waveguides*

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A wavelength splitter with ultra-compact and simple structure is proposed and analyzed by using both plane wave expansion (PWE) method and finite difference time domain (FDTD) method. The device is based on directional coupling between two parallel lithium niobate ($LiNbO_3$, LN) nanowire optical waveguides. The wavelength splitter with a coupling region length of 5 μm can separate 1.31μm and 1.55 μm wavelengths for corresponding outputs with transmittance higher than 97%.

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Wavelength splitter, namely demultiplexer, is one of key elements for optical communication system, because it can split a beam containing two different wavelengths into two output beams. The trends for expanding the optical communication system capacity and improving the optical integration lead to the increasing demand for the small size of wavelength splitter. In the past several years, the researchers have proposed and demonstrated wavelength splitters based on photonic crystals (PCs) with different structures[1-6]. However, because PC-based devices have an intrinsic disadvantage that the device structures must follow the orientation of PC lattice, flexible control of lightwaves becomes impossible. In addition, because PC-based devices need a wide PC background (at least several lattice constants) and usually occupy much space in transverse dimension, it is inconvenient to achieve highly integrated photonic integrated circuits (PICs).

Currently, lithium niobate ($LiNbO_3$, LN), due to its excellent electro-optic, acousto-optic and nonlinear optical properties, has wide practical applications in optical waveguide substrates, optical communication modulators, optical isolators, narrow-band filters, etc[7-11]. And it has broad application prospects in the photon mass storage and optical integration, and is recognized as one of the main candidate materials of "optical silicon" in the era of photonics. Recent research indicates that the lithium niobate nanowire waveguide (LNNW) has the ability to provide efficient delivery for super-compact devices with arbitrary shape in very small space[12].

Obviously, the use of LNNWs is expected to get ultra-compact integrated optical devices with superior performance. In this paper, an ultra-compact wavelength splitter is designed based on LNNWs. The dispersion characteristics of LNNWs are calculated. On this basis, the ultra-compact wavelength splitter for optical communication is built by LNNWs. And, with the plane wave expansion (PWE) method and finite difference time domain method, the characteristics of guided optical wave and field distribution of the wavelength splitter are calculated and analyzed. As a result, the wavelength splitter is obtained with coupling region length of 5 μm, and it can separate 1.31 μm and 1.55 μm wavelengths for corresponding outputs with the transmittance higher than 97%.

To take advantage of the different coupling characteristics of LNNWs at different wavelengths, the wavelength splitter based on LNNW is designed. Here the considered straight waveguide can be regarded as single-row LNNWs composed of some closely connecting short LNNWs that construct a cubic array with a refractive index $n = 2.2$. The width of the LN cuboids is set to be a, where a is the width of the smallest cycle unit for PWE method, as shown in Fig.1(a), where black region represents LNNWs, while white region is air. Fig.1 (b) shows the TE band structure of the single-row LNNW, which is calculated by the PWE method for an $a \times 9a$ supercell shown by the dashed frame in Fig.1(a). The shaded region (light line region) represents the extended modes. It can be seen from Fig.1(b) that the band curve is below the

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light line region, which indicates that the mode is a guided one in the LNNW. For operating at optical communication wavelengths, a is specified as 350 nm. Two normalized frequencies of 0.2672 (a/λ) and 0.2258 (a/λ) can be obtained for the wavelengths of 1.31 μm and 1.55 μm, respectively. Therefore, the coupling length of two straight waveguides described above with width of 0.35 μm and parallel to each other equals 5 μm, and two different wavelengths (λ_1, λ_2) can be output from the upper and lower output ports.

In the cycle system, the light wave is expressed as a periodic function of propagation constant k in horizontal direction, and the related light frequency ω changes continuously along with k in each Brillouin zone. At boundary of each Brillouin zone, the frequency $\omega(k)$ will change suddenly. In general, $(0, 0.5)\times 2\pi/a$ shows the value k in a period. However, in this paper, we only take the value in (0, 0.5) and ignore the $2\pi/a$ part. Therefore, $ka/2\pi$ is needed to indicate the corresponding units for (0, 0.5) in abscissa axis.

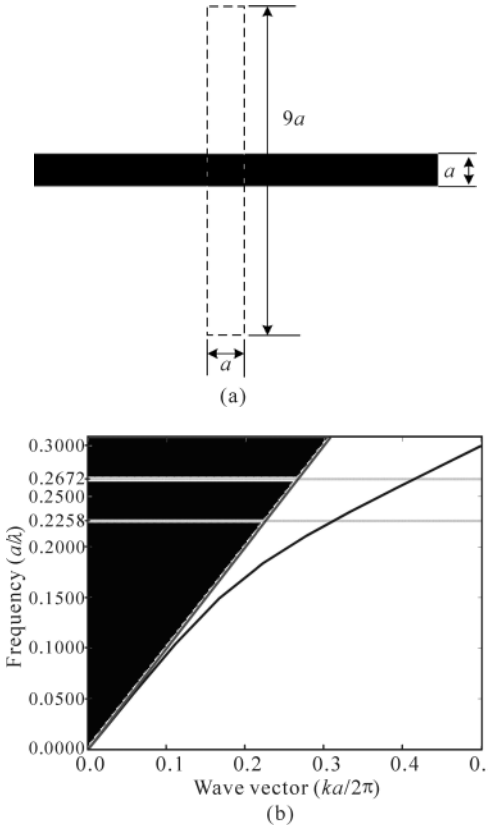

Fig.1(a) A single lithium niobate waveguide model; (b) Band structure of (a)

To perform the function of wavelength splitter, a directional coupling model is structured by arranging two parallel single LNNWs with a distance d, as shown in Fig.2(a). By the PWE calculation, d=1.5a is chosen for the directional coupling model. Fig.2(b) shows the band structure at d=1.5a for the $a\times 9a$ supercell shown by the dashed frame in Fig.2(a). Clearly, it can be seen from Fig.2(b) that there are two modes with different wave vectors and mode patterns. In Fig.2(b), $ka/2\pi$ indicates the corresponding units for (0, 0.5) in abscissa axis.

In fact, through this directional coupling model, a guided mode from a single LNNW can be excited into two modes. Then the two modes interfere with each other via establishing phase difference along the propagation direction, and electromagnetic energy can be transferred from one LNNW to the other after a coupling length L_c, which is defined as[13]:

$$L_c = \frac{\pi}{|k_1 - k_2|} , \tag{1}$$

where k_1 and k_2 represent the wave vectors for the first and second excited band modes, respectively. If the two coupling lengths L_{c1} (for λ_1) and L_{c2} (for λ_2) satisfy $(2N-1)\times L_{c1}=2N\times L_{c2}$, where N is a natural number, we can separate λ_1 and λ_2 to different output waveguides.

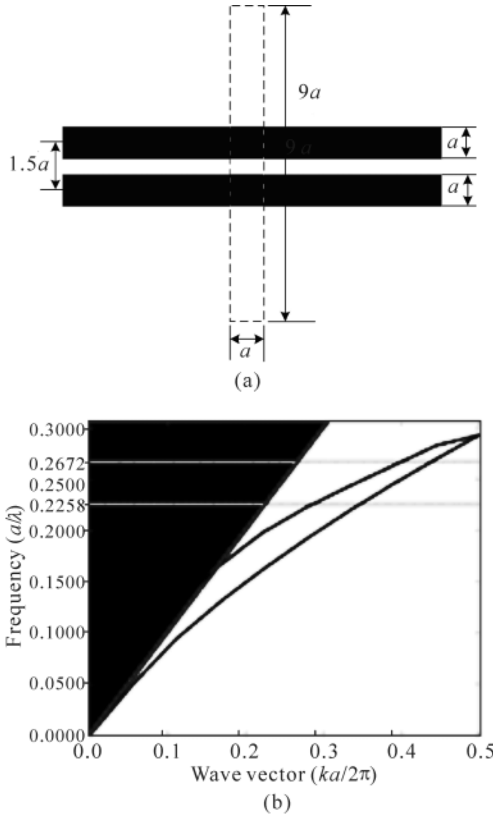

Fig.2(a) Model of two parallel single LNNWs; (b) Band structure of (a)

For the light with wavelengths of 1.31 μm and 1.55 μm, the respective coupling lengths L_{c1}= 5 μm and L_{c2}=2.51 μm can be calculated by taking k_1 and k_2 from Fig.2(b) and substituting them into Eq.(1). The results satisfy $L_{c1}\approx 2L_{c2}$. Therefore, if the coupling region length L is set to be 5 μm, the light with wavelength of 1.31 μm can be totally coupled from one LNNW to the other, while the light with wavelength of 1.55 μm will be totally coupled back into the original LNNW after twice couplings. To confirm the validity, two-dimensional (2D) finite-difference time-domain (FDTD) simulations with perfectly matched layer (PML) boundary conditions are run in the directional coupling region with L=5 μm. Figs.3 and 4 show the steady-state field distributions of wavelength 1.55 μm and 1.31 μm, respectively, which agree well with the calculations.

Also, the transmission of corresponding light is calculated and shown in Figs.3 and 4. The results show that wavelength splitter for 1.31 μm and 1.55 μm with the coupling length of 5 μm has the light transmission over 97%.

For comparison, the wavelength splitters based on photonic crystal waveguide reported in Refs.[1] and [2] have coupling lengths of 24 μm and 15 μm, while the wavelength splitter based on LNNWs in this paper has coupling length of 5 μm. Moreover, for the waveguide splitter based on the photonic crystal, the distance between two parallel array waveguides is limited within the lattice constant, while for wavelength splitter based on LNNWs, the distance between two parallel LNNWs can be easily changed. In addition, although photonic crystal wavelength splitter in Ref.[6] has coupling length of 5 μm, the proposed wavelength splitter in this paper has a more simple structure, and the straight waveguide design is easier to implement.

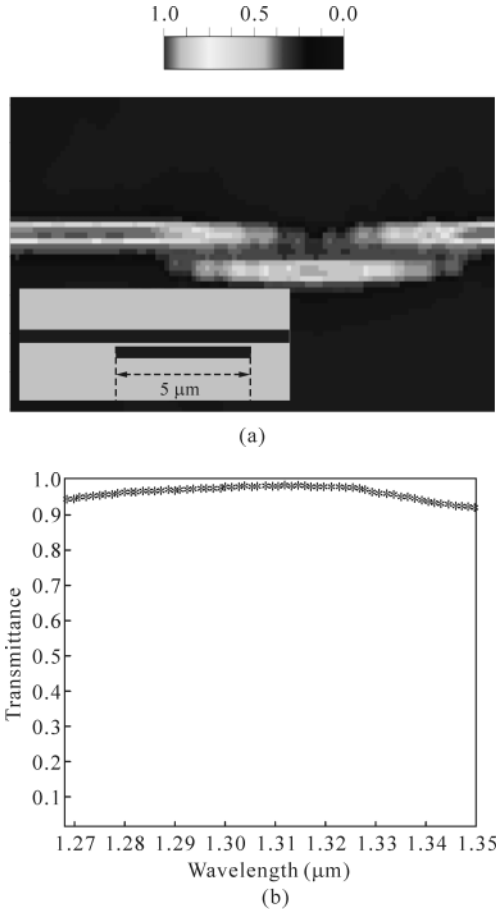

Fig.3(a) Steady-state field distribution of wavelength splitter at a wavelength of 1.55 μm; (b) Its corresponding transmission rate

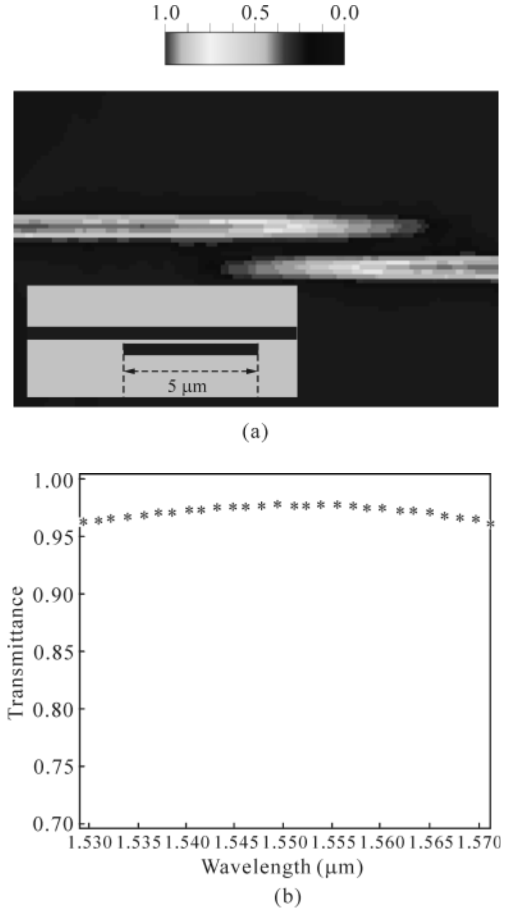

Fig.4(a) Steady-state field distribution of wavelength splitter at a wavelength of 1.31 μm; (b) Its corresponding transmission rate

The wavelength splitter is proposed and simulated numerically based on LNNWs for optical communication wavelengths. Numerical simulation shows that this device can split 1.31 μm and 1.55 μm wavelengths with a transmittance higher than 97%. Compared with those reported ones based on PC waveguides, the device is ultra-compact and simple and it is useful for highly integrated PICs.

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