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Three-channels wavelength division multiplexing based on asymmetrical coupling

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ABSTRACT

In order to realize the wavelength division multiplexing (WDM) device with compact channels and high transmission, a novel three-channel WDM device based on a two-dimensional photonic crystal with a square lattice is proposed. Three parallel line defect waveguides are introduced in this structure to control the propagation of light. Elliptical and rectangular resonators are employed to carry out the selection of light wavelengths by the coupling resonant effects. The point defect cavity is placed at the end of the middle waveguide to further filter the wavelengths. We theoretically analyze the effects of the distances between the resonator and the micro-cavity and between asymmetrical resonators on the light propagation by the finite-difference time-domain (FDTD) method. Three different wavelengths (1560, 1580, and 1620 nm) in the communication window range with maximum transmission over 90% are obtained. The findings may provide potential applications in filters, WDM optical communication systems and other optoelectronics devices.

1. Introduction

Photonic crystals (PCs) have attracted great attention due to the potential ability to control the propagation of light by photonic bandgaps (PBGs) [1,2]. As one new-type of artificial periodic structure composed of two or more dielectric materials, PCs are very suitable candidates for the realization of small-scale optical devices, such as optical filters, PC fibers, and wavelength division multiplexings (WDMs) [3–7]. In order to realize the accurate control of light, WDM devices need to being compacted. In the last decades, various types of WDM devices with miniature scale based on PCs have been reported. For example, modified-T dense WDM has been proposed by Rostami et al., heterostructure WDM with ring resonators has been proposed by Djavid et al. and so on [8–11]. However, low transmittance of some complex structures becomes a major obstacle to numerous applications in optoelectronic devices. To the best of our knowledge, the micro-cavities formed by introducing point defects in PCs do not suffer from the intrinsic radiation loss which can contribute to the realization of high-quality factor and high drop efficiency for WDMs [11–13]. In addition, the combination of elliptical resonator with micro-cavity has not been considered although it may present interesting optical properties for WDMs.

In this work, we propose a novel compact WDM structure based on a two-dimensional (2D) PC with a square lattice by combining an elliptical resonator with a L4 rectangular resonator. Elliptical and rectangular resonators are employed to realize the selection of wavelengths by the resonant coupling effects. Three line-defect waveguides along the Γ–K direction are introduced into the PC for the propagation of light. The transmission spectra are analyzed by the finite-difference time-domain (FDTD) with perfectly matched layers as boundary conditions [14,15]. Three wavelengths (1560, 1580, and 1620 nm) with high transmission (100%, 90%, and 100%) are successfully separated in three output channels. Moreover, the positions of the two resonators and the micro-cavity play an important role on the resonant frequency and transmission intensity in our proposed structure.

2. Structure model

The geometrical model structure of the proposed WDM is depicted in Fig. 1, which is composed of three parallel waveguide channels, two asymmetrical elliptical and rectangular resonators and one micro-cavity. The amplitude of the electric field intensity is a. The distance between the two resonators is d. The incident energy and exporting energy are denoted by $|S_{+i}|^2$ and $|S_{-i}|^2$, respectively. The coupled mode equations between these cavities are given by

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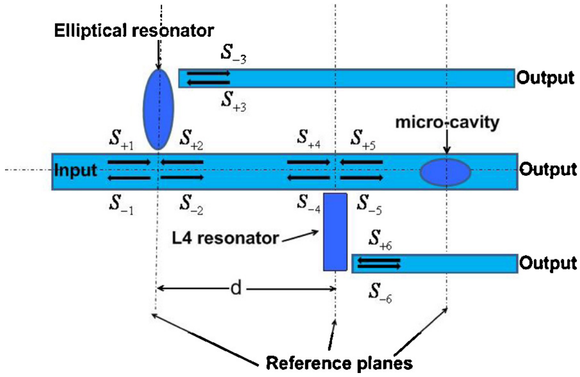

Fig. 1. Three-channel asymmetry WDM based on a 2D PC.

[16–18].

$$\frac{da}{dt}=j\omega a-\left(\frac{\omega_0}{2Q_0}+\frac{\omega_0}{2Q_b}+\frac{\omega_0}{2Q_d}\right)a+e^{j\theta_1}\sqrt{\frac{\omega_0}{2Q_b}}S_{+1}+e^{j\theta_2}\sqrt{\frac{\omega_0}{2Q_b}}S_{+2}+e^{j\theta_3}\sqrt{\frac{\omega_0}{Q_d}}S_{+3} \quad (1)$$

$$Q_i=\frac{\omega_0\tau_i}{2}\quad (i=0,b,d) \quad (2)$$

$$S_{-1}=\gamma_2 a+S_{+2} \quad (3)$$

$$S_{-2}=\gamma_1 a+S_{+1} \quad (4)$$

In the absence of an excitation of resonate cavity modes, S_{+1} is produced by S_{+2} directly. The escape rate $1/\tau$ is related to the external Q of the bus and drop waveguides. Q_i ($i=0, b, d$) represent the intrinsic, into the bus waveguide, and drop waveguide quality factors, respectively. ω_0 is the resonant frequency of the cavity. The coefficient γ is determined by the energy conservation of the physical system. The exponential distribution of the field or the energy density is easily integrated and denoted by $e^{-j\theta_i}$, and θ_i ($i=1, 2, 3$) represent the coupling coefficient of the phases decided by the reference planes.

$$S_{-1}=S_{+2}-e^{-j\theta_2}\sqrt{\frac{\omega_0}{2Q_b}}a \quad (5)$$

$$(6)S_{-2}=S_{+1}-e^{-j\theta_1}\sqrt{\frac{\omega_0}{2Q_b}}a$$

$$S_{-3}=-S_{+3}-e^{-j\theta_3}\sqrt{\frac{\omega_0}{Q_d}}a \quad (7)$$

$$r=\frac{\frac{1}{2Q_f}}{j\left(\frac{\omega-\omega_{0f}}{\omega_{0f}}\right)-\frac{1}{2Q_f}} \quad (8)$$

$$S_{-4}=rS_{+4}$$

$$Q_f=\frac{\omega_{0f}}{\Delta\omega},\quad \Delta\omega=\frac{\cos^2(\Delta\beta_{0f}L)}{\bar{\beta}_1},\quad \bar{\beta}=\frac{\beta_e+\beta_0}{2},\quad \bar{\beta}=\left.\frac{d\bar{\beta}}{d\omega}\right|_{\omega=\omega_{0f}} \quad (9)$$

When the incident light with a frequency of ω is only laughed into the bus waveguide from its left, we have $S_{+3}=0$, $S_{+6}=0$, by executing the Eqs. (1)–(9). The resonant frequency of the coupling cavities is denoted by ω_{0f}. The propagation constants of even and odd modes in the basic modes are denoted by β_e and β_0, respectively. Finally, the calculated diffraction $D(\omega)$, transmission $T(\omega)$ and reflection $R(\omega)$ of the up output channel from the Fourier transform of the above equations are given by Eqs. (10) and (11). And similar T and R of the down and middle output channels can be continued calculating in the same way.

$$D(w)=\left(\frac{S_{-3}}{S_{+1}}\right)^2=\left[\frac{e^{j(q_1-q_3)}\sqrt{\frac{1}{2Q_b}}\sqrt{\frac{1}{Q_d}}(1+re^{-jb2d})}{j\left(\frac{w-w_{0c}}{w_{0c}}\right)+\frac{1}{2Q_0}+\frac{1}{2Q_d}+\frac{1}{2Q_b}(1+re^{-jb2d})}\right]^2 \quad (10)$$

$$R(\omega)=\left(\frac{S_{-1}}{S_{+1}}\right)^2=\left[\frac{re^{-j\beta 2d}\left[j\left(\frac{\omega-\omega_{0c}}{\omega_{0c}}\right)+\frac{1}{2Q_0}+\frac{1}{2Q_d}\right]-\frac{1}{2Q_b}(1+re^{-j\beta 2d})}{j\left(\frac{\omega-\omega_{0c}}{\omega_{0c}}\right)+\frac{1}{2Q_0}+\frac{1}{2Q_d}+\frac{1}{2Q_b}(1+re^{-j\beta 2d})}\right]^2 \quad (11)$$

$$T=1-R-D \quad (12)$$

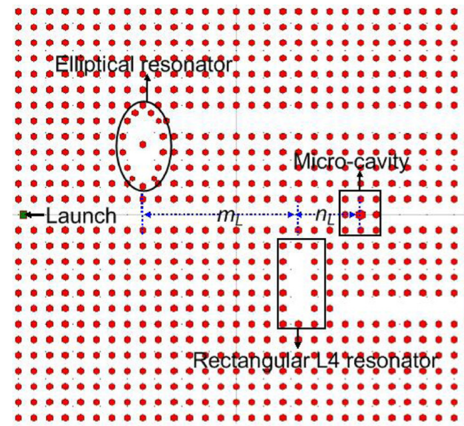

Fig. 2. Three-channel WDM with asymmetrical resonators.

Fig. 2 represents the proposed WDM structure composed of a 2D PC with a square lattice of Si rods in the air host. The lattice constant is $p=560$ nm, the refractive index (n) of Si is 3.464, and the radius of Si rods is $r=103$ nm. A Gaussian pulse which is wide enough in frequency domain to cover the range of frequencies is launched. Three output ports, formed by removing one row of rods, are labeled with A, B, and C, respectively. Three power monitors are placed at the output ports to detect the output spectra. The elliptical cavity and the L4 cavity are designed by removing the dielectric rods to form corresponding shapes. The optical field can be coupled from the input waveguide into the up and down output waveguides at the resonant frequencies. A point defect micro-cavity is placed at the end of the bus waveguide by setting the radius of middle rod to $1.5r$, which can be used to further filter the light. In this structure, the PBG locates in the normalized frequency (p/λ) region of 0.30–0.43 for TE polarization by using plane wave expansion method (λ is the wavelength of light in free space), including the communication window.

3. Result and discussion

In order to understand our WDM structure, we firstly study the effect of the positions of resonators on the transmission behaviors. Fig. 3(a) shows the peak positions as a function of the distance