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Tunable multiple all-optical switch based on multi-nanoresonator-coupled waveguide systems containing Kerr material

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ABSTRACT

By using a 2-D finite difference time domain and transfer matrix method, we have theoretically and numerically analyzed the optical transmission characteristics of optical waveguide coupling to ring cavity array. The simulation results reveal that the dual-ring cavity waveguide configuration with Kerr nonlinear material can act as a double channel all-optical switch. The contrast ratio of the two switch channels is 16.6 dB and 10.37 dB, respectively. We also designed a bidirectional all-optical switch based on two parallel waveguides coupled to ring cavity structure. In addition, multi-channel optical switches are achieved by increasing the number of cavity. The designed all optical switching models will be helpful to dynamic control of light in photonic circuits.

1. Introduction

It is believed that all-optical switching is one of the basic elements in future integrated photonic circuits. Therefore, both in theory [1–6,8,14] and experiment [7,9,10,12,13], all-optical switch has attracted considerable research. In theory, LANF Jia-Hong has investigated the controlled optical switch in an one-dimensional resonator waveguide coupled to a Whispering-Gallery Resonator with a $\wedge$-type system [6]. Henry Wen has theoretically investigated a wavelength-selective all-optical switch using Raman-induced loss in a silicon resonator add-drop filter [7]. Evgency Bulgakov has considered optical switching in a T-shaped photonic waveguide coupled with two identical nonlinear cavities [8]. In experiment, Cai has reported a nano-optical switch driven by optical force in a laterally coupled-ring resonator [9]. Some waveguide photonic devices have been demonstrated by numerical simulation or by experimental design. Such as tooth shaped waveguide filters [18], and tunable multi-channel wavelength demultiplexer [17]. Among the above work, using Kerr nonlinear effects is a practical way to control signal light transmit.

In this paper, a new kind of tunable multiple all-optical switch based on ring cavity-waveguide system is designed and the transmission properties are investigated numerically. We also proposed a bidirectional all-optical switch, which composed of two parallel waveguides coupled with a ring cavity filled with Kerr nonlinear material. The 2-dimensional finite difference time domain method is used in the simulations. The model of our paper has the advantages of small size, ultra-fast response time and low control light intensity, which will provide a theoretical basis for optimization of all-optical switch in nanoscale.

2. Analytical model

The model considered in this paper is shown in Fig. 1(a). Suppose the ring cavity is single-mode cavity, with the natural frequencies represented by $\omega_{o,i}$, $\kappa_{o,i}$ is the decay rate of the energy escape to the external environment of the ith ring resonator, $\kappa_{e,i}$ is the decay rate due to the energy escape into the waveguide, the relationship to the quality factor is $\kappa_{o,i}=\omega_{o,i}/2Q_{o,i}$, $\kappa_{e,i}=\omega_{o,i}/2Q_{e,i}$.$Q_{o,i}$ and $Q_{e,i}$ are the intrinsic and coupling quality factors of the ith ring cavity, respectively [11]. We suppose the distance between the ring cavities is long enough, so we ignore the direct coupling of the ring cavity. Fig. 1(b) is a single unit of the system.

For this system, the Heisenberg equation of motion is linear, and the annihilation operators in the ith ring resonator can be written as [11,15]

$$\frac{da_i(t)}{dt}=-j\omega_{o,i}-(0.5\kappa_{o,i}+\kappa_{e,i})a_i(t)+e^{j\theta_i}\sqrt{\kappa_{e,i}}S_{in}+e^{j\theta_i}\sqrt{\kappa_{e,i}}C_{in}\ (i=1,2\ldots N) \tag{1}$$

where S_{in} and S_{out} are the signal light wave flow operators from the two sides of the bus waveguide. C_{in} and C_{out} stand for the control light wave flow operators from the two sides of the bus waveguide, θ_i is the phase of coupling coefficient. For simplify, we chose $\theta_i=0$ and $j=\sqrt{-1}$.

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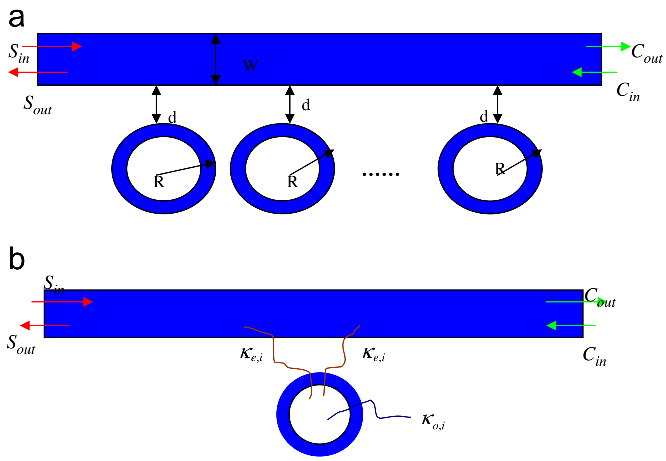

Fig. 1. (a) Model of waveguide coupling to ring resonator array. (b) A single unit of the system.

Define the Fourier transform of $a_i(t)$, and

$$a_i(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega_{o,i}}(t-t_0) a_i(\omega) d\omega \tag{2}$$

We can get the annihilation operator $a_i(t)$ in the frequency domain $a_i(\omega)$

$$a_i(\omega) = \frac{\sqrt{\kappa_{e,i}} S_{in}^i(\omega) + \sqrt{\kappa_{e,i}} C_{in}^i(\omega)}{(0.5\kappa_{o,i} + \kappa_{e,i}) - j(\omega - \omega_{o,i})} \tag{3}$$

A relationship between the input light field and output field is [4]:

$$\begin{aligned} S_{out}^i(\omega) + S_{in}^i(\omega) &= \sqrt{\kappa_{e,i}} a_i(\omega) \\ C_{out}^i(\omega) + C_{in}^i(\omega) &= \sqrt{\kappa_{e,i}} a_i(\omega) \end{aligned} \tag{4}$$

We can find the relationship between signal light and control light:

$$\begin{aligned} S_{out}^i &= \left[\frac{j(\omega-\omega_{o,i}) - 0.5\kappa_{o,i}}{(\kappa_{e,i}+0.5\kappa_{o,i}) - j(\omega-\omega_{o,i})}\right] S_{in}^i + \left[\frac{\kappa_{e,i}}{(\kappa_{e,i}+0.5\kappa_{o,i}) - j(\omega-\omega_{o,i})}\right] C_{in}^i \\ C_{out}^i &= \left[\frac{j(\omega-\omega_{o,i}) - 0.5\kappa_{o,i}}{(\kappa_{e,i}+0.5\kappa_{o,i}) - j(\omega-\omega_{o,i})}\right] C_{in}^i + \left[\frac{\kappa_{e,i}}{(\kappa_{e,i}+0.5\kappa_{o,i}) - j(\omega-\omega_{o,i})}\right] S_{in}^i \end{aligned} \tag{5}$$

We can write the relationship between input and output light field of the ith ring cavity in a matrix form:

$$\begin{aligned} \begin{bmatrix} S_{out}^i \\ C_{out}^i \end{bmatrix} &= \begin{bmatrix} \frac{j(\omega-\omega_{o,i}) - 0.5\kappa_{o,i}}{(\kappa_{e,i}+0.5\kappa_{o,i}) - j(\omega-\omega_{o,i})} & \frac{\kappa_{e,i}}{(\kappa_{e,i}+0.5\kappa_{o,i}) - j(\omega-\omega_{o,i})} \\ \frac{\kappa_{e,i}}{(0.5\kappa_{o,i}+\kappa_{e,i}) - j(\omega-\omega_{o,i})} & \frac{j(\omega-\omega_{o,i}) - 0.5\kappa_{o,i}}{(\kappa_{e,i}+0.5\kappa_{o,i}) - j(\omega-\omega_{o,i})} \end{bmatrix} \begin{bmatrix} S_{in}^i \\ C_{in}^i \end{bmatrix} \\ &= M_i \begin{bmatrix} S_{in}^i \\ C_{in}^i \end{bmatrix} \end{aligned} \tag{6}$$

We also define the transfer matrix associate with the free propagation between the ring cavities $M_0 = \begin{bmatrix} 0 & e^{j\varphi} \\ e^{-j\varphi} & o \end{bmatrix}$, when the optical path difference between two ring cavities has a phase of $\phi = 2\pi \times n.n$ is an integer, then $M_0 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$.

The transfer matrix of the whole system can be described as:

$$M = M_N M_0 M_{N-1} \cdots M_0 M_1 = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{7}$$

where M_{11}, M_{12}, M_{21}, M_{22} are the four matrix elements of the matrix M.

When there is no control light input, ($C_{in} = 0$), the system transmittance can be defined as:

$$T = \left|\frac{S_{out}}{S_{in}}\right|^2 = |M_{11}|^2 \tag{8}$$

3. Numerical simulation results and discussion

First, we considered a single ring cavity side coupled with the waveguide. When the input Gaussian lights are injected to the proposed structure, the incident light will be coupled into the waveguide and the ring resonators, cavity modes in the ring cavity will be excited when the resonant condition is satisfied [19]. Fig. 2(a) shows the relationship between the transmission and the wavelength of the incident pulse. We observed when the detuning of incident light and cavity mode are equal to zero, the signal light transmittance is 5.7%, which leads to a notch appeared in the transmission spectrum, the minimal value of the transmission is $(\kappa_o)^2/(\kappa_o + 2\kappa_e)^2$, where, $\kappa_o$is the decay rate of the light field due to the internal loss of the ring cavity, κ_e is the decay rate due to the ring cavity coupling to the waveguide. For the frequency of the signal light far bigger thanκ_o, κ_e, the cavity mode is not excited and the transmittance is $T = (i\Delta - 0.5\kappa_o/\kappa_e + 0.5\kappa_o - i\Delta)^2$. To further verify the above calculation, we have studied the transmission properties of a single ring cavity coupled waveguide system by using the 2D-FDTD simulation. As in Fig. 1(a), w and R are the width of the waveguide and the outer radius of the ring cavity, d stands for the distance between the ring cavity and the waveguide. The ring cavity and waveguide are filled with a popular dielectric material whose dielectric constant is $\varepsilon = 9$. In the following simulations, the grid size in the x and y directions are chosen as $\Delta x = \Delta y = 50$ nm, $\Delta t = \Delta x/2c$, where c is the free space speed of light. The perfectly matched layer has been used as the absorbing boundary conditions. In the simulation, the radius of the ring cavity R = 1750 nm, the width w of the waveguide is 200 nm, d = 200 nm. The transmission of the structure is $T = E_t/E_i$. E_t, E_t are the transmission electric field and the incident electric field, respectively. It can be seen from Fig. 2(b) that see there is a transmission dip with minimum transmittance 3% at the resonant wavelength of 1475 nm. The resonant wavelength of

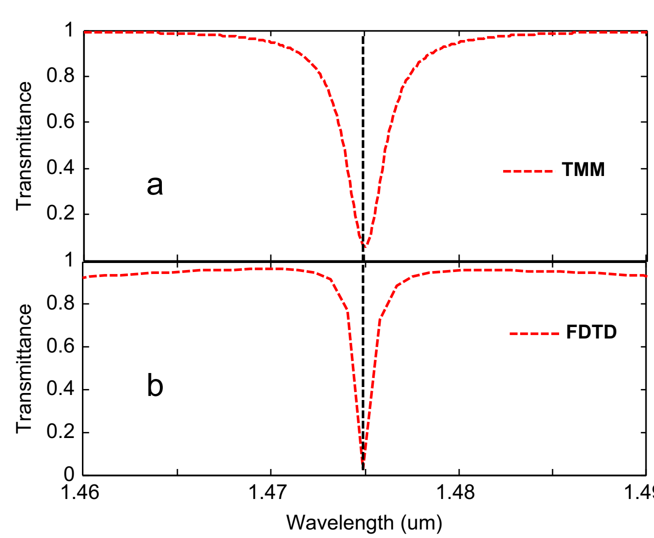

Fig. 2. (a) Transmission characteristic of a single unit by transfer matrix calculation. $\kappa_e = 0.8THZ$, $\kappa_o = 0.5THZ$. (b): FDTD calculation transmission spectra of a single ring cavity coupled to waveguide structure. The outer radius of the cavity R is 1750 nm. The ratio of the inner radius and outer radius is 0.9. w=200 nm. d=200 nm.