Proposal for a Kerr-Tunable All-Optical Switch Based on Photonic Crystal Ring Resonators

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Abstract-in this paper, a Kerr-tunable all-optical switch is presented which works in photonic crystal platform and implement octagonal-shape ring resonator(s) for enhancing the level of nonlinear light amplitude required for the device operation. Two switches are designed and compared: one based on a single (SR) and the other based on a double-vertically (DR) aligned ring resonators. Silicon (Si) nanocrystal is used as the driving material for the nonlinear parts. Since the transmission spectra of the DR switch has a higher Q-factor rather than SR and also since the optical power reads more nonlinear rods within the DR, thus the optical power required is much lower (at least 10 folds) than the SR switch. The required time for DR switch to change its state from on to off is computed to be less than 10 ps, at λ₀=1552nm. The minimum power required to turn DR switch state on/off is less than 6mW/µm². Performance of the switch is simulated by means of finite difference time domain (FDTD) method, which confirmed the ultra-compact sized for the structure working with an ultrafast speed.

Keywords: Photonic Crystal, Ring Resonator, Nonlinear Switch, Optical Kerr effect.
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1 Introduction

Photonic crystal (PhC) [1], based devices have attracted lots of attention for their ability to sustain light within very high $Q$-factor and low mode volume cavities, resulting in ultra-compact sized optical integrated circuits. They require only a few microwatts of power to establish suitable nonlinear effects, and furthermore, due to Si-based technology of PhCs, complex fabrication processes are easily derived. Directional coupler structures reported in [2], suffer from large coupling arms resulting in larger amounts of required optical powers. On the other hand, nonlinear optical processes have shown amazingly ultrafast responses on the order of 10ps [3]. Based on our previous reports of octagonal-shape 2D-PhC [4], here in this paper we report on a Kerr-like nonlinear full-optical switching block capable of complete on/off operating at threshold input intensities as low as 6mW/µm$^2$ for a double-vertically (DR) aligned PCRRs switch. The required time for DR switch to change its state from on to off is computed to be less than 10ps, at $\lambda_0=1552\text{nm}$. Performance of the structure is simulated by means of finite difference time domain (FDTD).

2 Materials and Method

Due to their large $Q$-factor (ability to confine light within small volumes and for huge amount of times), ring resonator and cavities are used where nonlinear effects are required. The continuously circulations of light inside the resonator, at some specific frequencies, coherently builds up its intensity to higher levels and a strong AC Kerr effect is achieved. The amount of nonlinearity dependent refractive index (RI) due to an applied electric field is [4]:

$$\Delta n_{nl} = \frac{3\chi^{(3)}}{4Z_0}\left|E_0\right|^2 = n_2I$$ (1)

where $Z_0$ is the free space impedance and $n_2$ is nonlinear refractive index expressed in term of intensity $I$. The nonlinear Schrodinger equation (NLS) is used for optical signal propagation in nonlinear media. Following the corresponding equations at, the transmission ($E_t$) and reflection ($E_r$) field at input and output ports are found as [5]:

$$E_t = E_{in1}(\sqrt{1-\gamma_t}c).$$ (2)

$$E_r = \begin{cases} 
\frac{-1-k_1}{1-\sqrt{(1-\gamma_t)(1-\gamma_r)c}\sqrt{K_1K_2}e^{-\pi L/2}e^{i(\phi_1+\phi_2)}} 
\left[1-\sqrt{(1-\gamma_t)(1-\gamma_r)c}\sqrt{(1-K_1)(1-K_2)}e^{-\pi L/2}e^{i(\phi_1+\phi_2)}\right] 
\end{cases}$$ (3)

where $\gamma_t, \gamma_r$ are the fractional intensity loss; and $K_1, K_2$ are intensity coupling coefficients of the couplers. In our case, $E_{m1}$ represents the incident field at input port and also we assumed $E_{m2}=0$. The Fig. 1a shows our used structure which consists of an octagon-like ring structure based on a square lattice with lattice constant of $a=558\text{nm}$, formed by rods of radius $r=0.2a \sim 112\text{nm}$. The octagon-like
ring has defect rods of radius \( r = 0.1a \sim 60 \text{ nm} \). Linear lattice rods are taken to be the same as \( \text{Si}_{0.75}\text{Ge}_{0.25} \) with relative permittivity of \( \varepsilon_{\text{Si}-\text{Ge}} = (3.6)^2 \) placed in air background. Ring’s inner nonlinear rods have relative permittivity of \( \varepsilon_{\text{inner}} = n_{\text{Si}-\text{Ge}}^2 \), whereas outer nonlinear ring rods are supposed to have relative permittivity the same as lattice; i.e. \( \varepsilon_{\text{outer}} = n_{\text{Si}-\text{Ge}}^2 \). As shown in Fig. 1b, in order to tune the center wavelength at \( \lambda_0 = 1550 \text{ nm} \), we have tuned the inner ring rod’s linear refractive index to \( n_0 = 1.6 \). For the nonlinear rods, we chose to work with an arbitrary material with nonlinear refractive index as \( n_2 = 10^{-16} \text{ m}^2/\text{W} \).

### Results and Discussion

In Fig. 2 a-d, four sampled whispering gallery modes of SR are shown at different normalized frequencies of \( a/f/c = a/\lambda = 0.3186, 0.3696, 0.3852, \) and \( 0.3864 \), respectively. These modes indicate the possible field patterns of some standing waves which can form within the ring. These standing waves are responsible for resonances of ring and under some of this standing wave at the output wavelengths are resonated and escape from one side to the other side (from input to output). In Fig. 3a, the transmission spectra of SR is shown. The drop efficiency is about 100% here. However due to resonator loss, the output channel amplitude has not reached more than 95%. In Fig. 3b, the transmission spectra of DR is calculated. In comparison with the single ring, one can clearly observe that the bandwidth of resonance (FWHM, \( \Delta \lambda \)) of two vertical rings has extremely decreased (at the constant \( \lambda_0 \)). Since \( \Delta \lambda \) has an inverse relation to the \( Q \)-factor (\( Q = \lambda_0/\Delta \lambda_0 \)), one can conclude that the \( Q \)-factor has increased. It is found that for a faster switching, higher \( Q \)-factors are better.

It is conventional to show the occurring of critical coupling within any resonator. Here, the Figs. 4 a-d show this phenomena known as critical coupling, which in paper is called on/off states of the SR and DR switch. As concluded from these figures the critical coupling is 100% and no power is transferred at this state from input port to through port. The other conclusion is that the SR switch works under backward dropping in which the input power is transferred to backward port, however the DR switch works under forward dropping regime. To find the time required for a pulse to pass the DR and reaches the output (i.e. DR switch changes its state from off to on) is shown in Fig. 5 and calculated to be less than 10 ps, at \( \lambda_0 = 1550 \text{ nm} \).
To find the most impactful parameter on the wavelength shift (in other words switch turn on/off), the linear refractive indices of different parts of DR are varied by very small steps. These variations are defined under three different cases: 1) changing the inner RI, and 2) changing the outer RI of DR rods.

It’s true that changing the inner rings RI is more useful than changing the outer RI, but since the outer RI also has a tiny effect on wavelength shift, thus it seems that combining these two would yield an enhanced nonlinear operation. As shown in Fig. 7, the RI of DR core rods is chosen as $n_{Ring}=1.55$ which is 0.5 RIU (refractive index unit) less than original designed value of $n_0=1.6$. This is to induce the nonlinear RI shift due to input intensities. Placing the nonlinear rods on both inner and outer rods, the power required to turn switch on/off is found to be as low as $I=6\text{mW}/\mu\text{m}^2$ for both drop and through ports of DR switch.

3 Conclusion

Since photonic crystal platforms are of promising means to achieve ultrafast switching operation as well as low consumption power and ultra-small footprint, thus we proposed a tuneable all-optical switch based double-vertically (DR) aligned Kerr-like nonlinear photonic crystal ring resonators. Silicon (Si) nano-crystal was used in nonlinear parts. The minimum optical power required to turn switch on/off was less than $6 \text{mW}/\mu\text{m}^2$. The time required for DR switch to change from on to off state at $\lambda_0=1552 \text{nm}$ was less than 10 ps.

References


