پیشنهادی برای سوییچ تنظیم پذیر تمام نوری مبتنی بر اثر کر در بستر بلورهای فوتونی

علیرضا طاوسی[۱]، مهدی صفاری[۲] و محمدعلی منصوری بیرجندی[۲]

۱-گروه مهندسی برق، دانشگاه ولایت، ایرانشهر، ایران

۲- دانشکده مهندسی برق و کامپیوتر، دانشگاه سیستان و بلوچستان، زاهدان، ایران

چکیده – در این مقاله، یک سوییچ تمام نوری تنظیم پذیر مبتنی بر اثر غیر خطی کر در بستر بلورهای فوتونی پیشنهاد می‌شود. برای افزایش بازده اندرکنش بین نور و ماده غیرخطی، یک تشدیدگر حلقوی هشت ضلعی در بستر ساختار شبکه مربعی از بلورهای فوتونی تعبیه شده است. ماده غیر خطی با ضریب شکست n_0=۱/۵ و ضریب غیرخطی n_2=۱۰$^{-۱۶}$$m^2/W$ به عنوان ماده اصلی غیرخطی انتخاب شده است. ثابت خواهیم کرد با قرار دادن دو تشدیدگر حلقوی هشت ضلعی به صورت آبشاری می‌توان با افزایش طول موثر اندرکنش، توان مصرفی و سرعت سوییچ را به شدت کاهش داد (حداقل ۱۰ مرتبه کمتر). درنهایت زمان سوئیچ بین حالت خاموش و روشن برای این قطعه در حدود ۱۰ پیکو ثانیه و توان مصرفی آن کمتر از ۶$mW/\mu m^2$ برای طول‌موج کاری λ_0=۱۵۵۲nm محاسبه شده است. نتایج با کمک روش FDTD تحلیل شده است و ساختار دارای ابعاد بسیار کوچکی می‌باشد.

کلید واژه- اثر غیرخطی کر، اپتیک غیرخطی، بلورفوتونی، تشدیدگر حلقوی.

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

Alireza Tavousi[1], Mehdi Saffari[2], Mohammad Ali Mansouri-Birjandi[2]

[1]Department of Electrical Engineering, Velayat University, Iranshahr, Iran

[2]Faculty of Electrical and Computer Engineering, University of Sistan and Baluchestan, Zahedan, Iran

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 10ps, at λ_0=1552*nm*. The minimum power required to turn DR switch state on/off is less than 6$mW/\mu m^2$. 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.

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

A. Tavousi alitavoosi@gmail.com

M. Saffari msaffari1340@gmail.com

M. A. Mansouri-Birjandi mansouri@ece.usb.ac.ir

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 λ_0=1552nm. 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]:

$$\Delta n_{NL} = \frac{3\chi^{(3)}}{4Z_0 n_L}|E_0|^2 = n_2 I \tag{1}$$

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]:

$$E_t = E_{in1}.(\sqrt{1-\gamma_1 c}). \left[\sqrt{1-k_1} - \frac{\sqrt{(1-\gamma_1 c).(1-\gamma_2 c)}.K_1.\sqrt{1-K_2}.e^{-\alpha L/2}.e^{j(\phi_{NL1}+\phi_{NL2})}}{1-\sqrt{(1-\gamma_1 c).(1-\gamma_2 c)}.\sqrt{(1-K_1).(1-K_2)}.e^{-\alpha L/2}.e^{j(\phi_{NL1}+\phi_{NL2})}}\right] \tag{2}$$

$$E_r = E_{in1}. \left[\frac{-j\sqrt{(1-\gamma_1 c).(1-\gamma_2 c)}.\sqrt{K_1.K_2}.e^{-\alpha L/4}.e^{j\phi_{NL1}}}{1-\sqrt{(1-\gamma_1 c).(1-\gamma_2 c)}.\sqrt{(1-K_1).(1-K_2)}.e^{-\alpha L/2}.e^{j(\phi_{NL1}+\phi_{NL2})}}\right] \tag{3}$$

where γ_1, γ_2 are the fractional intensity loss; and K_1, K_2 are intensity coupling coefficients of the couplers. In our case, E_{in1} represents the incident field at input port and also we assumed E_{in2}=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*=558nm, formed by rods of radius *r=0.2a ~112nm*. The octagon-like ring has defect rods of radius $r=0.1a \sim 60$ *nm*. Linear lattice rods are taken to be the same as $Si_{0.75}Ge_{0.25}$ with relative permittivity of $\epsilon_{Si\text{-}Ge}= n_{Si\text{-}Ge}^{2} = (3.6)^{2}$ placed in air background. Ring's inner nonlinear rods have relative permittivity of $\epsilon_{Inner}= n_0^2=1.6^2$, whereas outer nonlinear ring rods are supposed to have relative permittivity the same as lattice; i.e. $\epsilon_{Outer}= n_{Si\text{-}Ge}^{2}$. As shown in **Fig. 1b**, in order to tune the center wavelength at λ_0=1550nm, 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_0=1.5 and $n_2=10^{-16}$ m^2/W.

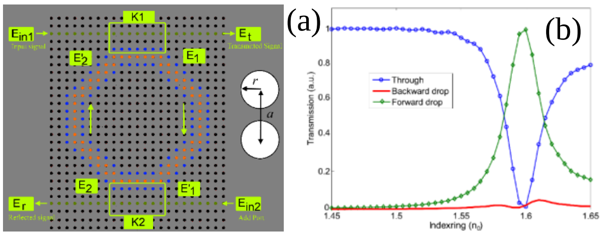

Fig. 1 (a) Schematic of a unit (SR) nonlinear PCRR, (b) Tuning of SR for finding the level of RI shift required to change switch state from on to off, at λ_0=1550nm.

3 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 λ_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.

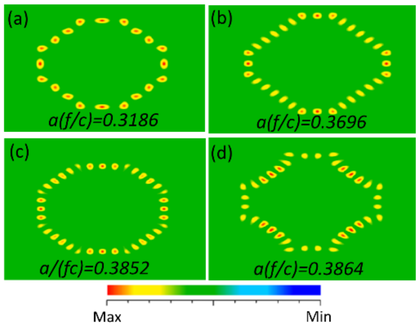

Fig. 2 Sample whispering gallery modes for SR at four different normalized frequencies of (a) $a.f/c=a/\lambda$=0.3186 (b) a/λ=0.3696 (c) a/λ=0.3852 (d) a/λ=0.3864.

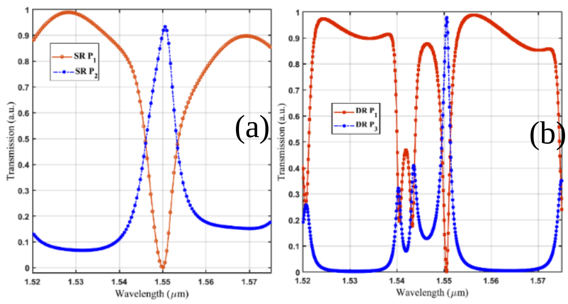

Fig. 3 the transmission/drop spectra of (a) SR (b) DR at at λ_0 = 1550 nm.

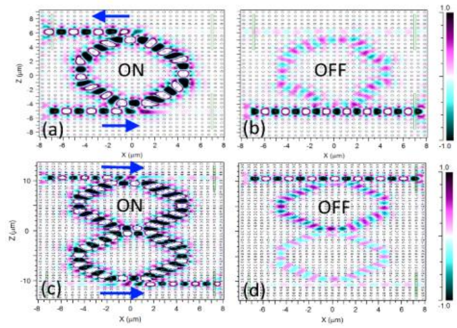

Fig. 4 The transient state of the SR and DR switch at their on/off states. (a) SR on (b) SR off (c) DR on (d) DR off.

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 λ_0 = 1550 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.

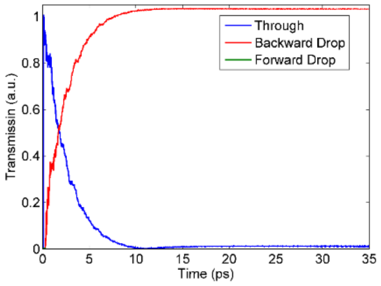

Fig. 5 the time monitor to find required time for DR switch to change state from off to on at λ_0 = 1550 nm.

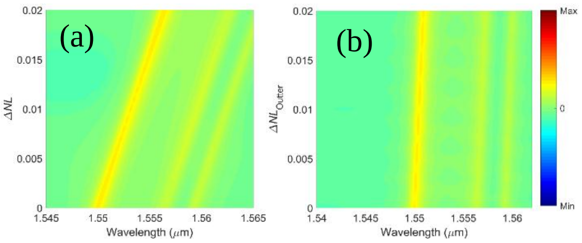

Fig. **6** Study of RI shift required to have wavelength shift. (a) Inner case (b) Outer case.

The results of this studies are shown in **Figs. 6 a-b**. As concluded from these figures, changes happening within the inner rods of DR are more important rather than those of outer DR. In inner case, a tiny variation of RI as low as 0.005 at least induces 1.5 nm wavelength shift. This information is also useful for wavelength division multiplexing applications.

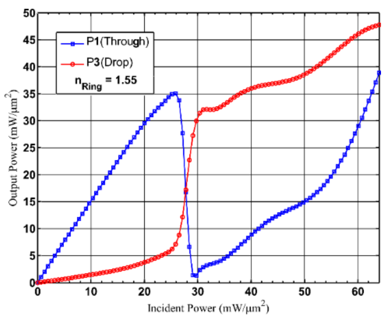

Fig. 7 Study of incident power required for turning the DR switch on/off in Inner PCRR scenario.

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=6mW/μm^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 mW/μm^2. The time required for DR switch to change from on to off state at λ_0=1552 nm was less than 10 ps.

References

[1] M. A. Mansouri-Birjandi, M. Janfaza, and A. Tavousi, "Flat-Band Slow Light in a Photonic Crystal Slab Waveguide by Vertical Geometry Adjustment and Selective Infiltration of Optofluidics," *Journal of Electronic Materials,* journal article vol. 46, no. 11, pp. 6528-6535, 2017.

[2] F. Cuesta-Soto *et al.*, "All-optical switching structure based on a photonic crystal directional coupler," *Optics Express,* vol. 12, no. 1, pp. 161-167, 2004.

[3] A. Bristow *et al.*, "Ultrafast nonlinear response of AlGaAs two-dimensional photonic crystal waveguides," *Applied physics letters,* vol. 83, no. 5, pp. 851-853, 2003.

[4] M. A. Mansouri-Birjandi, A. Tavousi, and M. Ghadrdan, "Full-optical tunable add/drop filter based on nonlinear photonic crystal ring resonators," *Photonics and Nanostructures-Fundamentals and Applications,* vol. 21, pp. 44-51, 2016.

[5] G. Rostami and A. Rostami, "All-optical integrated coding system for optical analog to digital (A/D) converter," *Laser Physics Letters,* vol. 1, no. 8, pp. 406-410, 2004.