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FAST AND SLOW LIGHT ENHANCEMENT USING CASCADED MICRORING RESONATORS WITH THE SAGNAC REFLECTOR

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Abstract

A cascaded microring resonator based on silicon waveguides with an MMI (Multimode Interference) based Sagnac reflector is proposed in this study. By controlling the coupling coefficients with the used of the MMI based Sagnac reflector, the double of both pulse delay and advancement for the slow and fast light can be achieved. The new structure can produce the fast and slow light phenomenon on one chip with a double of the time delay and pulse advancement. By using the Sagnac reflector, the device is very compact. Transfer matrix method and FDTD (Finite Difference Time Domain) simulation are used to obtain the characteristics of the device. The transmission, phase, group delay and pulse propagation are analyzed in detail. Our FDTD simulations show a good agreement with the analytical theory.

Keywords: *Microring resonator, fast light, slow light, silicon waveguides, FDTD, transfer matrix method, multimode interference (MMI), microresonators*

1. Introduction

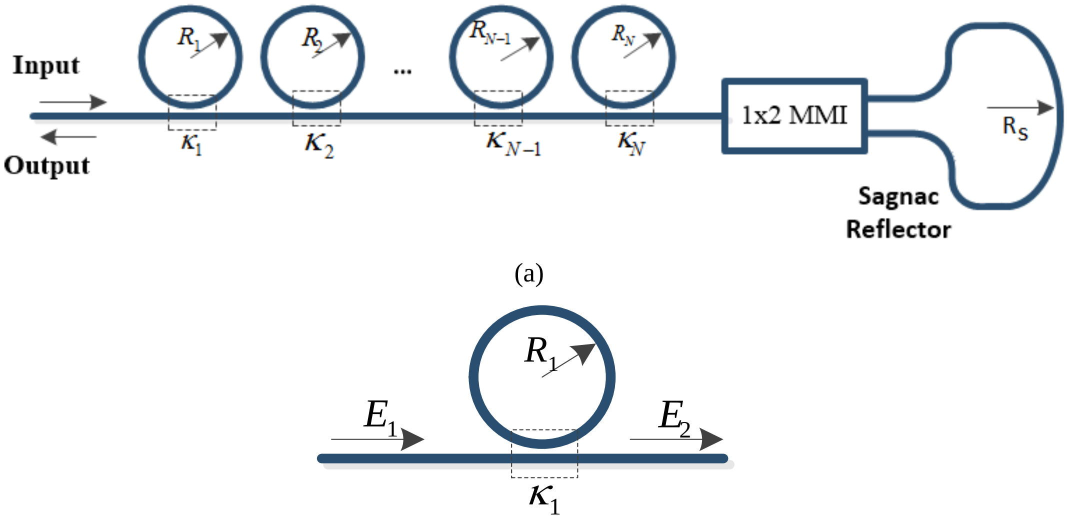
In recent years, optical microring resonators have been of great interest for applications in optical communications such as optical delay lines, optical switches, modulators, filters, dispersion compensators etc. [1, 2]. Micro-ring resonator structures consists of a number of single micro-ring resonators cascaded in series or in parallel can be used for higher order filters with extended free spectral ratios [3] or switching [4], modulating applications [5], fast and slow light [6].

Analysis of the group delay and transmission characteristics of cascaded microring resonators used for optical filters and dispersion compensators have been studied [7-9]. However, these structures have positive group delay and mainly designed for pulse delay applications. Slow and fast light generation are emerging as a very attractive research topic. Various techniques have been developed to realize fast light and slow light in atomic vapors and solid-state materials [10]. One application among these techniques is to control the group velocity v_g of light pulses to make them propagate either very slow ($v_g < c$) or very fast ($v_g > c$ or v_g is negative), where c is the velocity of light.

In this study, we propose a new cascaded microring structure based on silicon waveguides with a Sagnac loop reflector. The Sagnac loop reflector has been applied to many application structures such as filtering and fast light structures [11, 12]. By controlling the coupling coefficients of the coupler used in microring resonators in the proposed structure, negative and positive group delay can be obtained. This means that the light velocity can be controlled and therefore the fast and slow light can be induced by the structure [13-15]. Here, we use a Sagnac loop reflector based on an 1x2 MMI (Multimode Interference coupler) at the end of the structure to enhance the fast and slow light. The use of an MMI based reflector for the reflection to double the pulse delay and pulse advancement. It is shown that the group delay, time delay and advancement are doubled compared to the case without using the MMI Sagnac loop reflector. We use silicon microring resonators because of high quality of fabrication by using CMOS compatible process and device compactness with a high index contrast system.

2. Design

The structure consisting of N-single microring resonators cascaded in series with a Sagnac loop reflector is proposed in Figure 1(a).



(a)

(b)

Figure 1: (a) *Cascaded microring resonators with Sagnac loop reflector amd (b) Single microring resonator*

2.1. Single microring resonator

For a single microring resonator as shown in Figure 1(b), the output field can be related to the input field by the expression [16]

$$H_1 = \frac{E_2}{E_1} = \frac{\tau_1 - \alpha_1 \exp(j\theta_1)}{1 - \alpha_1 \tau_1 \exp(j\theta_1)} \tag{1}$$

Where E_1, E_2 are the field amplitude at the input and output; τ_1 and $\kappa_1 = \sqrt{1 - |\tau_1|^2}$ are the transmission and coupling coefficients of the coupler; α_1 is the loss factor in the ring waveguide and $\theta_1 = \frac{2\pi}{\lambda} N_{eff} L_{R1}$ is the accumulated phase shift over the ring waveguide. N_{eff} is the effective refractive index of the waveguide, λ is the wavelength and $L_{R1} = 2\pi R_1$ is the circumference of the ring waveguide.

The effective phase shift of the microring resonator can be defined by

$$\phi_{single} = arg\left\{\frac{E_2}{E_1}\right\} = artan\left\{\frac{\alpha_1 \kappa^2 \sin(\omega)}{(1 + \alpha_1{}^2)\tau - (1 + \tau^2)\alpha_1 \cos(\omega)}\right\} \tag{2}$$

The normalized group delay is given by $\tau_n = -\frac{d\phi_{\text{single}}}{d\omega}$. The absolute group delay is $\tau_d = T\tau_n$, where T is the unit delay of the signal propagating over the microring waveguide. The resonance is occurred at the phase $\theta_1 = 2m\pi$, where m is an integer. At resonance, $\tau_1 > \alpha_1$ the ring resonator and waveguide is under-coupled and leading to pulse advancement or fast light; when $\tau_1 < \alpha_1$, they are over-coupled and leading to pulse delay or slow light; the critical coupling occurs when $\tau_1 = \alpha_1$.

The transmission, phase and group delay of the single microring resonator at the transmission coefficients $\tau_1 = 0.9975$, 0.9966 and 0.99 respectively are shown in Figure 2. The parameters are set as follows: the loss factor of the waveguide $\alpha_1 = 1\text{dB/cm}$, the length of the microring waveguide $L_{R1} = 300\mu\text{m}$. The simulation shows that the positive and negative group delay can be achieved by adjusting the coupling coefficient of the coupler. It is assumed that a silicon waveguide with a height of 220 nm and width of 400 nm and refractive index $N_{eff} = 2.25$.

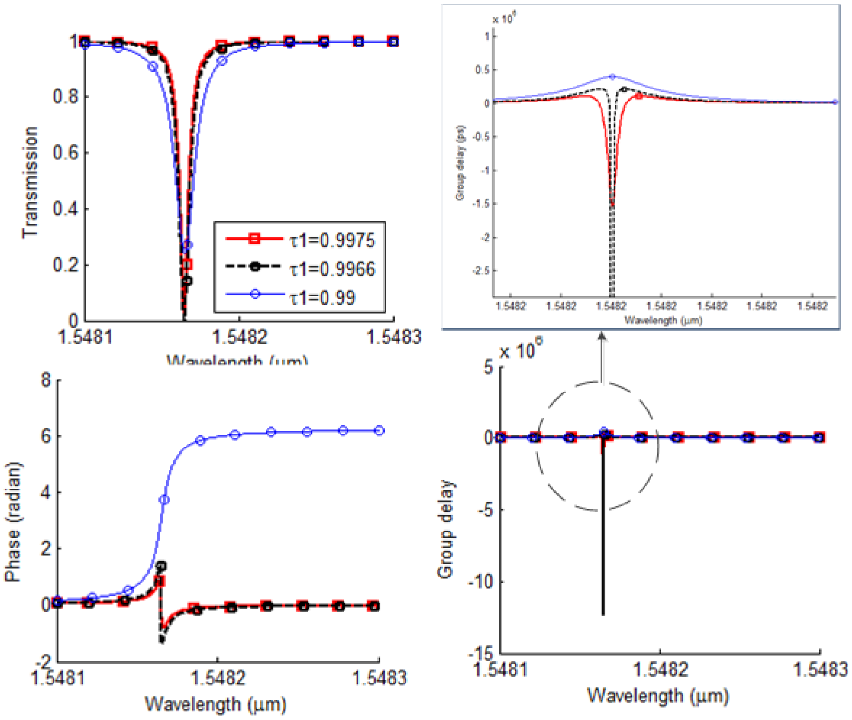


Figure 2: *Transmission, phase and group delay characteristics of the single microring resonator*

We now investigate the pulse propagation over the single ring resonator. It is assumed that the input pulse is Gaussian and can be expressed as [17]

$$E(t) = \exp(-(t/T_{HW})^2)\exp(j2\pi ct/\lambda_0) \tag{3}$$

Where λ_0 is the resonance wavelength of the single microring resonator, $T_{HW} = T_b/2$ is the bit half width at $1/e^2$ intensity and T_b is the bit period. From the simulations of Figure 2, the resonance wavelength is $\lambda_0 = 1.54817\,\mu m$. The input and corresponding output pulses with the transmission coefficients $\tau_1 = 0.9975,\ 0.9966$ and 0.99 are shown in Figure 3, where the input pulse width $T_p = 50\,ps$ [18]. The simulations show that pulse delay of 20ps can be obtained when $\tau_1 = 0.99$ and when $\tau_1 = 0.9975$ the pulse advancement of 12ps is obtained.

2.2. Cascaded microring resonators

A side coupled integrated spaced sequence of resonators (SCISSOR) or cascaded microring resonator without the Sagnac reflector has been firstly proposed by Heebner and Boyd [19]. It was shown that by using SCISSOR structure, fast and slow light can be obtained. Here, we consider a SCISSOR as shown in Figure 1 with a Sagnac loop reflector. For simplicity, we assume that N ring resonators are identical. As a result, the transfer function of the SCISSOR can be written by

$$H_{SCISSOR} = H_1 H_2 \ldots H_N = \left(\frac{E_2}{E_1}\right)^N = \left\{\frac{\tau - \alpha\exp(j\theta)}{1 - \alpha\tau\exp(j\theta)}\right\}^N \tag{4}$$

Here $\tau = \tau_1$ and $\alpha = \alpha_1$ is the loss factor in the ring waveguide and $\theta = \frac{2\pi}{\lambda} N_{eff} L_R$.

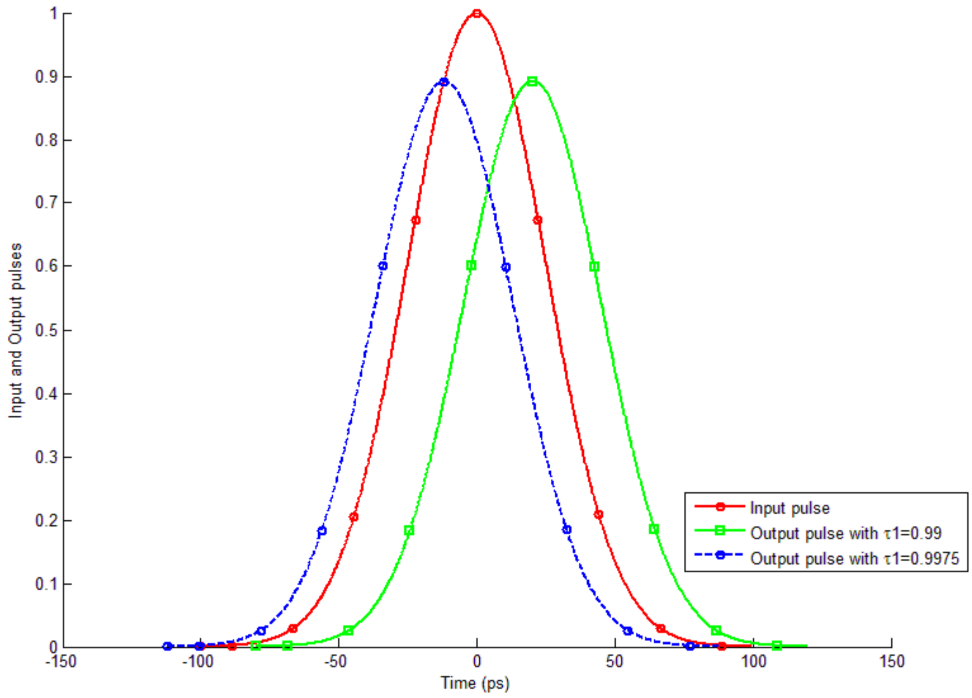


Figure 3: *Input and output pulses at the single microring resonator*

The transmission, phase and group delay of the cascaded microring resonator for N=1, 2, 3 are shown in Figure 4 and 5. It is assumed that the transmission coefficient of the coupler is $\tau_1 = 0.99$ and 0.9975. The simulation results show that slow and fast light are induced by adjusting the coupling coefficients. In addition, the pulse delay and pulse advancement are increased by N times compared with the single microring resonator.

2.3. Cascaded microring resonators with the Sagnac reflector

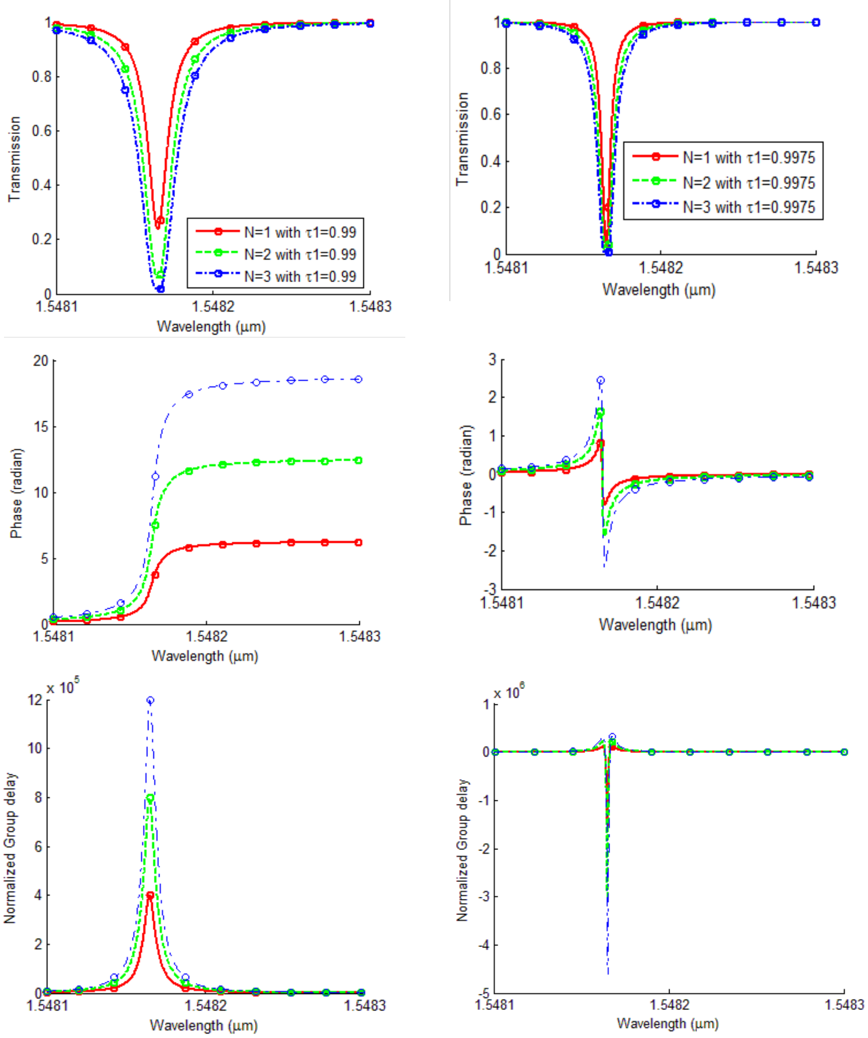
Figure 1 shows the cascaded microring resonator with the Sagnac reflector. In this study, we use an 1x2 MMI coupler in the Sagnac reflector. As a result, the transfer function of the proposed structure in Figure 1 can be expressed by

$$H = (2j\alpha_s\kappa_s\tau_s)\left\{\frac{\tau - \alpha\exp(j\theta)}{1 - \alpha\tau\exp(j\theta)}\right\}^{2N} \qquad (5)$$

Where τ_s and $\kappa_s = \sqrt{1 - |\tau_s|^2}$ are the transmission and coupling coefficients of the coupler of the Sagnac reflector and α_s is the loss factor in the ring waveguide of the Sagnac reflector.

Figure 6(a) and (b) show the transmission, phase, group delay and output pulses propagating over the structure with and without Sagnac reflector. It is assumed that the structure consisting of N identical microring resonators (N=1 and 2) with the transmission coefficient of $\tau_1 = 0.99$. By using the Sagnac reflector, we obtain the pulse delays of 43ps and 83ps for N=1 and 2 respectively, compared with 20ps and 40ps without using the Sagnac reflector.

When $\tau_1 = 0.9975$, the undercoupled condition occurs. Therefore, the fast light can be induced by using the proposed structure. Figure 7(a) and (b) show the transmission characteristics and output pulses propagating over the structure with and without Sagnac reflector. It is shown that pulse advancements of 25ps and 50ps are achieved when the Sagnac reflector is used (compared with 12ps and 24ps without the Sagnac reflector).



(a) $\tau = \tau_1 = 0.99$ (b) $\tau = \tau_1 = 0.9975$

Figure 4: *Transmission characteristics of the cascaded microring resonators (a)* $\tau = \tau_1 = 0.99$ and (b) $\tau = \tau_1 = 0.9975$

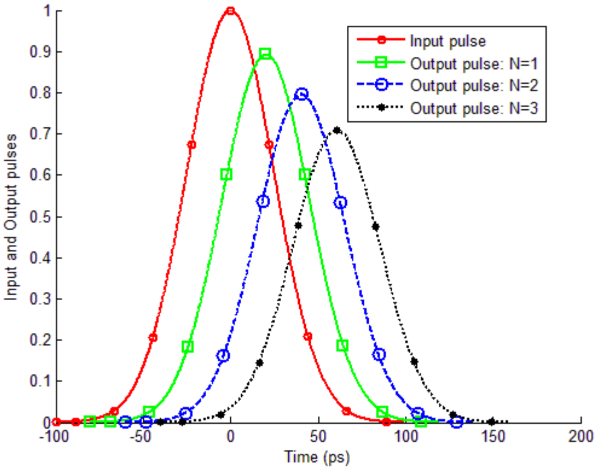
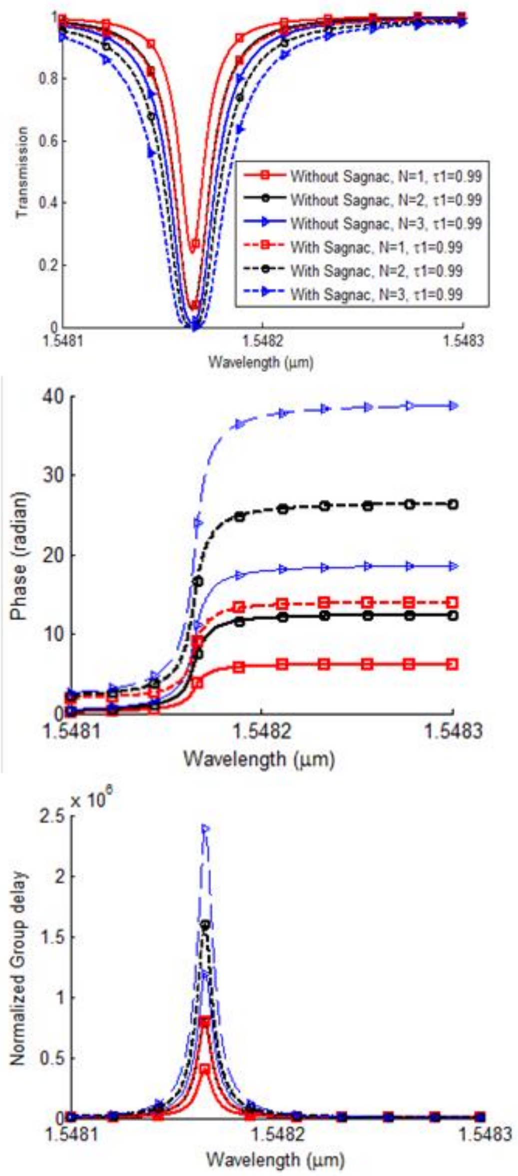
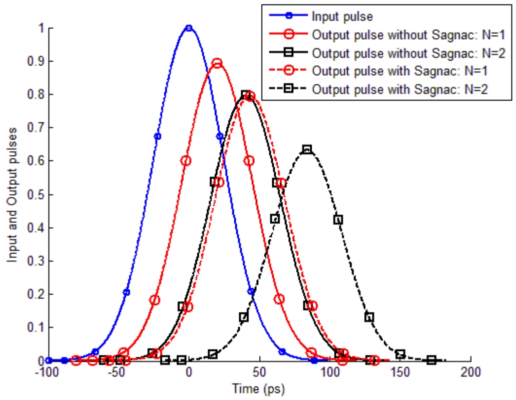


Figure 5: *Input and output pulses at the cascaded microring resonator structure*

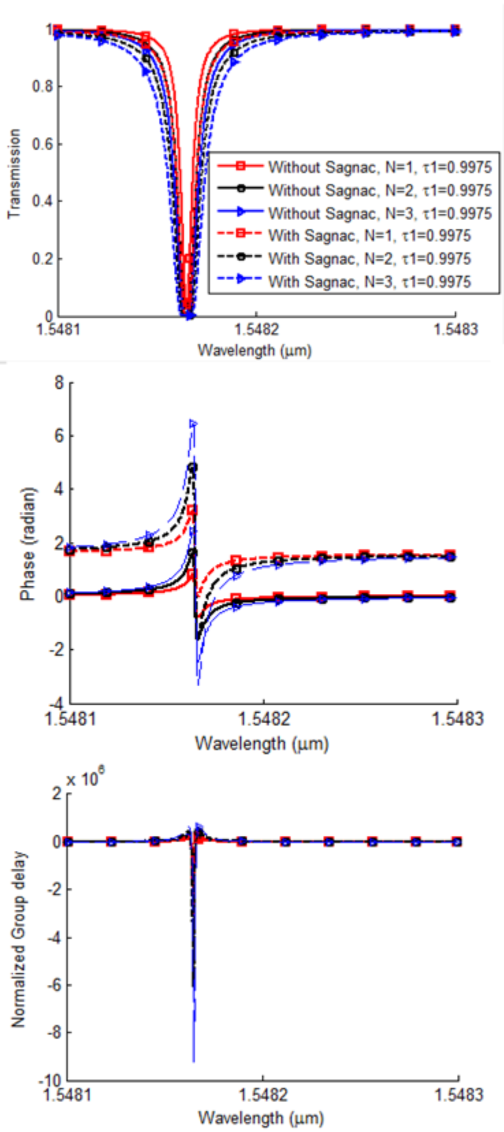


(a)

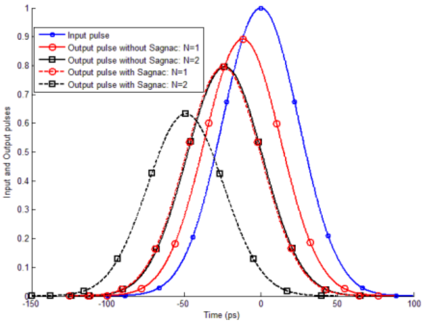


(b)

***Figure 6**: Transmission characteristics of the cascaded microring resonators (a)* $\tau = \tau_1 = 0.99$ *and (b) output pulses*



(a)



(b)

***Figure 7**: Transmission characteristics of the cascaded microring resonators (a)* $\tau = \tau_1 = 0.9975$ *and (b) output pulses*

By controlling the coupling coefficients of ring resonators, the fast and slow light can be achieved. The pulse delay and advancement can be increased by N times if N identical ring resonators are used. Figure 8 shows the time delay and advancement of the pulse propagating through our prosed structure. We can see that by using the Sagnac reflector, the pulse delay and advancement can be doubled compared with the conventional SCISSOR structure.

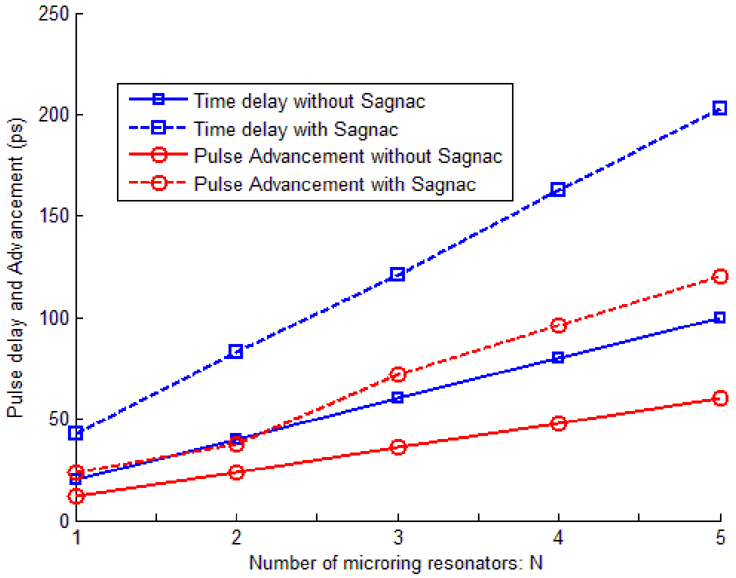


Figure 8: *Time delay and advancement with and without the Sagnac reflector*

To verify the accuracy of the transfer matrix analysis, we compare the results obtained with the FDTD. For our FDTD simulations, the radius of the microring resonator is to be $R = 5\mu m$, the waveguide width is $W_a = 400nm$, the gap between the microring waveguide and the straight waveguide is chosen to be $g = 160nm$ in order for the power transmission coupling ($|\tau|^2$) to be $|\tau|^2 = 0.9$ as shown in Figure 10(a). Here we take into account the wavelength dispersion of the silicon waveguide using the expression $N_{eff}(\lambda) = 4.7020 - 1.6667\lambda$ for $\lambda = 1.5 - 1.6\mu m$ (Figure 10(b)).

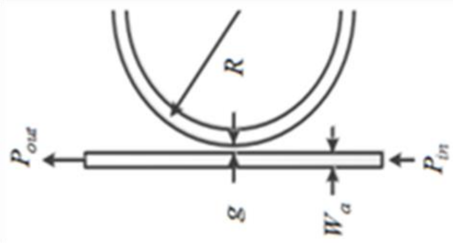
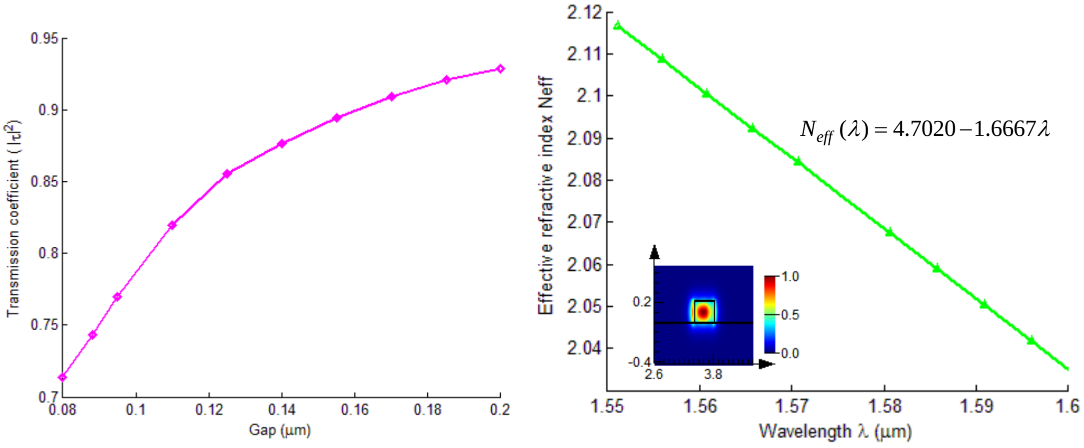


Figure 9: *Directional coupler used for microring resonator*



(a) (b)

***Figure 10**: FDTD simulations (a) transmission coefficient at different gap and (b) wavelength dispersion of the silicon waveguide with a width of 400nm (the inset shows the field at $\lambda=1.55\mu m$)*

A Gaussian light pulse of 15fs pulse width is launched from the input to investigate the transmission characteristics of the device. The grid size $\Delta x=\Delta y=0.02nm$ and $\Delta z=0.05$ are chosen in our simulations. As shown in Figure 11(a) with a number of the microring resonator N=1 and Figure 12(a) with N=2, the transmissions calculated by the FDTD are quite similar to the transmission calculated by the analytical theory. Figure 11(b) and 12(b) show the FDTD field distributions at on and off-resonances.

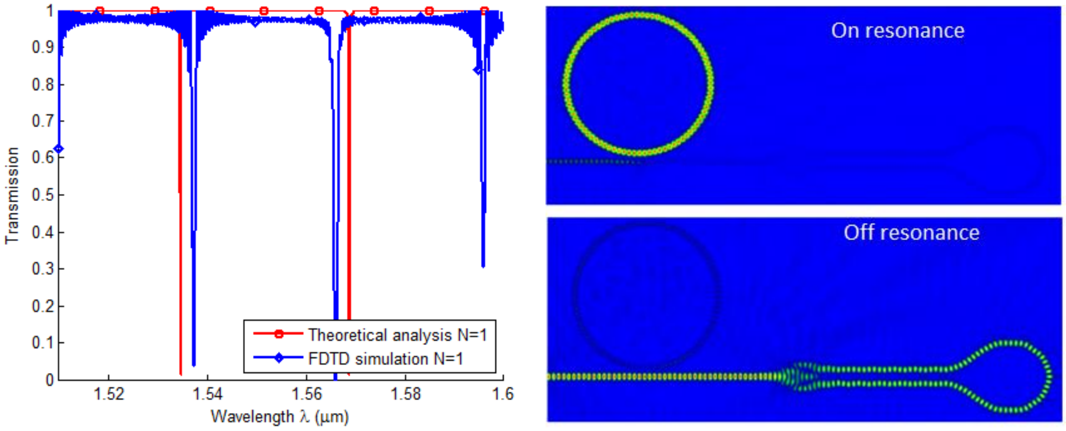


***Figure 11**: FDTD simulation of the proposed structure with one ring resonator and Sagnac reflector.*

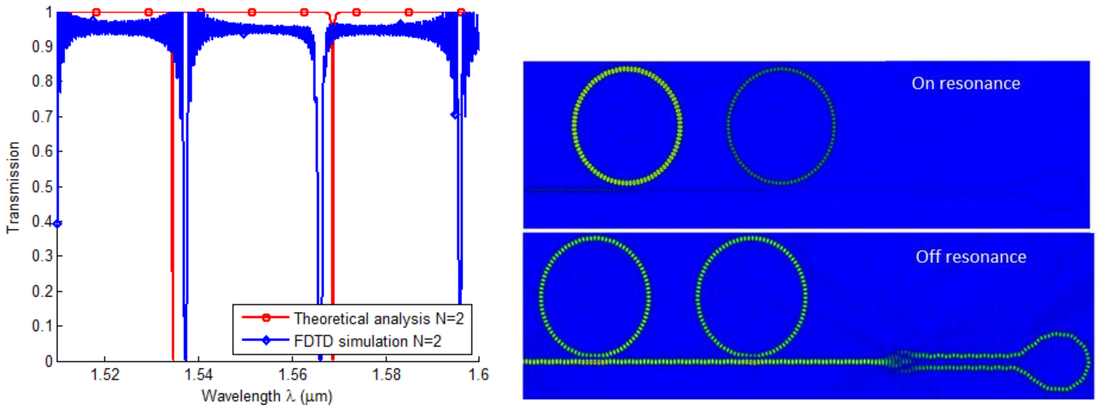
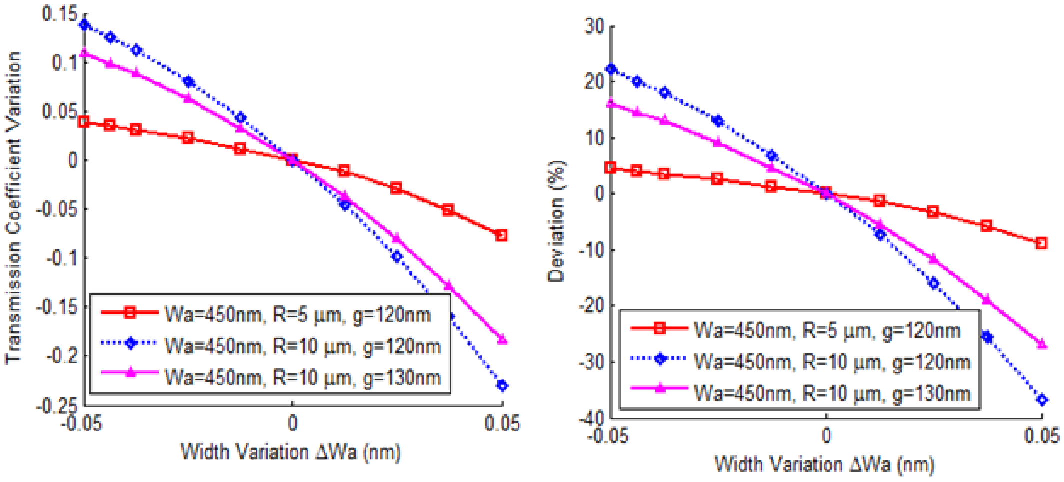


Figure 12: *FDTD simulation of the proposed structure with two ring resonators and Sagnac reflector*

The simulation results for the deviation of the transmission coefficient $\Delta\tau^2$ depending on the waveguide width variation ΔW_a are shown in Fig. 13. Due to the manufacturing tolerances, the variation in waveguide width occurs and leading to a new waveguide width expressed by $W = W_a \pm \Delta W_a$. Adding to the change of the transmission coefficient, the deviation of the waveguide width also leads to the change in effective index. For a positive ΔW_a, the effective index is increased. For any gap and radius, a positive ΔW_a leads to a decrease in the transmission coefficient. For $\Delta W_a = +10\text{nm}$, the transmission coefficient is decreased by 0.044 for g=120nm and 0.037 for g=130nm at the same width Wa=450nm and radius R=10µm. While this coefficient is decreased only by 0.012 if the ring radius R=5µm. As a result, the transmission coefficient of the coupler is quite stable for a smaller ring radius and larger gap. For a width variation within ±20nm, a deviation of the transmission coefficient of 13% can be obtained. For either e-beam or DUV lithography, size deviations of up to ±20 nm from design are very easy [20].



(a) (b)

Figure 13: *Change of the transmission coefficient and the deviation from the calculated value at Wa=450nm as the effect of the width variation*

3. Conclusion

We have proposed a cascaded microring resonator with an MMI based Sagnac reflector. The transmission, phase, group delay and pulse propagation characteristics are analyzed. The proposed structure can induce the fast and slow light by controlling the coupling coefficients of the couplers. The time delay and advancement can be doubled compared with the conventional SCISSOR structure without the Sagnac reflector. The fabrication tolerance is high and suitable for CMOS fabrication technology.

ACKNOWLEDGEMENTS

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