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Photon Storage in a Dynamic Two-Ring-Two-Bus System

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Abstract

We propose a novel dynamic two-ring-two-bus system to achieve photon storage. We have demonstrated numerically that the photon can be stopped and released by tuning the ring coupled to two buses in a short time. The two-ring-two-bus system is fabricated on the silicon-on-insulator platform, with the Q factor changing significantly when shifting one resonance. Due to the flexibility and simplicity, it is a promising candidate for the future optical storage and buffering device.

Keywords

Resonators, Optical Storage, Integrated Photonics

1. Introduction

The ever-increasing demand to store light for long time using compact devices, has led to a variety of approaches to manipulating light. Ideally, an optical buffer should have not only a large delay, but the delay should be constant over a broad bandwidth. Optical memory schemes have been demonstrated using slow light including both optical [1] [2] [3] and electromagnetically induced transparency (EIT) [4] [5]. Some investigations have demonstrated the storage time within the resonator can become larger than the inverse of the bandwidth of the input pulse by introducing a time-changing Q-factor [6] [7]. Notomi and Mitsugi [8] showed that the physical effect behind this method is the adiabatic tuning of an oscillator, such as a guitar string. In addition, it is also possible to stop light by dynamically changing a coupled resonator system as was predicted by Yanik and Fan [5].

In this paper, we investigate an optical storage device based on two mutually coupled ring resonators, with one ring coupled to two waveguides (*i.e.*

ring-bus-ring-bus, 2R2B). The storage time can be longer than the photon lifetime in the system by dynamically tuning the refractive index of resonator. The way of changing the refractive index is flexible. The dynamic optical storage is demonstrated using numerical simulations. We choose the silicon microrings as the platform because it has a high Q factor and a small mode volume, and can be fabricated on a chip. We get the quality value changed significantly.

2. Theoretical Analysis

The schematic structure is shown in **Figure 1**. The transmission coefficients in the ring 1-bus and ring 1-ring 2 coupling regions are denoted as t_1 and t_2 (the coupling coefficient is $k_{1,2} = \left(1 - t_{1,2}^2\right)^{1/2}$), respectively. Using the transfer functions of the one-ring system [9], the through (T) and drop (D) transfer functions of the two-ring-two-bus system can be given by **Figure 1**. Example of a figure caption

$$D = \left|\frac{E_D}{E_{IN}}\right|^2 = \left| -\frac{\sqrt{a_1}\tau_{21}(1-t_1^{\,2})\exp(-i\delta_1/2)}{1-a_1 t_1^{\,2}\tau_{21}\exp(-i\delta_1)} \right|^2 \quad T = \left|\frac{E_T}{E_{IN}}\right|^2 = \left|\frac{t_1 - a_1 t_1 \tau_{21}\exp(-i\delta_1)}{1 - a_1 t_1^{\,2}\tau_{21}\exp(-i\delta_1)}\right|^2$$

where $\tau_{21} = \left[t_2 - a_2 \exp\left(-i\delta_2\right)\right] / \left[1 - a_2 t_2 \exp(-i\delta_2)\right]$. $\delta_{1,2} = \omega n 2\pi R_{1,2}/c$ and $a_{1,2}$ are the round-trip phase shift and attenuation of ring 1 or ring 2, respectively. We can consider the effect of ring 2 as introducing additional loss and phase shift for ring 1.

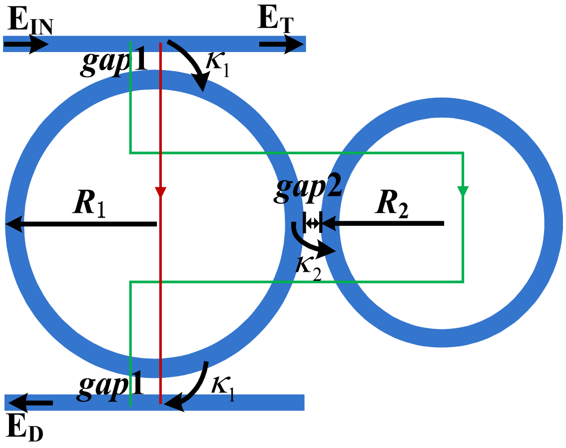

Figure 1. Schematic of the 2R2B structure.

Next, we calculate the transmission spectra and optical intensities in the rings. The radius of ring 1 is set as 28 μm, while the radius of ring 2 is 21 μm. The transmission coefficients are $t_1 = 0.809$, $t_2 = 0.9$. The effective index of waveguides is assumed as n = 2.748. When the original resonances of two rings are aligned, the light first couples to ring 1, and then reaches ring 2. The transmission spectrum of two microrings exhibits an EIT-like resonance (as shown in **Figure 2(a)**) and the light is confined in both rings. When we change the refractive index and shift the resonance of ring 1, the resonance of ring 2 becomes a

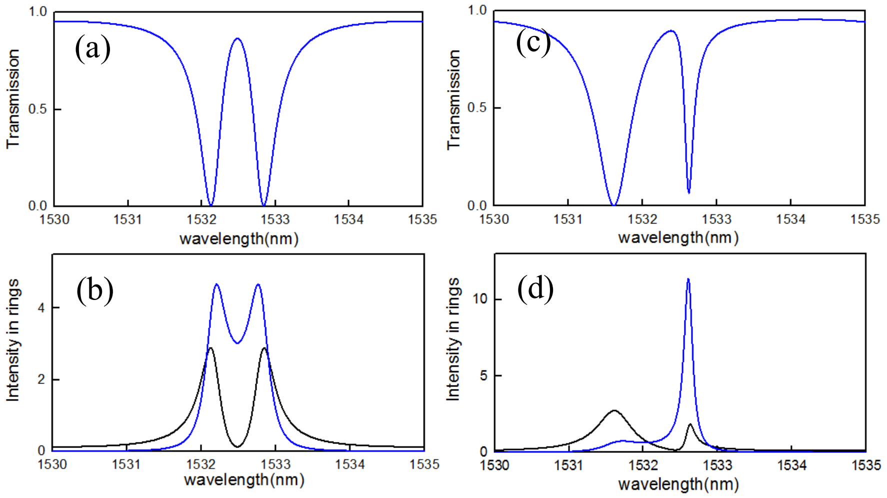

Figure 2. Tuning the cavity: (a) , (b) no tuning. (c), (d) the index of ring 1 is decreased 0.01. Shown are (a), (c) transmission spectrum and (b), (d) corresponding signal intensities in ring 1 (black solid curve) and ring 2 (blue solid curve).

narrow resonance, as seen in **Figure 2(c)**. The light is mostly located in ring 2 and the Q factor of the system increases significantly (**Figure 2(d)**).

3. Simulation and Experiment

The 2D FDTD simulation is performed by launching a 15 ps Gaussian pulse at the resonant wavelength (λ_{res} = 1532.56 nm) into the device. In our structure, the width of all waveguides is 400 nm. The gap between the waveguide and ring 1 is 200 nm, and the gap between the two rings is 300 nm. Two rings are resonant at this wavelength, when we change the refractive index of the ring 1, it is decoupled from the ring 2 and waveguides. The light in the ring 2 can be trapped. Without the dynamic tuning of the cavity, light leaks out of the cavity continuously as it couples into waveguide. The only condition is that the change needs to occur in a time shorter than the cavity lifetime, while the light is confined in the resonator.

When we decrease the index of ring 1 by $\Delta n = 0.01$, the resonant wavelength blue-shifts. The refractive index is decreased linearly from t = 20 ps to t = 20.3 ps, then it is maintained at n = 2.738 (the dashed blue line in **Figure 3(a)**). As seen in **Figure 3(c)** and **Figure 3(d)**, the ring 1 is decoupled with waveguides and the ring 2, and the field is mostly located in the ring 2 after tuning. The light in the ring 1 has leaked out of the cavity. Besides, if we recover the index after 40 ps (the solid red line in **Figure 3(a)**), the ring 1 recouples to the ring 2 and the waveguide, which releases the trapped pulse consequently. Then we apply two stages of modulating refractive index to the ring 1 and derive time-domain waveforms of the output pulse and ring 2 (**Figure 4**).

As seen in **Figure 4(a)**, the output intensity drops to almost zero when the index is tuned (the solid red line), owing to the broken coupling of the ring 1 and waveguides. At the same time, the signal light is captured in ring 2 and this

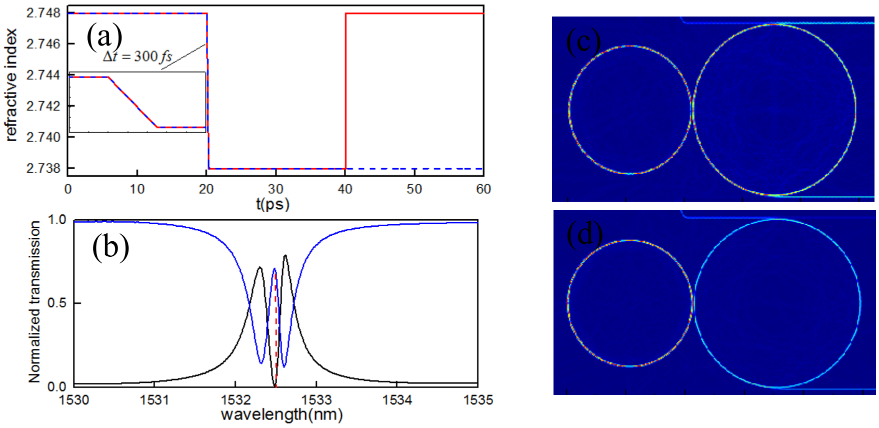

Figure 3. (a) Temporal variation of the refractive index at Δt = 300 fs in the ring 1. (b) The simulated transmission and the dashed red line corresponds to resonant wavelength. (c) Field distribution in the 2R2B system at 19 ps. (d) Field distribution in the 2R2B system at 21 ps.

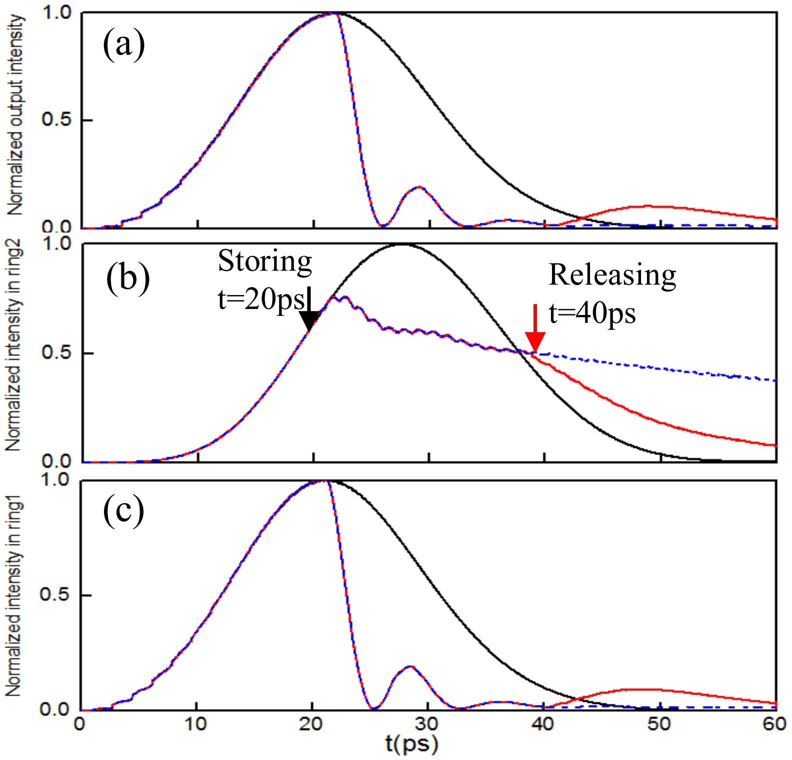

Figure 4. Numerical simulation results. (a) Envelope of electric field for the two stages of the modulated operations in the drop. Solid black line: Output waveform without dynamic tuning. Solid red line: Output waveform with dynamic tuning from 20 ps to 40 ps. Blue dashed line: Output waveform with dynamic tuning after 20 ps. (b) Envelope of electric field for the modulated operations in ring 2. (c) Envelope of electric field for the modulated operations in ring 1.

state can be kept for dozens of picoseconds at least. When the index back to its initial value, the waveform of output pulse demonstrates that a released pulse appears(solid red line in **Figure 4(a)**). And the resonances of two cavities

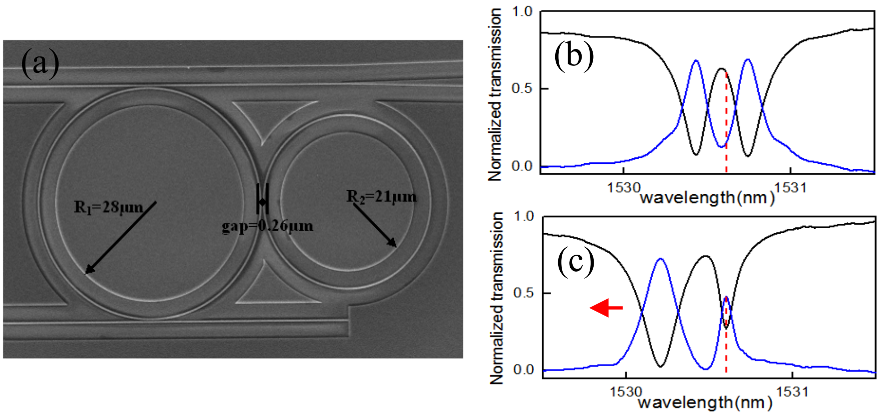

Figure 5. (a) The SEM image of the two-ring-two-bus system. (b) The measured transmission at initial state. (c) The measured transmission after modulating the resonance peak of ring 1.

become matched again, the light in ring 2 is allowed to couple into ring 1 (the solid red line in **Figure 4(c)**). These results are direct evidences proving that the buffering is achieved and storage time is 20 ps approximately. By contrast, if we don't recover the index, there is no released pulse at output (the dashed blue line in **Figure 4(a)**). Correspondingly there is no light in ring 1. This is because the modulation causes a mismatch between the resonances of ring 1 and ring 2, it prevents the light in ring 2 from escaping to ring 1. Besides, we also see an evidence of oscillations of decreasing intensity after the index change has been completed in **Figure 4(a)**. We interpret these oscillations as resulting from beating of light at the shifted frequency with light at the original frequency. It is believed to be small enough to have no influence on the buffering performance.

Then, we fabricated the two-ring-two-bus system in silicon. The SEM image of device is shown in **Figure 5(a)**. The gap between two rings is 0.26 μm, and R1 = 28 μm, R2 = 21 μm. The desired results are obtained. **Figure 5(b)** shows the measured through and drop transmission before tuning ring 1. It is a class-like EIT resonant peak and there is a symmetric resonance splitting around 1530.61 nm. When we decrease the radius of ring 2, the resonant wavelength of ring 2 is blue-shifted, resulting in two greatly separated resonances for the system. It is found that the Q factor of the system is significantly increased from 10204 to 19132. The results imply that if the refractive index of the microring is changed by injecting pump pulse, the system will be able to store and release optical pulse dynamically.

4. Conclusion

In summary, we have demonstrated an optical buffer based on a two-ring-two-bus structure by tuning a ring. The photon storage and release are demonstrated numerically in the structure. The Q value changing from 10,204 to 19,132 is realized by shifting the resonance peak of ring 1. Our buffer is independent of the mechanism used for index tuning, and the tuning time is smaller than the photon time, such as carrier injection and Kerr effect. The captured pulse can be held long enough to exceed the constraints of the delay-bandwidth product imposed on the passive all-optical approaches. Although the buffering time was shorter than those of previous studies, we believe that it can be improved as the Q factor of the ring increases.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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