Concentric silicon micro-ring resonators with enhanced transmission notch depth

Xiaohui Li*[a], Ziyang Zhang[b], Qiang Li [b], Min Qiu [b], Yikai Su *[a]

a State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University,

800 Dongchuan Rd, Shanghai 200240, China, yikaisu@sjtu.edu.cn

b Department of Microelectronics and Applied Physics, Royal Institute of Technology, 164 40 Kista, Sweden

ABSTRACT

In this work, we have analyzed, fabricated and demonstrated concentric micro-ring resonators in silicon-on-insulator (SOI) structure for enhanced transmission notches. The operation principles of the concentric ring resonators are studied by time-domain coupled-mode theory. Directional coupling between concentric rings offers another freedom in designing deep notch optical filters and ultra-sensitive biosensors. The finite-difference-time-domain (FDTD) simulations have shown the improvement of the notch depth, evenly distributed mode field and the effect of the resonance shift. The device is demonstrated in silicon-on-insulator structure. Transmission notch depth improvement of ~ 15dB is demonstrated for the 21-20.02-μm-radius double-ring structure comparing with the single 21-μm-radius ring.

Keywords: concentric micro-ring resonators, silicon-on-insulator

1. INTRODUCTION

Micro-ring resonators based on silicon-on-insulator (SOI) structure are promising building-blocks for ultra-compact and highly integrated photonic circuits. The fabrication technology is mostly CMOS-compatible. Potential applications include optical filtering, switching, signal processing and bio-sensing [1]. Micro-ring resonators with high quality factors (Q) and deep transmission notches are desired in most cases.

However, it is practically challenging to achieve deep notches in the transmission spectra for the single-waveguide-single-ring structure. To reach the conventional critical coupling, the resonator intrinsic factor (Q_i) and the coupling quality factor with the waveguide (Q_e) must be equal. The resonant channel is then completely dropped. Usually, the width of the ring and waveguide and the air gap between them should be tuned carefully for that purpose.

Optoelectronic Materials and Devices III, edited by Yi Luo, Jens Buus, Fumio Koyama, Yu-Hwa Lo
Proc. of SPIE Vol. 7135, 71350Q · © 2008 SPIE · CCC code: 0277-786X/08/$18 · doi: 10.1117/12.804230

In this work we present a new scheme to improve the transmission notch depth by placing another concentric ring and generating directional coupling between the rings. The coupled modes diffuse across the rings, which may be favourable for bio-sensing applications as it expands the detection area.

2. COUPLED MODE THEORY FOR CONCENTRIC RINGS

Fig. 1 shows the device schematic. Here we define the energy of the resonant mode in the outer ring as a(t), and similarly defined is the inner ring resonant mode b(t). The coefficients for the waveguide-ring coupling and the ring-ring coupling are denoted as k and u, respectively. The transfer function can be expressed by [2-4]

$$T(w)=\frac{|S_o|^2}{|S_i|^2}=\left|1-\frac{|k_a^2|[j(w-w_b)+\frac{1}{t_b}]}{[j(w-w_a)+\frac{1}{t_a}][j(w-w_b)+\frac{1}{t_b}]+u^2}\right|^2 \qquad (1)$$

where ω_a is the resonant frequency, τ is the photon life time. $1/\tau=1/\tau_e+1/\tau_i$, where $1/\tau_e$ is decay rate into the waveguide and $1/\tau_i$ is decay rate due to intrinsic loss. The quality factor (Q) is decided by the photon life time, i.e., $Q=\omega_0\tau/2$. The waveguide-ring coupling coefficient and the power decay rate are related by $|\kappa|^2=2/\tau_e$. To simplify the analysis, we only consider the case when the two rings happen to resonate at the same frequency, which can be realised by fine-tuning the free-spectrum-range of the individual rings. For complete drop, the mutual coupling coefficient must satisfy

$$u_m^2=(\frac{1}{t_{ae}}-\frac{1}{t_{ai}})\frac{1}{t_b}=\frac{w_0^2}{4Q_b}(\frac{1}{Q_{ae}}-\frac{1}{Q_{ai}}) \qquad (2)$$

From Eq.(2) when conventional critical coupling takes place, i.e., when $Q_{ai}=Q_{ae}$, there should be no mutual coupling between the rings. When $Q_{ai}\neq Q_{ae}$, the complete drop situation can be achieved with $u^2=u_m^2$.

In practice, it is difficult to guarantee the conventional critical coupling for complete channel drop. However, with the help of the inter-ring coupling it is possible to improve transmission notch depth and reach new critical coupling. Thus, concentric ring structure opens up another freedom when designing deep-notch filters.

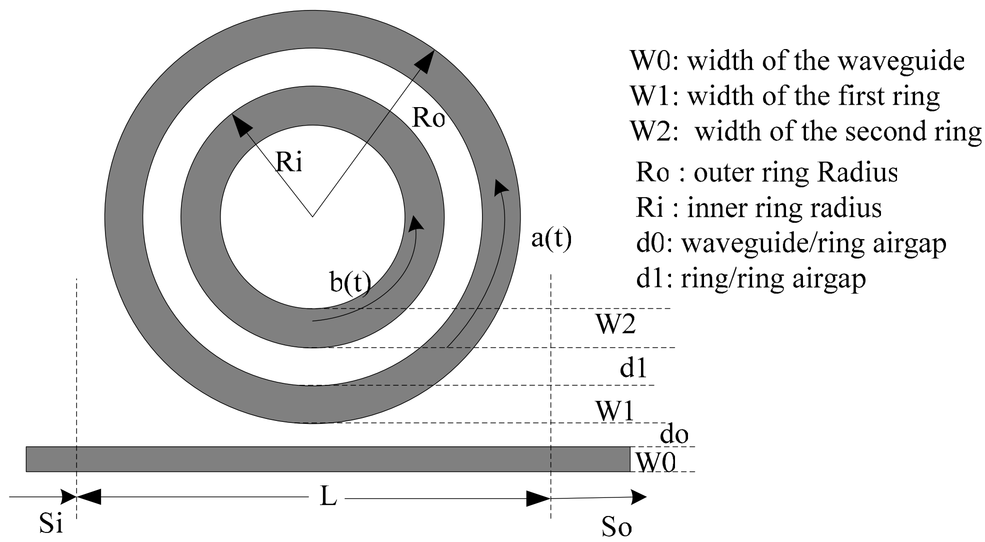


Fig. 1 Schematic of the two concentric ring resonators and a waveguide coupled system.

3. SIMULATION CONFIRMATION OF MODE COUPLING

We use the two-dimensional finite-difference-time-domain (2D FDTD) simulations to obtain the power transmission spectra and the modal distribution. The index and widths of the waveguide and rings are set for single-mode operation. Fig. 2 shows the improved transmission notches. From Fig. 3, we can see that the mode is evenly distributed in the two rings. It may offer a larger detection area for bio-sensing.

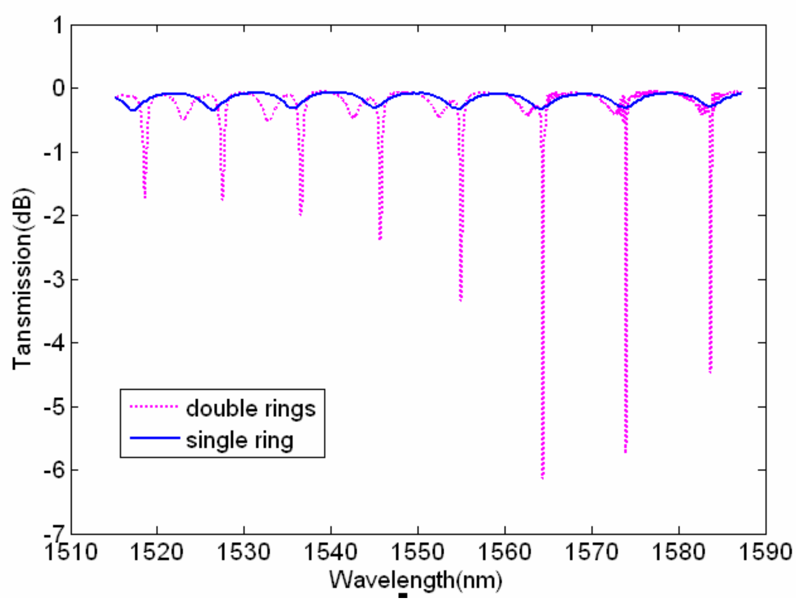
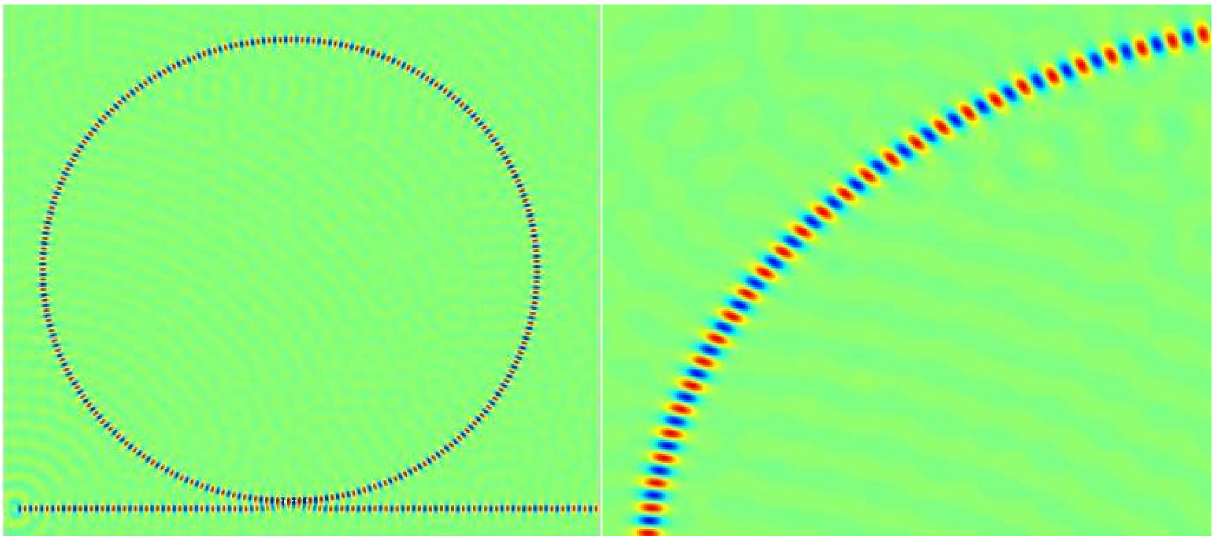
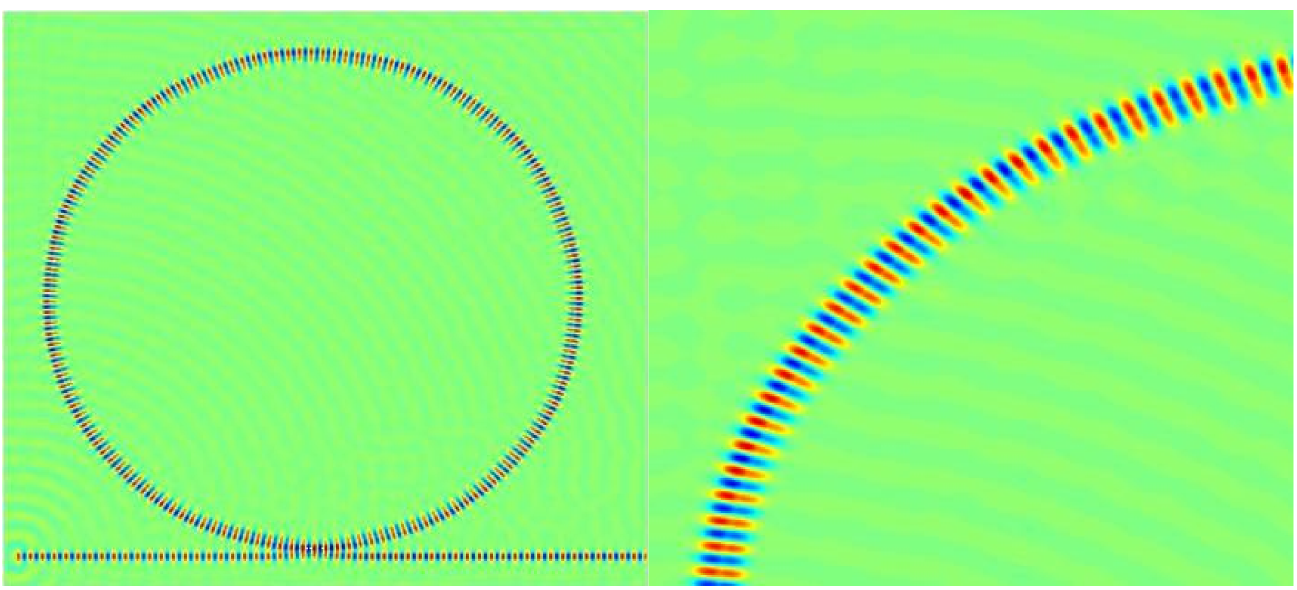


Fig. 2 Simulation results for the power transmission spectra. Solid curve: the 21μm single ring with 0.1 μm waveguide/ring airgap; dashed curve: the concentric rings with 0.1 μm waveguide/ring and ring/ring airgap.



(a) The single ring field distribution and the zoomed-in picture



(b) The double ring field distribution and the zoomed-in picture

Fig. 3 Field distribution of the 21 μm single ring (a) and double concentric rings (b) at the resonant wavelengths 1564.027 and 1564.394nm, respectively, with the same structural parameters as those in Fig. 2.

4. DEVICE FABRICATION AND RESULTS

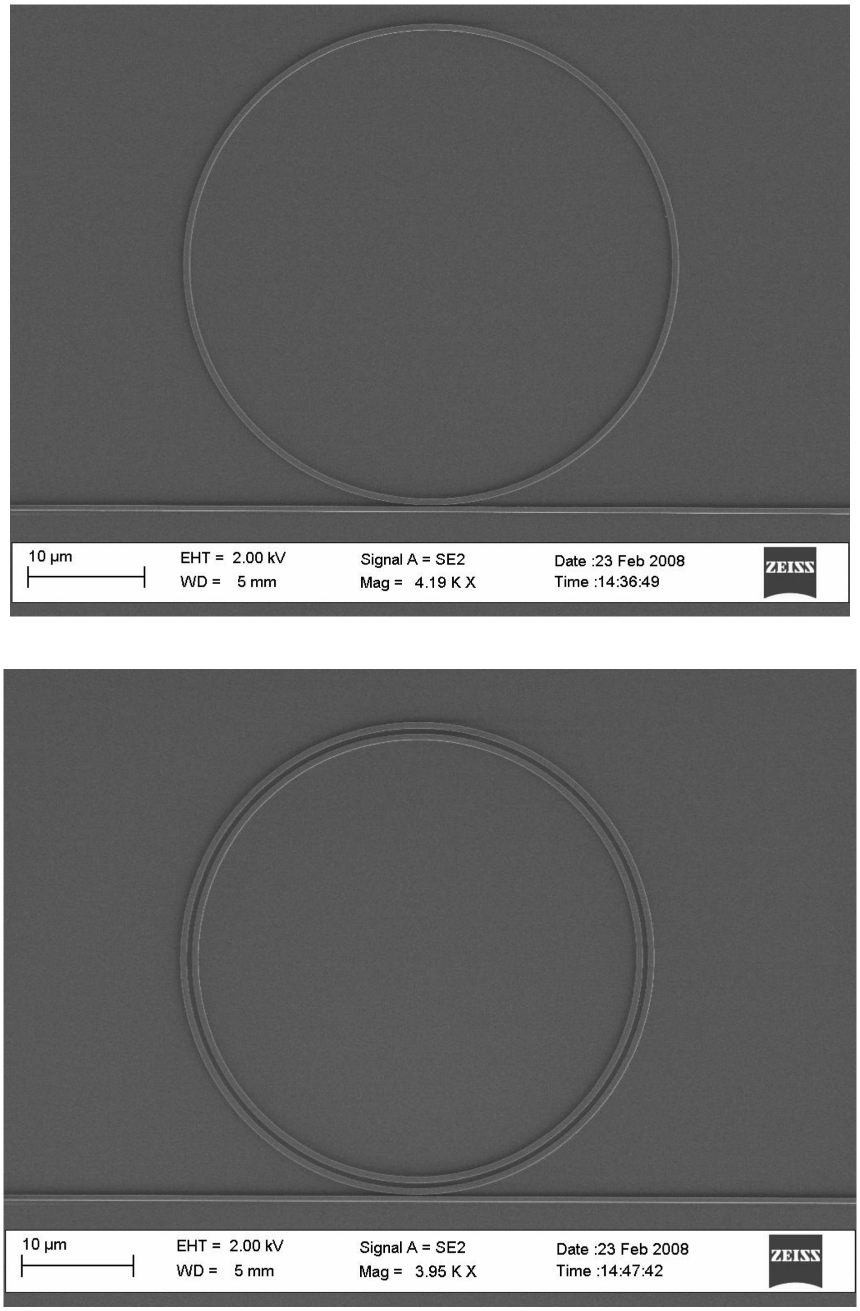


Fig. 4 SEM photos of (a) a single 21-µm-radius ring side coupled to a waveguide and (b) concentric double-ring structure with outer ring radius 21 µm, inner ring radius 20.02 µm, and airgap width 480 nm between the rings.

We use commercial SOI wafers for device fabrication. The top silicon layer is 250 nm thick and the silica buffer layer is 3 µm. The device pattern is first defined in electron beam lithography (Raith 150, 25kV) and then transferred to the silicon layer by reactive ion etching. The waveguide width starts with 10 µm and gradually tapers down to 480 nm. The ring cross-section is 500 nm (wide) by 250 nm (thick). The width of the air gap between the ring and waveguide is 110 nm to ensure good coupling with the waveguide.

The SEM photos of the 21-µm-radius-outer ring structure are shown in Fig.4. The transmission measurement results are shown in Fig.5. Around 1568.14 nm, the notch depth improves about 15 dB. The intrinsic Q is estimated to be ~ 5.1×10^4.

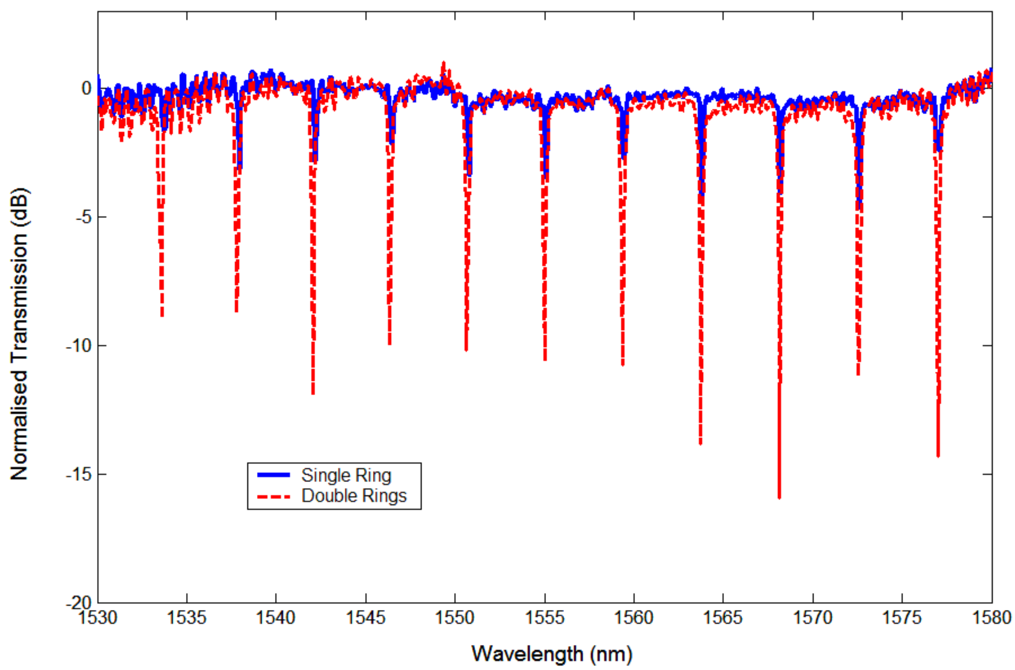


Fig. 5 Transmission measurement results: the full spectrum scans for the single ring (solid curve) and double ring (dashed curve) structures shown in Fig. 4.

5. MULTIPLE CONCENTRIC RINGS

By carefully fine-tuning the resonances, more rings can be added to further increase the modal area. The results are summarized in Fig. 6. Some red-shift of resonant frequencies is observed for different number of rings or value of airgap. When concentric rings are added, the effective index of the coupled mode should increase because more high-index dielectric material is added. For the resonant mode, the round trip phase delay $Kn_{eff}C=2M\pi$, where integer M is the longitudinal mode number, C is the perimeter of the round trip. K is the wave number, $K=2\pi/\lambda$, and λ is the wavelength.

If n_{eff} increases, for the same mode number M and approximately the same C, λ should also increase, thus causing red-shift of the resonance.

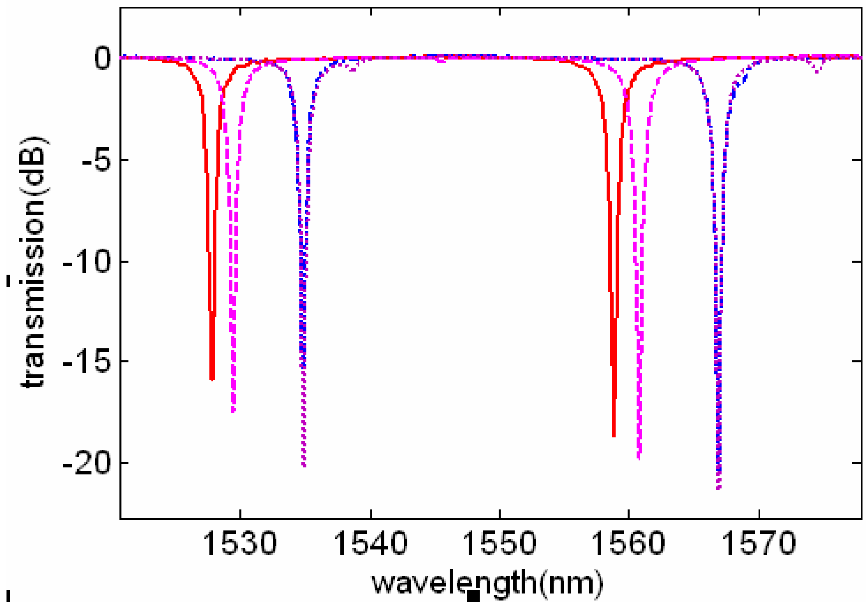


Fig. 6 Comparison of the transmission spectra for the single ring, double and triple concentric rings resonators with Ro=5 μm d0=0.2 μm and W0=W1= W2= W3=0.6 μm. Solid line: single ring with d0=0.2 μm; dashed line: double rings with d0=0.2 μm d1=0.2 μm; dotdash line: double rings with d0=0.2 μm d1=0.1 μm; dotted line: three rings with d0=0.2 μm d1= d2=0.1 μm.

6. CONCLUSIONS

In this work, we have analyzed, fabricated and demonstrated concentric micro-ring resonators in SOI structure for enhanced transmission notches. The simulations have shown the improvement of the notch depth, evenly distributed mode field and the effect of the resonance shift. Transmission notch depth improvement of ~ 15dB is demonstrated for the 21-20.02-μm-radius double-ring structure.

7. ACKNOWLEDGEMENT

This work was supported by the NSFC (60777040), Shanghai Rising Star Program Phase II (07QH14008), Swedish Foundation for Strategic Research (SSF), and the Swedish Research Council (VR).

REFERENCES

[1] C. Chao et al, “Design and Optimization of Microring Reaonators in Biochemical Sensing Applications”, Journal of lightwave. Technol. VOL.24, NO. 3,MARCH, 1395-1402 (2006)

[2] B. E. Little et al, “Microring Resonator Channel Dropping Filters”, Journal of lightwave. Technol. VOL.15, 998-1005 (1997).

[3] C. Manolatou et al, “Coupling of Modes Analysis of Resonant Channel Add-drop Filters”, IEEE Journal of quantum electronics, VOL. 35,1322-1331 (1999)

[4] Z. Zhang et al, “Resonance-splitting and enhanced notch depth in SOI ring resonators with mutual mode coupling,” Opt. Express..16, 4621-4630 (2008).