Publication information

Title	Microring and microdisk resonator-based devices for on-chip optical interconnects, particle manipulation and biosensing
Author(s)	Poon, Andrew Wing On; Feng, Shaoqi; Cai, Hong; Lei, Ting; Chen, Hui; Luo, Xianshu
Source	Proceedings of SPIE--the international society for optical engineering, Laser Resonators and Beam Control XIII; San Francisco, CA; United States , v. 7913, 23 January 2011 through 25 January 2011; Code 84540, Article number 791313
Version	Pre-Published version
DOI	https://doi.org/10.1117/12.877082
Publisher	Society of Photo-Optical Instrumentation Engineers (SPIE)

Copyright information

Copyright © 2011 Society of Photo-Optical Instrumentation Engineers. One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.

Notice

This version is available at HKUST Institutional Repository via

<http://hdl.handle.net/1783.1/44353>

If it is the author's pre-published version, changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published version.

Microring and microdisk resonator-based devices for on-chip optical interconnects, particle manipulation and biosensing

(invited)

Andrew W. Poon^{*}, Shaoqi Feng, Hong Cai, Ting Lei, Hui Chen, Xianshu Luo[‡]
Photonic Device Laboratory, Department of Electronic and Computer Engineering,
The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong
[‡]Current address: Institute of Microelectronics, A*STAR (Agency of Science, Technology and Research), 11 Science Park Road, Singapore Science Park II, Singapore 117685

ABSTRACT

Silicon photonics using microdisk and microring resonators are finding technologically important applications from telecommunications and on-chip optical interconnects to optofluidics and biosensing. Silicon-based microresonators that partially confine light by total internal reflection are versatile device structures which are highly wavelength-selective, reconfigurable via various refractive index tuning mechanisms, micrometer-scale footprint, and readily in/out-coupled with integrated waveguides. In this paper, we will highlight our latest progress in silicon photonics using microdisk and microring resonators for on-chip optical interconnects, optofluidics and biosensing applications including the experimental demonstrations of: (i) optical time delay and advance using silicon microring resonators integrated with p-i-n diodes; (ii) photocurrent spectroscopy of microdisk resonators using two-photon-absorption induced photocarriers; (iii) optical trapping and transporting of microparticles using a water-clad silicon nitride microring resonator; and (iv) coupled microdisk resonator optical waveguide-based refractive index sensors.

Keywords: Silicon photonics, microresonators, optical interconnects, optical delay, photodetection, optofluidics, optical manipulation, sensing

1. INTRODUCTION

Microresonators, including geometric forms in microring and microdisk, are key building blocks for a host of on-chip silicon photonic devices including lasers¹, modulators², switches³, filters⁴, delays⁵ and photodetectors⁶⁻¹⁰. Over the past decade, microresonator-based devices have enabled continuous advancement in expanding operational bandwidth, shrinking device size and reducing power consumption. On the relatively new field of silicon-based optofluidics, optical field enhancement and wavelength selectivity of microresonators have been leveraged to open up new possibilities in creating an integrated platform for probing, detecting and handling of microparticles^{11, 12}. On the optical sensing front, due to the high-Q microresonator resonance wavelength shifts upon refractive index changes, we have in recent years witnessed a host of high sensitivity, compact-sized and potentially complementary-metal-oxide-semiconductor (CMOS)-compatible refractive index sensors that show promise for label-free biosensing applications¹³⁻¹⁵.

In this paper, we review our recent work and report latest progress in using microring and microdisk resonators on a silicon chip for addressing new functionalities in optical interconnects, particle manipulations and sensing. In section 2, we present the experimental demonstration of an electro-optically tunable time delay and advance on the throughput transmission of a waveguide-coupled silicon microring resonator integrated with p-i-n diodes. In section 3, we discuss using the two-photon absorption generated photocurrent as a spectroscopic tool for electrically probing the silicon microdisk resonator resonance modes internal fields. In section 4, we demonstrate a microparticle add-drop device using a silicon nitride (SiN) microring resonator integrated with microfluidic channels. In section 5, we propose a technique

* eeawpoon@ust.hk; phone 852 23587905; fax 852 23581485; www.ece.ust.hk/~pdl

for refractive index sensing using spatial field patterns in coupled-resonator optical waveguides (CROWs) with proof-of-principle demonstrations. In section 6, we conclude the paper with discussion on future work.

2. OPTICAL TIME DELAY AND ADVANCE USING MICRORING RESONATORS

Optical time delay and advance¹⁶⁻¹⁸ has been attracting growing interest for potential applications in telecommunications and in on-chip optical interconnects. Optical time delay serving as an all-optical buffer for storing one and even multiple data bits in digital communication systems is of particular interest. Besides, optical time delay for analog signals are also useful as true time delays for microwave photonic applications and in particular for phase-arrayed antennas¹⁹. Moreover, slow light can also find applications in improving the sensitivity of interferometry²⁰.

Recently, silicon microresonator-based on-chip optical slow- and fast-light devices²¹⁻²³ were investigated featuring the advantages of compact footprint and potential photonic integration. Tunable time-delay and advance have been demonstrated via optically induced thermal effect, either in a single microring resonator with mutual coupling induced mode splitting²¹ or in double microring resonators with electromagnetically induced transparency (EIT)-like resonance²². However, the shortcomings of such optically induced thermal tuning are relatively high optical power consumption of tens of mW and slow tuning speed of μs ²¹. Previously, we demonstrated electro-optical tunable time delay of up to -95 ps and advance of up to 96 ps in a silicon-microring-resonator-based notch filter integrated with a lateral p-i-n diode by blue-shifting the resonance wavelength through carrier-injection-based plasma dispersion effect²³. Our demonstrated electrical power consumption is in the range of up to few mW and a tuning speed of sub-ns. However, such approach requires resonance wavelength tuning in order to tune the time delay and advance. Most recently, we demonstrated an improved electro-optical tuning of time delay/advance from -84 to 114 ps at a fixed resonance wavelength in a silicon microring resonator coupled with a feedback waveguide by tuning an additional feedback phase without directly tuning the microring resonance wavelength¹⁶.

However, in both our previous demonstrations²³, we have only investigated the time delay/advance using the phase-shift technique with a sine-wave intensity modulated light at a fixed arbitrary chosen modulation frequency. Given the measured time delay/advance in a microresonator is dependent on the bandwidth of the modulated light, in this paper we investigate in detail the dependency of the time/delay on the sine-wave modulated light.

Figure 1(a) shows the analytically calculated transmission intensity (using transfer matrix) and time response (frequency derivative of the optical phase) of a microresonator-based notch filter. The intensity spectrum shows an inverted Lorentzian lineshape with an extinction ratio (ER) of 20 dB and a quality factor (Q) of 10^4 . The microresonator works in the under-coupling regime and displays a maximum of ~ 140 -ps time advance at the resonance wavelength²³.

Figure 1(b) shows the modeled anomalous phase response of the notch filter, which gives rise to the time advance. For an input light carrier centered at the resonance wavelength and intensity-modulated with a sine-wave of frequency f_{RF} , the two sidebands that are separated by f_{RF} experience different optical phase response through the filter, which results in time advance. Given the nonlinear phase response in the vicinity of the resonance center wavelength, the two sidebands with different bandwidths thus give rise to different time responses.

Here, we analytically investigate the dependency of the measured time delay and advance on the modulation frequencies under various microresonator Q and ER values^{23, 24}. Figure 1(c) shows the calculated time advance for a microring resonator-based notch filter with Q of 10^4 and ER of 20 dB. The theoretical maximum time advance at the resonance center wavelength is ~ 140 ps, while the modeled time advance assuming a modulation bandwidth of 0.2 GHz, 0.5 GHz and 1.0 GHz are 140 ps, 138 ps and 130 ps, respectively. Thus, the modeled time delay/advance can be compromised by the use of a relatively large modulation bandwidth. Figure 1(d) shows the calculated time advance for the filter with Q of 10^4 and ER of 30 dB. The phase response in the vicinity of the resonance center wavelength is steeper than that in Fig. 1(c). The time advances with a modulation bandwidth of 0.2 GHz, 0.5 GHz and 1.0 GHz are 460 ps, 400 ps and 300 ps, respectively. Figure 1(e) shows the calculated time advance for the filter with Q of 3×10^4 and ER of 20 dB. The phase response in the vicinity of the resonance center wavelength is also steeper than that in Fig. 1(c). The time advances with a modulation bandwidth of 0.2 GHz, 0.5 GHz and 1.0 GHz are 420 ps, 360 ps and 270 ps, respectively.

Fig.1 (a) Modeled intensity (black) and time (red) response of a microresonator-based notch filter. (b) Modeled phase response of a microresonator-based notch filter. Two arrows separated by frequency difference f_{RF} represent the sidebands of the input sinusoidal signal. (c) – (e) Effects of modulation frequency on time advance under various microresonator parameters (c) $Q = 10^4$ and $ER = 20$ dB, (d) $Q = 10^4$ and $ER = 30$ dB, (e) $Q = 3 \times 10^4$ and $ER = 20$ dB. Black solid-lines: theoretical calculations; red dashed-lines: modeling with $f_{RF} = 0.2$ GHz; blue dotted-lines: modeling with $f_{RF} = 0.5$ GHz; green dashed-dotted lines: modeling with $f_{RF} = 1$ GHz.

Figure 2(a) shows the schematic of a p-i-n diode integrated feedback-microring resonator on a silicon chip, which is based on our previous work^{25, 26}. Both the microring resonator and part of the feedback-waveguide are laterally integrated with p-i-n diodes, which are denoted as diodes A and U. Figure 2(b) shows the optical micrograph of the fabricated device comprising the feedback-microring resonator connected to a microring resonator centered at a different resonance wavelength without feedback coupling (denoted B). All the optical transmission is measured after device B.

We measure the device optical transmission intensity and time response using a network analyzer²⁷. Figure 2(c) shows the schematic of the experimental setup for measuring time delay and advance. The light modulated by the network analyzer with RF frequency f_{RF} is launched at the input-port of the chip. The light output from the chip is divided by a 3-dB coupler. One half of the output light is amplified by an erbium-doped fiber amplifier (EDFA), converted to electrical signal and returned to the network analyzer. Another half of the output light is collected with a photodetector in order to measure the transmission spectrum. This configuration ensures that the measured transmission spectra are not affected by the EDFA amplified spontaneous emission (ASE) noise, which could affect the measured device performance, i.e., Q and ER . We can calculate the time delay and advance using $\Delta\tau = \Delta\Phi / (2\pi f_{RF})$, with $\Delta\Phi$ the electrical phase difference between a transmission dip at an on-resonance wavelength and a high transmission level at an off-resonance wavelength. The f_{RF} determines the maximum measurable delay and advance, which is $1/2f_{RF}$ corresponding to $\Delta\Phi = -\pi$ and $+\pi$. While both f_{RF} and phase angle resolution determine the measured time resolution.

Fig.2 (a) Schematic of a silicon feedback-microring resonator with laterally integrated p-i-n diodes in a SOI substrate. (b) Optical micrograph of the fabricated device comprising the feedback-microring resonator connected to an electro-optically tunable microring-resonator-based notch filter without the feedback-waveguide. (c) Schematic of the experimental setup for measuring time delay and advance. PC: Polarization controller. EDFA: Erbium-doped fiber amplifier. Solid-line: optical path in the experimental setup. Dashed-line: electrical path in the experimental setup.

Figure 3(a) shows the measured TE-polarized (electric field parallel to the chip) transmission spectrum of the device. The measured intensity response is independent on the modulation frequencies. The inset shows the resonance with a Q of 7000 and an ER of 18 dB. Figure 3(b) shows the measured time advance of the device with $f_{RF} = 0.2$ GHz, 0.5 GHz and 1 GHz. We observe that the measured maximum time advance for $f_{RF} = 0.2$ GHz, 0.5 GHz and 1 GHz are 187 ps, 151 ps and 125 ps, respectively, with a full-width half-maximum spectral width of 0.01 nm, 0.006 nm and 0.005 nm.

Fig.3 (a) Measured TE-polarized transmission spectrum of the device from 1554.94 to 1555.98 nm. Inset: measured transmission spectrum of the device from 1554.5 to 1555.5 nm. (b) Measured time advance within a narrow spectrum from 1554.94 to 1554.98 nm in the vicinity of the resonance dip with various modulation frequencies. Red lines: $f_{RF} = 0.2$ GHz; blue lines: $f_{RF} = 0.5$ GHz; green lines: $f_{RF} = 1.0$ GHz.

3. TWO-PHOTON ABSORPTION SPECTROSCOPY IN MICRODISK RESONATORS

Two-photon absorption (TPA) is considered as the most pronounced nonlinear absorption in silicon photonic devices for the wavelength range around 1550 nm. The TPA-generated carriers, when coupled with free-carrier absorption (FCA), are deleterious to high-power devices such as silicon Raman lasers and amplifiers. In these devices, losses induced by TPA and FCA significantly limit the optical pumping and the gain²⁸. In order to eliminate the TPA-generated photocarriers in these high-power devices, a widely adopted approach is to integrate a p-i-n diode along the waveguide in order to sweep out the carriers from the optical mode region^{29, 30}. This leads to successful demonstration of a host of nonlinear optic devices including silicon Raman amplifiers and lasers^{31, 32}. On the other hand, the TPA-generated carriers are collected for other applications including nonlinear optic detectors^{6, 30} and TPA-photovoltaic devices^{33, 34}.

We recently demonstrated cavity-enhanced photocarrier generation in a silicon microring resonator with 20-fold on-resonance to off-resonance photocurrent enhancement. The photocarrier generation is based on the linear surface-state absorption (SSA). The nonlinear photocurrent generation occurred for the microring resonator with $Q \approx 8000$ upon around 100 μW coupled power. Thus, it is expected that the TPA-generated photocurrent would be even more pronounced in microdisk resonators which typically support higher Q than microring resonators⁸.

Figure 4(a) and (b) show the schematic and the optical micrograph of our microdisk resonator with an integrated p-i-n diode. Fig. 4(c) shows the schematic cross-section. The central region of the microdisk is p⁺-doped, and the slab region (~ 30 nm in height) outside the microdisk is n⁺-doped. The n⁺-doped region and the microresonator sidewall is separated by 0.5 μm . The rim of the microdisk resonator is lightly p-doped. The microdisk resonator has a diameter of 5 μm , and a height of 210 nm.

Figure 4. (a) Schematic of the microdisk resonator with an integrated p-i-n diode. (b) Optical micrograph of a microdisk resonator integrated with a p-i-n diode. (c) Schematic of the microdisk cross-section showing the lateral p-i-n diode. (d) Measured throughput-port transmission spectrum, (e) drop-port transmission spectrum and (f) photocurrent spectrum of the microdisk resonator.

Figure 4(d) shows the optical transmission spectrum measured from the throughput-port of the waveguide-coupled microdisk resonator upon an estimated coupled power of ~ 125 μW . The most pronounced modes exhibit an ER exceeding 10 dB. While, other modes exhibit only shallow dips in the transmission spectrum. These dips are strongly modulated by the background transmission due to possibly lower- Q higher-order modes.

Figure 4(e) shows the drop-port transmission spectrum. The highest drop-port transmission intensity peaks correspond to the modes with the largest ER values in the throughput transmission spectrum. The presence of other lower intensity peaks reveals the multimode feature of the microdisk resonator. The free spectral range (FSR) of ~ 22 nm corresponds to the microdisk circumference.

Figure 4(f) shows the corresponding measured photocurrent spectrum of the microdisk resonator upon a 5-V reverse bias across the p-i-n diode. The photocurrent spectrum shows pronounced peaks clearly revealing the microdisk whispering-gallery modes (WGMs). The highest collected current shows a peak height that exceeds $1000\times$ of the background photocurrent. This photocurrent ratio between the on-resonance and off-resonance wavelengths is 50-fold larger than that previously observed in the relatively weak SSA-induced photocurrent in a lower-Q microring resonator. The photocurrent spectrum also clearly reveals the WGMs with significantly improved signal-to-noise ratio compared to the optical transmission spectra, especially for the high-Q modes which do not couple with the waveguide as efficient as the low-Q modes. From the photocurrent spectrum, we measure a highest Q is $\sim 2 \times 10^5$.

We apply the photocurrent spectroscopy technique to study a double-notch (DN)-shaped microdisk resonator. DN-shaped microdisk resonator is a non-conventional shaped microdisk with a key merit of gapless input- and output-coupling via two submicrometer-sized notches. The gapless coupling facilitates inter-cavity coupling between DN-shaped microdisk resonators in many-element coupled-resonator optical waveguides (CROWs) for high-order filtering and optical delays⁷. However, due to its non-circular shape, the understanding of WGMs in conventional circular-shaped microdisk resonators is not readily applicable to analyze DN-shaped microdisk resonators.

Figure 5(a) and (b) show the schematic and the optical micrograph of our double-notch-shaped microdisk resonator with an integrated p-i-n diode. DN-shaped microdisk comprises two half-circles with different radii $R_1=20$ μm and $R_2=19.2$ μm . Fig. 5(c) shows the schematic cross-section. Compared with the circular-shaped microdisk resonator, the DN-shaped microdisk resonator requires a wider intrinsic region on the disk rim as the optical fields tend to penetrate deeper into the central core of the microdisk.

Figure 5. (a) Schematic of the double-notch-shaped microdisk resonator with an integrated p-i-n diode. (b) Optical micrograph of the double-notch-shaped microdisk resonator integrated with a lateral p-i-n diode. (c) Cross-sectional schematic of the lateral p-i-n diode. (d) Measured photocurrent spectrum and (e) the corresponding throughput transmission spectrum of the double-notch-shaped microdisk resonator. The photocurrent peaks that are aligned (misaligned) with the optical transmission dips are marked with open (closed) triangles.

Figure 5(d) shows the measured photocurrent spectrum from the DN-shaped microdisk resonator with an estimated coupled power of $\sim 125 \mu\text{W}$ upon a reverse bias voltage of 0 V. The photocurrent spectrum reveals sub-nano-ampere current peaks. The photocurrent generation is relatively low compared with that in the circular-shaped microdisk resonator (Fig. 4(f)) due to the relatively low-Q modes in the larger sized ($\sim 19.2 \mu\text{m}$ radius) DN resonator, and the relatively wide p-i-n diode intrinsic region ($\sim 4.5 \mu\text{m}$). From the photocurrent spectrum, we measure a highest Q is $\sim 10^4$.

Figure 5(e) shows the corresponding measured optical transmission spectrum. From the optical transmission spectrum, it is not clear whether the high-Q modes exist due to the strong background modulation from higher-order low-Q modes. Besides, the asymmetric resonance line shapes (Fano line shapes) make it difficult to extract the linewidth and thus the resonance Q from the transmission spectrum. In contrast, the photocurrent spectrum probing the cavity internal field-generated photocarriers can better reveal these high-Q modes.

We note that the resonance peak wavelengths in the photocurrent spectrum and the resonance dip wavelengths in the optical transmission spectrum do not always align. For example, the photocurrent resonance peak at 1508.5 nm is aligned with a local high-transmission peak adjacent to a sharp resonance dip. This indicates an interference effect of the transmission resonance with a coherent transmission background, which can be interpreted as a classical analogue of Fano resonance interference.

4. MICRORING RESONATORS FOR MICROPARTICLES TRAPPING AND TRANSPORTING

Planar microresonator-based optofluidic chips for optical manipulation of microparticles utilize the surface wave on the microresonator which has the benefit of resonance-cavity enhancement, and surface wave controlling through wavelength tuning. Recently, Yang et al.,¹² demonstrated an SU-8-based optofluidic microring resonator switch for optical particle transport. Lin et al.,³⁵ demonstrated the optical trapping of microparticles on silicon microring resonators. Mandal et al.,¹¹ reported trapping, manipulation and transporting of microparticles using silicon photonic crystal resonators. Here, we show our recent work on optical manipulation of microparticles using a silicon nitride (SiN) microring resonator-based add-drop filter. We demonstrated microparticles throughput, trapping in round trips and dropping by selecting the carrier wavelength and the resonance Q factor. Such device can function as a microparticle add-drop filter for “microparticle circuits” in lab-on-a-chip applications³⁶.

Figure 6. (a) Schematic of optical manipulation of microparticles on a microring resonator-based add-drop device. I: input-port; II: input-coupling; III: input-arc; IV: output-coupling; V: drop-port; VI: feedback arc; VII: throughput-port. (b) Optical micrograph of the optofluidic device. (c) Schematic of the experimental setup for optical manipulation.

Figure 6(a) schematically illustrates the mechanism of microparticles optical manipulation on a traveling-wave microring resonator-based add-drop device. Microparticles that are located in close proximity to the waveguide and spatially overlap with the waveguide surface wave can be vertically trapped by the gradient force and longitudinally driven by the scattering force. At a microring off-resonance wavelength (λ_{off}), optically driven microparticles are transported to the throughput-port. At a microring on-resonance wavelength (λ_{on}), the guided field in the throughput-waveguide is destructively interfered while that in the microring and the drop-waveguide is constructively interfered. Thus, the on-resonant microring can route the microparticles from the input-waveguide to the microring. For sufficiently enhanced microring field (namely larger than the drop-waveguide field), the microparticles can be trapped in round-trips. While for relatively less enhanced microring field (namely comparable to the drop-waveguide field), the microparticles can be

output-coupled to the drop-waveguide. Here we spatially partition the device into seven regions (I-VII) in order to describe the microparticle trajectories.

Figure 6(b) depicts the optical micrograph of the integrated optofluidic device. We adopt SiN material as the optical layer because of its (i) relatively wide transparency window from the visible to the near-IR bands, (ii) high refractive index contrast between SiN and water ($\sim 2/1.33$) for compact device footprint, and (iii) CMOS-compatible fabrication process. For the microfluidic layer, we adopt photolithographic method in order to pattern silica channel walls for controlled alignment. The fluidic channel is 6 μm in height and covered with a cover glass.

Figure 6(c) schematically shows the experimental setup. The racetrack microring add-drop device comprises two arcs with diameter of 80 μm and coupling length of 30 μm . The coupled waveguides and the microring waveguide are 0.4 μm in width and 0.7 μm in height. The evanescent coupling gap spacing is ~ 0.35 μm . In order to study few-microparticles manipulation events across a relatively large device footprint, we inject diluted colloidal solution of 1- μm -sized polystyrene particles with density of $\sim 12 \times 10^7$ particles/ml into the fluidic channel. We image the microparticles by a 50 $\times$ microscope objective lens onto a charge-coupled device (CCD) camera, with white-light side-illumination. We end-fire ~ 120 -mW 1.55- μm TM-polarized (electric field perpendicular to the chip) laser light into the input-waveguide using a lensed fiber. Given a ~ 18 – ~ 22 -dB insertion loss, we estimate that the coupled optical power inside the waveguide is below 10 mW.

Figures 7(a) and (b) show the measured throughput- and drop-port transmission spectra of two microring resonator-based add-drop devices with identical design: (a) Device I: The resonance Q factor is ~ 1698 according to the drop-port spectrum. The throughput transmission spectrum displays split modes, with extinction ratio of ~ 11 dB. (b) Device II: The Q factor is ~ 941 according to the throughput spectrum.

When we tune the input laser wavelength to off-resonance wavelengths B(1565.5 nm) for device I and B'(1564.5 nm) for device II, microparticles are transported to the throughput-port following trajectory I-II-VII (see Fig. 6(a)) in both devices. As an example, figures 6(c)-(f) show that a microparticle is trapped by the input waveguide and transported to the throughput-port by device I at wavelength B.

Figure 7. (a) Measured throughput- and drop-port transmission spectra of device I with Q ~ 1698 . (b) Measured throughput- and drop-port transmission spectra of device II with Q ~ 941 . (c) Optical micrograph of device I with microparticle positions (labeled by the yellow circles) at various times upon illumination at off-resonance wavelength B. (d) - (f) Zoom-in images of the microparticle (labeled by the yellow arrows) at times (d) 0 s, (e) 5 s and (f) 15 s.

When we tune the input laser wavelength to on-resonance wavelength A(1564.02 nm) for device I and A'(1563.22 nm) for device II, microparticles show different trajectories in two devices. Figures 8(a)-(e) show that at on-resonance wavelength A on device I with Q ~ 1698 , a microparticle is trapped by the input waveguide and routed to the microring input-arc in trajectory I-II-III. Figures 8(f)-(i) show that another microparticle is trapped by the output-coupling waveguide and routed back to the microring feedback-arc in trajectory IV-VI. The observation that the microparticle at resonance wavelength A can be routed back to the microring feedback-arc suggests that the microresonator field intensity is sufficiently higher than that in the drop-waveguide.

Figure 8. (a) Optical micrograph of device I with microparticle positions (labeled by the yellow circles) at various times upon illumination at on-resonance wavelength λ . (b) - (e) Zoom-in images of the microparticle (labeled by the yellow arrows) at times (b) 0 s, (c) 4 s, (d) 7 s and (e) 38 s. (f) - (i) Zoom-in images of another microparticle (labeled by the yellow arrows) at times (f) 0 s, (g) 4 s, (h) 12 s and (i) 43 s with a stuck microparticle (labeled by the green arrow).

Figure 9. (a) Optical micrograph of device II with microparticle positions (labeled by the yellow circles) at various times upon illumination at on-resonance wavelength λ' . (b) - (e) Zoom-in images of the microparticle (labeled by the yellow arrows) at times (b) 0 s, (c) 18 s, (d) 21 s and (e) 71 s. (f) - (i) Zoom-in images of another two microparticles (labeled by the yellow arrows) at times (f) 0 s, (g) 23 s, (h) 40 s and (i) 43 s with a stuck microparticle (labeled by the green arrow).

Figures 9(a)-(e) show that at on-resonance wavelength λ' on device II with Q of ~ 941 , a microparticle is trapped by the input waveguide and routed to the microring input arc in trajectory I-II-III. Figures 9(f)-(i) show that another two microparticles are trapped by the on-resonance microring resonator and routed to the drop-port following trajectory III-IV-V. The observation that the microparticles are output-coupled to the drop-waveguide at resonance wavelength λ' suggests that the microring field intensity is comparable to that in the drop-waveguide.

Figure 10. FDTD-simulated TM-polarized field-intensity distribution at (a) an off-resonance wavelength, (b) an on-resonance wavelength with Q of ~ 411 and (c) an on-resonance wavelength with $Q \sim 180$. (d) - (g) Simulated field-intensity profiles along the white/red dashed-lines in (a)-(c).

We employed two-dimensional finite-difference time-domain (FDTD) simulations of SiN racetrack microring add-drop devices to demonstrate the mechanisms of particle throughput, trapping, and dropping functions. The simulated racetracks comprising two arcs with diameter of $10\ \mu\text{m}$ and coupling length of $10\ \mu\text{m}$. The coupled waveguides and the microring waveguide are $0.4\ \mu\text{m}$ in width. We simulated two racetracks with coupling gap between the bus-waveguides and the microring of $0.3\ \mu\text{m}$ and $0.2\ \mu\text{m}$, showing resonance Q -factors of ~ 411 and ~ 180 respectively. For each simulated field pattern (Figs. 10(a)-(c)), we compare the field-intensity at (i) the plane of $1\ \mu\text{m}$ offset from the end of input-coupling region I (white dashed lines), and (ii) the plane of $1\ \mu\text{m}$ offset from the end of output-coupling region II (red dashed lines). These two planes are critical as they show field intensity difference between the bus-waveguide and the microring waveguide, and in turn determine trajectories of particles after passing through the coupling regions.

Figure 10(a) shows the simulated TM-polarized field-intensity distribution of the device with an evanescent coupling gap of $0.3\ \mu\text{m}$ at an off-resonance wavelength. Figure 10(d) shows the field-intensity in the throughput-waveguide is higher than that in the microring waveguide. The microparticles thus follow the higher surface field-intensity to the throughput-waveguide.

Figure 10(b) shows the simulated field-intensity distribution of the same device at an on-resonance wavelength. Figure 10(e) shows the field-intensity in the microring waveguide is higher than that in the throughput-waveguide. The particle at the bus waveguide transports to the microring waveguide at the coupling region. Figure 10(f) shows the field intensity in the microring feedback-arc is higher than that in the drop-waveguide, thus the particles travel on the microring resonator following the high intensity. At an on-resonance wavelength microparticles can be routed to the microring waveguide and keep trapped on the microring functioning as particle trapping.

Figure 10(c) shows the simulated field-intensity distribution of the device with a narrowed evanescent coupling gap of $0.2\ \mu\text{m}$ at an on-resonance wavelength. On the throughput waveguide, on-resonance lightwave couples to the microring resonator and thus give rise to the particles transport to the microring waveguide. However, Fig. 10(g) shows that the field-intensity in the drop waveguide is slightly higher than that in the microring feedback-arc waveguide. The simulations thus suggest at an on-resonance wavelength with a relatively low Q and weakly enhanced cavity field microparticles can be routed to the drop-waveguide functioning particle drop.

The optical manipulated particle throughput, trapping, and dropping are generic to different waveguide coupled microresonators of different shapes. Recently, we are investigating the optical manipulation of microparticles on microdisk devices which provide multiple trapping channels formed by spatial field patterns of multimode WGMs³⁷. The multimode microdisk resonators thus open up more particle manipulation possibilities by tuning optical wavelength to different WGM resonance wavelengths.

5. COUPLED MICRODISK RESONATOR OPTICAL WAVEGUIDE-BASED REFRACTIVE INDEX SENSORS

Optofluidic biosensing is a fast emerging interdisciplinary research area which integrates optical devices and microfluidics on the same chip for biosensing applications. For label-free biosensing, the effective refractive index change serves as a key parameter upon the receptors reacting with the analyte. A host of optical phenomena and devices have been exploited for label-free biosensing including surface plasmon resonance (SPR), interferometers, photonic crystal fibers, photonic crystals, WGM microresonators, and waveguides, etc.³⁸. In particular, silicon microresonator-based optical sensors¹³⁻¹⁵ have been attracting significant attentions due to key merits of high sensitivity to refractive index change ($\sim 10^{-4} - \sim 10^{-5}$ RIU), compact size (tens of $\mu\text{m} - \sim 100 \mu\text{m}$) and potential for large-scale-integration in optofluidic applications. The conventional single-element microresonator-based sensing is based on measuring sharp resonance wavelength shifts or line shape modulations upon refractive index changes. However, such methods require microresonators with high-quality factors.

Here, we discuss an alternative sensing principle using a CROW³⁹ on a SiN substrate. The optical sensing is based on the CROW spatial mode-field intensity pattern variation upon a refractive index change at a fixed wavelength within the CROW transmission band. The method only relies on measuring the out-of-plane light scattering from each coupled microresonator.

Figure 11 illustrates the working principle of CROW sensors using multi-channel spatial detection. Figure 11(a) shows the schematic structure of a generic N-element CROW. Each resonator element has a round-trip length L proportional to cavity size d . The coupling and reflection coefficients between the coupled microresonators are denoted as κ and r . Figure 11(b) schematically shows the CROW periodic transmission bands spectrally shift upon various effective refractive indices n_0 , $n_0 + \Delta n$ and $n_0 + \Delta n'$. In principle, CROWs comprising identical microresonators exhibit periodic transmission bands due to the inter-cavity coupling induced mode splitting. In the case that the microresonators are single-mode, the number of split modes (states) within each transmission band is equal to the microresonator number, N . The states exhibit distinctly different mode-field patterns. Upon a minute change in effective refractive index that induces an inter-state transition at a fixed wavelength λ_p , the mode-field pattern varies significantly (Fig. 11(c)) while the transmission bands only spectrally shift within the bandwidth (Fig. 11(b)). Thus, it is conceivable to extract discrete (digital) effective refractive index change from measuring the CROW mode-field intensity pattern change, given proper calibration and image processing.

Figure 11. Working principle of CROW sensors using multi-channel spatial detection. (a) Schematic of a generic N-element CROW. The coupling and reflection coefficients are labeled as κ and r . (b) CROW periodic transmission bands upon various effective refractive indices n_0 , $n_0 + \Delta n$ and $n_0 + \Delta n'$. Probe wavelength λ_p corresponds to states 1, 2 and 3 as the transmission bands spectrally shift. (c) CROW multi-channel spatial mode-field intensity patterns at states 1, 2 and 3 at a fixed λ_p .

In order to model the CROW sensor sensitivity, we adopt the transfer-matrix based approach assuming cascaded identical Fabry-Perot cavities. As an initial device design, we aim at finding the key design parameters (κ , N , L) for high sensitivity to effective refractive index change while discerning spatial pattern variation at a single transmission

wavelength. Figure 12(a) shows the modeled linewidth-to-FSR ratio as a function of κ upon various N and cavity size d . In order to enable sensing interrogation at a single wavelength, it is desirable to have a relatively large transmission band linewidth-to-FSR ratio, which imposes a relatively large κ (the shaded region). Figure 12(b) shows the inter-state spacing $\Delta\lambda$ as a function of k upon various N and cavity size d . The inter-state spectral spacing $\Delta\lambda$ depends on the inter-cavity coupling κ , the cavity number N , and the constituent resonator round-trip length L ($L = 2d$, in a Fabry-Perot cavity), following the relation of $\Delta\lambda \propto \kappa/(NL)$ ³⁹. A small $\Delta\lambda$ is desired as it determines the digital detection limit. This imposes relatively large N and large L . Proper designs of the inter-cavity coupling strength (κ), the detailed microresonator morphology (shapes / sizes) and the number of identically designed coupled microresonators N are critical to obtain closely spaced periodic transmission bands. In order to attain $\sim 10^{-5}$ RIU detection limit, we believe parameters $N = 20$ -50 and $L = 100$ -400 μm (corresponding to $d = 50$ -200 μm) are reasonable, as shown in the Fabry-Perot-cavity-based modeling in Fig. 12.

Figure 12. Modeling of cascaded Fabry-Perot cavities. (a) Calculated linewidth-to-FSR ratio as a function of coupling coefficient κ with various cavity number N and cavity size d . (b) Calculated inter-state spectral spacing $\Delta\lambda$ and the corresponding effective refractive index change Δn as a function of coupling coefficient κ with various cavity number N and cavity size d .

Figure 13. (a) Scanning electron microscope (SEM) picture of our fabricated 11-element SiN CROW device. (b) Zoom-in view of the gaplessly coupled region of two adjacent microdisks. (c) Schematic of the proof-of-principle experiment. A wavelength-tunable laser is end-fired into the CROW device by a lensed fiber. A near-infrared (near-IR) camera is used to image the out-of-plane light scattering. The CROW transmission output is monitored by a photodetector.

For proof-of-principle demonstration, we use a microdisk-based CROW comprising 11 gaplessly coupled microdisks with input- and output-coupled waveguides based on our previous work^{40, 41}. Figure 13(a) shows the scanning electron microscope (SEM) picture of our fabricated SiN CROW devices. The input laser is coupled from the waveguide to the spiral with a gap of 0.4 μm , and then propagates in gapless coupled double-notch microdisks, which each has a diameter of 40 μm and two 0.8 μm wide notches. Figure 13(b) shows the zoom-in view of the gaplessly coupled region between two adjacent microdisks in a CROW device. The device is fabricated by i-line (365 nm) photolithography and dry

etched in a SiN-on-silica substrate and air-clad. Figure 13(c) shows the schematic of experimental setup. We characterize the CROW optical transmission spectra using a wavelength-tunable diode laser in the 1550-nm range and a photodiode detector. The laser light is end-fired to the CROW device by a lensed fiber. The out-of-plane light scattering is imaged onto a near-infrared camera.

Figure 14(a) shows the optical micrograph of a 11-channel CROW. The input-port, drop-port and light propagation trajectory are labeled by arrows in the figure. Figure 14(b) shows the measured periodic drop-port transmission spectrum exhibiting relatively broadband transmission with a FSR corresponding to the microdisk round-trip length. We record the out-of-plane light scattering images for each wavelength within a transmission band with a step of 0.02 nm. Figure 14(a) inset shows a typical measured light-scattering pattern from the coupling region between two seamlessly joint microdisks. The scattering is particularly pronounced in the coupling region due to the sharp junction interfaces (see Fig. 13(b) and Fig. 14(a)). We define 11 integration windows, 10 in the vicinity of the inter-disk coupling regions, and 1 in the vicinity of the coupling junction between the end-disk and the drop-waveguide. We integrate the light scattering intensity inside each window in order to realize an 11-channel CROW sensor. Figure 14(c) shows the measured 11-channel spatial patterns upon various wavelengths inside a transmission band of 1540 – 1545 nm.

In order to quantitatively analyze the pattern variations over wavelengths, we calculate the correlation matrix of these intensity arrays. The value of element $R(a, b)$ in the matrix describes the similarity of the spatial array intensity distributions between two wavelengths A and B as follows:

$$R(a, b) = \frac{\sum a_i b_i - n A B}{(n-1) S_a S_b} \quad (1)$$

where the spatial array intensity values at two wavelengths are written as a_i and b_i ($i=1,2,\dots,n$) with $n=11$ for the device under test, A and B are the means of a and b , S_a and S_b are the standard deviations of a and b . The correlation coefficient thus describes the similarity between the array intensity distributions at two wavelengths, with a value range from 0 (unrelated) to 1 (exactly identical).

Figure 14. (a) Optical micrograph of the 11-element CROW. The arrows indicate the light input, drop port and propagation trajectory. Inset: measured out-of-plane light scattering intensity near the peak transmission wavelength from one of the gaplessly coupled regions. (b) Measured CROW drop-port periodic broadband transmission spectrum. (c) Measured light-scattering-based 11-channel spatial patterns from 1540 to 1545 nm. (d) Correlation curve of the measured 11-channel spatial pattern within a broadband transmission band from 1540 to 1545 nm.

Figure 14(d) shows the calculated correlation based on the measured 11-channel spatial spectrogram. The highly related regions (depicted in red, representing a correlation coefficient exceeding 0.95) are all located along the diagonal (i.e.

same wavelengths), which means that the scattering light intensity patterns at different wavelengths are distinguished from each other. Hence, based on our preliminary wavelength-scanning experiment with a wavelength tuning step of 0.02 nm at a fixed effective refractive index, we expect that the 11-channel CROW sensor should have a sensing resolution of $\sim 10^{-5}$ RIU. We are currently working to increase the CROW channel number in order to enhance the sensitivity and to demonstrate refractive index sensing using a fluidic cladding.

6. CONCLUSION

In summary, we reviewed our recent work on silicon photonic devices incorporating microring and microdisk resonators integrated with p-i-n diodes for optical time delay and advance, microdisk mode spectroscopy, and with microfluidic channels for microparticles trapping and transporting, and for potential refractive index sensing using spatial optical detection on multiple channels. Our work indicated that the p-i-n diode embedded microring resonator provides a viable on-chip solution for optical time delay and advance. While the two-photon absorption based photocurrent spectroscopy can be used to electrically probe the cavity-enhanced internal mode field, which proves to be useful in studying other novel shaped microresonators. It is noteworthy that this optical-to-electrical measurement method does not rely on the optical gain of the material, and thus provides a relatively direct measurement of resonance modes. On the optofluidic particle manipulation front, our work showed that it is feasible to optically manipulate single microparticles on a microring resonator-based add-drop device with both trapping and transporting modes depending on the carrier wavelength and the resonator quality factor. We therefore envision that by cascading multiple resonator-based microparticle add-drop devices, it should be possible to form a microparticle circuit on top of the optical circuit layer for microparticles sorting and transporting. On the optofluidic biosensing front, our proof-of-concept experiments suggested that coupled-resonator optical waveguide (CROW) enables an alternative refractive index sensing mechanism which is based on detecting spatial pattern variations upon refractive index change, which paves the way toward multi-channel imaging-based sensing.

ACKNOWLEDGEMENTS

This study was substantially supported by grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (Projects 618506, 618707, 618308, 618010). We acknowledge Amonics Inc. for the 20-dBm EDFA. X. Luo acknowledges the fellowship support from the HKUST NANO program. We also acknowledge the HKUST Nanoelectronics Fabrication Facility for all the device fabrication.

REFERENCES

- [1] Liang, D. and Bowers, J. E., "Recent progress in lasers on silicon," *Nat Photonics*, 4(8), 511-517 (2010).
- [2] Reed, G. T., Mashanovich, G., Gardes, F. Y. and Thomson, D. J., "Silicon optical modulators," *Nat Photonics*, 4(8), 518-526 (2010).
- [3] Poon, A. W., Luo, X., Xu, F. and Chen, H., "Cascaded Microresonator-Based Matrix Switch for Silicon On-Chip Optical Interconnection," *P IEEE*, 97(7), 1216-1238 (2009).
- [4] Xia, F., Rooks, M., Sekaric, L. and Vlasov, Y., "Ultra-compact high order ring resonator filters using submicron silicon photonic wires for on-chip optical interconnects," *Opt Express*, 15(19), 11934-11941 (2007).
- [5] Xia, F., Sekaric, L. and Vlasov, Y., "Ultracompact optical buffers on a silicon chip," *Nat Photonics*, 1(1), 65-71 (2007).
- [6] Bravo-Abad, J., Ippen, E. P. and Soljacic, M., "Ultrafast photodetection in an all-silicon chip enabled by two-photon absorption," *Appl Phys Lett*, 94(24), 241103 (2009).
- [7] Chen, H., Luo, X. and Poon, A. W., "Cavity-enhanced photocurrent generation by 1.55 μm wavelengths linear absorption in a p-i-n diode embedded silicon microring resonator," *Appl Phys Lett*, 95(17), 171111 (2009).
- [8] Chen, H. and Poon, A. W., "Two-photon absorption photocurrent in p-i-n diode embedded silicon microdisk resonators," *Appl Phys Lett*, 96(19), 191106 (2010).
- [9] Doylend, J. K., Jessop, P. E. and Knights, A. P., "Silicon photonic resonator-enhanced defect-mediated photodiode for sub-bandgap detection," *Opt Express*, 18(14), 14671-14678 (2010).

- [10] Logan, D. F., Velha, P., Sorel, M., De La Rue, R. M., Knights, A. P. and Jessop, P. E., "Defect-Enhanced Silicon-on-Insulator Waveguide Resonant Photodetector With High Sensitivity at 1.55 μm ," *IEEE Photon. Technol. Lett.*, 22(20), 1530-1532 (2010).
- [11] Mandal, S., Goddard, J. M. and Erickson, D., "A multiplexed optofluidic biomolecular sensor for low mass detection," *Lab Chip*, 9(20), 2924-2932 (2009).
- [12] Yang, A. H. J. and Erickson, D., "Optofluidic ring resonator switch for optical particle transport," *Lab Chip*, 10(6), 769-774 (2010).
- [13] Claes, T., Molera, J., De Vos, K., Schacht, E., Baets, R. and Bienstman, P., "Label-Free Biosensing With a Slot-Waveguide-Based Ring Resonator in Silicon on Insulator," *Photonics Journal, IEEE*, 1(3), 197 - 204 (2009).
- [14] De Vos, K., Bartolozzi, I., Schacht, E., Bienstman, P. and Baets, R., "Silicon-on-insulator microring resonator for sensitive and label-free biosensing," *Opt Express*, 15(12), 7610-7615 (2007).
- [15] Xu, D.-X., Vachon, M., Densmore, A., Ma, R., Janz, S., Delage, A., Lapointe, J., Cheben, P., Schmid, J. H., Post, E., Messaoudene, S. and Fedeli, J.-M., "Real-time cancellation of temperature induced resonance shifts in SOI wire waveguide ring resonator label-free biosensor arrays," *Opt Express*, 18(22), 22867-22879 (2010).
- [16] Boyd, R. W. and Gauthier, D. J., "'Slow' and 'fast' light," *Progress in Optics*, 43, 497-530 (2002).
- [17] Chiao, R. Y. and Milonni, P. W., "Fast light, slow light," *Optics and Photonics News*, 13(6), 26-30 (2002).
- [18] Heebner, J. E. and Boyd, R. W., "'Slow' and 'fast' light in resonator-coupled waveguides," *Journal of Modern Optics*, 49(14/15), 2629-2636 (2002).
- [19] Parra, E. and Lowell, J. R., "Toward applications of slow light technology," *Opt. Photonics News*, 18, 40-45 (2007).
- [20] Shi, Z., Boyd, R. W., Gauthier, D. J. and Dudley, C. C., "Enhancing the spectral sensitivity of interferometers using slow-light media," *Opt. Lett.*, 32(8), 915-917 (2007).
- [21] Wang, T., Liu, F., Wang, J., Tian, Y., Zhang, Z., Ye, T., Qiu, M. and Su, Y., "Pulse Delay and Advancement in SOI Microring Resonators With Mutual Mode Coupling," *Journal of Lightwave Technology*, 27(21), 4734-4743 (2009).
- [22] Manipatruni, S., Dong, P., Xu, Q. and Lipson, M., "Tunable superluminal propagation on a silicon microchip," *Optics Letters*, 33(24), 2928-2930 (2008).
- [23] Luo, X., Chen, H. and Poon, A. W., "Electro-optical tunable time delay and advance in silicon microring resonators," *Optics Letters*, 35(17), 2940-2942 (2010).
- [24] Schwelb, O., "Transmission, group delay, and dispersion in single-ring optical resonators and add/drop filters - A tutorial overview," *Journal of Lightwave Technology*, 22(5), 1380-1394 (2004).
- [25] Li, C., Zhou, L. and Poon, A. W., "Silicon microring carrier-injection-based modulators/switches with tunable extinction ratios and OR-logic switching by using waveguide cross-coupling," *Opt. Express*, 15(8), 5069-5076 (2007).
- [26] Zhou, L. and Poon, A. W., "Electrically reconfigurable silicon microring resonator-based filter with waveguide-coupled feedback," *Opt. Express*, 15, 9194 (2007).
- [27] Madsen, C. and Zhao, J., [Optical Filter Design and Analysis - A Signal Processing Approach], Wiley, (1999).
- [28] Liang, T. and Tsang, H., "Role of free carriers from two-photon absorption in Raman amplification in silicon-on-insulator waveguides," *Appl Phys Lett*, 84(15), 2745-2747 (2004).
- [29] Liang, T. and Tsang, H., "Efficient Raman amplification in silicon-on-insulator waveguides," *Appl Phys Lett*, 85(16), 3343-3345 (2004).
- [30] Liang, T., Tsang, H., Day, I., Drake, J., Knights, A. and Asghari, M., "Silicon waveguide two-photon absorption detector at 1.5 μm wavelength for autocorrelation measurements," *Appl Phys Lett*, 81(7), 1323-1325 (2002).
- [31] Rong, H., Liu, A., Jones, R., Cohen, O., Hak, D., Nicolaescu, R., Fang, A. and Paniccia, M., "An all-silicon Raman laser," *Nature*, 433(7023), 292-294 (2005).
- [32] Rong, H., Xu, S., Cohen, O., Rada, O., Lee, M., Sih, V. and Paniccia, M., "A cascaded silicon Raman laser," *Nat Photonics*, 2(3), 170-174 (2008).
- [33] Fathpour, S., Tsia, K. K. and Jalali, B., "Energy harvesting in silicon Raman amplifiers," *Appl Phys Lett*, 89(6), 061109 (2006).
- [34] Fathpour, S., Tsia, K. K. and Jalali, B., "Two-photon photovoltaic effect in silicon," *IEEE J Quantum Elect*, 43(11-12), 1211-1217 (2007).
- [35] Lin, S., Schonbrun, E. and Crozier, K., "Optical Manipulation with Planar Silicon Microring Resonators," *Nano Lett*, 10(7), 2408-2411 (2010).

- [36] Cai, H. and Poon, A. W., "Optical manipulation and transport of microparticles on silicon nitride microring-resonator-based add-drop devices," *Opt Lett*, 35(17), 2855-2857 (2010).
- [37] Cai, H. and Poon, A., "Optical microparticle manipulation using whispering-gallery-modes in a silicon nitride microdisk resonator," submitted to Conference on Lasers and Electro-Optics (Optical Society of America, 2011).
- [38] Suter, J. D., White, I. M., Zhu, H. Y., Shi, H. D., Caldwell, C. W. and Fan, X. D., "Label-free quantitative DNA detection using the liquid core optical ring resonator," *Biosensors & Bioelectronics*, 23(7), 1003-1009 (2008).
- [39] Yariv, A., Xu, Y., Lee, R. and Scherer, A., "Coupled-resonator optical waveguide: a proposal and analysis," *Opt Lett*, 24(11), 711-713 (1999).
- [40] Lei, T. and Poon, A., "Coupled-Resonator Optical Waveguide Sensors Using Multi-Channel Spatial Detection," submitted to Conference on Lasers and Electro-Optics (Optical Society of America, 2011).
- [41] Luo, X. and Poon, A. W., "Many-element coupled-resonator optical waveguides using gapless-coupled microdisk resonators," *Opt Express*, 17(26), 23617-23628 (2009).