Nonlinear Response of Silicon Double-Notch-Shaped Microdisk Resonators with Non-Evanescent Coupling

Hui Chen¹, Chao Li², Andrew W. Poon¹, and H. K. Tsang²

¹Photonic Device Laboratory, Department of Electronic and Computer Engineering
The Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong SAR, China
Tel: (852)-2358-7905; Fax: (852)-2358-1485; Email: eeawpoo@ust.hk

²Department of Electronic Engineering, The Chinese University of Hong Kong
Shatin, Hong Kong SAR, China

Abstract: We report double-notch-shaped microdisk resonators for silicon nonlinear-optic applications with direct in/out coupling via the microdisk notches. We measure optical bistability and resonance wavelength redshifts induced by the notch-coupled pump light.

© 2008 Optical Society of America

OCIS codes: (230.5750) Resonators, (130.4310) Integrated optics, Nonlinear

Recently, spiral-shaped microdisk resonators featuring a single notch for non-evanescent waveguide coupling has been demonstrated by one of us (AWP) on a silicon chip showing resonance Q of $\sim 10^4$ [1]. However, spiral-shaped microdisk resonators only allow non-evanescent coupling via a single notch. It is thus conceivable to employ two notches to form a double-notch-shaped microdisk resonator, which is potentially favorable for efficient optical in/out-coupling, particularly in the interest of nonlinear-optic applications. It has been known that silicon microdisk resonators exhibit nonlinear response in the input optical power range of mW [2], yet the evanescent side-coupling between the bus waveguide and the microdisk imposes precise waveguide fabrication or tapered-fiber positioning. We see that the double-notch-shaped microdisk offers an alternative microdisk structure with direct in/out-coupling via the notches and high- Q resonances. Here, we report our initial measurements of the nonlinear response of double-notch-shaped microdisk resonators.

Figures 1(a) and (b) show the scanning electron micrograph and the schematic of a waveguide-coupled double-notch-shaped microdisk resonator. The microdisk comprises two hemi-circular disks with radii R_1 and R_2 . The microdisk has a notch on each side with width of $w = R_1 - R_2$. Our fabricated microdisk resonator on a silicon-on-insulator wafer (device height of $\sim 0.34 \mu\text{m}$) shows resonance Q values on the order of 10^4 using R_1 of $50 \mu\text{m}$ and w of $1 \mu\text{m}$ (see Fig. 2(a)).

Figure 1(c) schematically shows the mechanism of a bistable transmission spectrum obtained by means of wavelength-increasing scanning. The circles represent the scanning wavelengths. When the wavelength is at off-resonance, the optical power injected into the resonator is relatively low and thus the resonator has “cold” cavity resonance (solid-line). As the wavelength approaches the resonance lineshape, an increase in the cavity optical power redshifts the resonance wavelength (dashed-lines) due to thermo effects. Thus, the wavelength scan follows the blue side of the resonance lineshape until the wavelength reaches the redshifted resonance dip. A further increment in wavelength reaches the red side of the resonance lineshape, causing a drop in the cavity optical power. Consequently, the cavity resonance blueshifts and results in an abrupt transition from a low- to a high-transmission, signifying optical bistability [3].

Fig 1. (a) Scanning electron micrograph of a waveguide-coupled double-notch-shaped microresonator ($R_1 \sim 50 \mu\text{m}$, $w \sim 0.4 \mu\text{m}$). (b) Schematic of a double-notch-shaped microresonator. (c) Mechanism of a bistable transmission spectrum obtained by means of wavelength-increasing scan. Circles: scanning wavelengths; Solid-line: “cold” cavity resonance; Dashed-lines: redshifted resonances upon injected optical power. (d) Schematic transmission spectrum obtained by means of wavelength-increasing scan.

Fig 2. (a)-(e) Measured transmission spectra upon various input optical power of a double-notch-shaped microresonator ($R_f \sim 50 \mu\text{m}$, $w \sim 1 \mu\text{m}$) for both wavelength increasing (solid-line) and wavelength decreasing scan (dashed-line). P_o : output power. (f) Bistability transition wavelength for wavelength increasing scan as a function of output power. (g) Bistable transmission spectrum measured in wavelength increasing scan with the output power $\sim 2 \text{ mW}$. The labeled positions represent the pump wavelengths we perform the probe spectra measurements (h)-(k).

We measure the resonator transmission with the laser source scanning in both wavelength-increasing ($\uparrow\lambda$) and wavelength-decreasing ($\downarrow\lambda$) directions upon various optical input power (Fig. 2(a)-(e)). For transmission output power around $100 \mu\text{W}$, both $\uparrow\lambda$ and $\downarrow\lambda$ scans show nearly identical transmission spectra of multimode resonances. The labeled resonance (*) in Fig. 2(a) reveals a Q of 6×10^4 . Further increment in the optical input power redshifts the resonance wavelength (Fig. 2(b)). As the output power reaches beyond $\sim 1 \text{ mW}$, we observe significant resonance lineshape broadening (Figs. 2 (c)-(e)). The transmission spectra reveal a sharp transition at wavelength * from a low- to a high-transmission, which is consistent with Fig. 1(d). The $\downarrow\lambda$ scan reveals a transition wavelength distinct from the $\uparrow\lambda$ scan upon the same optical input power. Figure 2(f) shows the bistability transition wavelength in the $\uparrow\lambda$ scan redshifts with the waveguide optical output power.

In order to study the cavity response upon different pump wavelengths, we measure the transmission spectrum of a low-power probe wavelength that is arbitrarily offset from the pump wavelength ($\sim 1559 \text{ nm}$). Figures 2(h)-(k) show the measured transmission spectra at the probe wavelength. Each spectrum is measured upon the pump wavelength approaching the labeled wavelength positions (shown in Fig. 2(g)) in $\uparrow\lambda$ scan. Figures 2(h)-(j) show the probe resonance redshifts as the pump wavelength scan from off-resonance (h) 1559.050 nm to on-resonance (j) 1559.425 nm , indicating an increase in the injected optical power in the cavity. Figure 2(k) shows that the probe resonance blueshifts after the pump wavelength scan through the bistable transition wavelength at $\sim 1559.44 \text{ nm}$, suggesting an abrupt decrease in the injected optical power. The probe resonances wavelength difference is around 0.1 nm when the pump scans from (j) 1559.425 nm to (k) 1559.440 nm , indicating a refractive index change of $\sim 2 \times 10^{-4}$. The probe resonance lineshapes are also slightly broadened while the pump is at on-resonance wavelengths as a result of an increase in the nonlinear loss.

[1] J. Y. Lee, X. Luo and A. W. Poon, "Reciprocal transmission and asymmetric modal distributions in waveguide-coupled spiral-shaped microdisk resonators," Opt. Express **15**, 14650-14666 (2007).

[2] M. Borsell, T. J. Johnson, and O. Painter, "Accurate measurement of scattering and absorption loss in microphotonic devices," Opt. Lett. **32**, 2954-2956 (2007).

[3] G. Priem, P. Dumon, W. Bogaerts, D. Van Thourhout, G. Morthier, and R. Baets, "Optical bistability and pulsating behaviour in silicon-on-insulator ring resonator structures," Opt. Express **13**, 9623-9628 (2005).