# Thermo-optical tunable planar ridge microdisk resonator in silicon-on-insulator

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**Abstract:** In this work, we design and demonstrate planar ridge microdisk resonators in silicon-on-insulator, which assemble the advantages of microring and microdisk resonators. The dependences of resonator optical modes on the slab thickness and the waveguide-to-resonator coupling gap are investigated. The highest Q-factor obtained is  $\sim 4 \times 10^5$ . Using the thermo-optical effect, we attain a resonance wavelength tuning efficiency of  $\sim 66.5$  pm/mW. We also compare the transmission spectra measured by using wavelength-scanning method and voltage-scanning method.

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### 1. Introduction

Silicon-on-insulator (SOI) based photonics has huge application potential, which is ideal for developing high density, multi-functional photonic integrated circuits, and hybrid optoelectronic integrated circuits [1–4]. Micrometer-scale resonators are the key building blocks for silicon photonics, thanks to the merits of high quality-factor (Q-factor) modes, compact size, and accessibility with optical waveguides [5–7]. Among various micro-resonators, microring and microdisk are the two most investigated structures. The microring resonator is easier to achieve single mode operation due to its waveguide structure, while the microdisk tends to be multimode. However, the microdisk resonator promises better Qs, as the microring resonator may suffer higher sidewall roughness-induced scattering loss from both inner and outer sidewalls than the microdisk resonator. For most of the applications, such as lasers, modulators, switches, and biosensor, high-Q microdisk resonators are attracting much more interests [6–14].

There are two kinds of microdisk structures, namely microdisk with undercut and planar microdisk. Benefitted from high index contrast (silica/air) and excellent smooth surface, the undercut microdisk can realize  $> 10^8$  Q-factor [15]. Evanescent coupling via a silica tapered fiber is necessary in order to couple light into such high-Q microdisk, which makes it less applicable for on-chip photonic integration. In a planar microdisk, a pre-fabricated waveguide is often employed to couple the light with the microdisk, which is much more stable, reliable and also easier for photonic integration. For planar microdisk with only one coupled waveguide, termed as notch filter, the throughput transmission spectrum displays multiple resonance dips. In such case, the resonance extinction ratios (ER) are not high, especially for those with high Q cavity. For microdisk with two coupled waveguides, termed as add/drop filter, the drop-port transmission spectrum which shows multiple resonance peaks can achieve high-ER resonance with compromised Q-factors due to the increased cavity loss from the second waveguide.

For high-Q micro-resonators, the resonance wavelengths are very sensitive to structure parameters and easily deviate from designed values. Therefore, dynamic resonance wavelength tuning mechanism, such as thermo-optical (TO) effect, is required in order to dynamically control the resonances. TO effect is one of the favorite choice due to its technological simplicity [16,17]. It is also applicable for low power reconfigurable filter and optical switch.

In this paper, we propose and demonstrate a ridge waveguide-based microdisk resonator, which inherit the merit from both microring and microdisk resonators. We show that as the decrease of the remained slab thickness, the microdisk mode number decreases with slightly compromised Qs. We show the dependence of the optical resonance as a function of the waveguide-to-resonator coupling gaps. We also demonstrate TO tunable optical switches with high ER and ultra-low tuning power.

# 2. Device fabrication and characterization

#### 2.1 Fabrications

We started the fabrication on a commercially available 200 mm SOI wafer with 220 nm-thick top silicon layer and 2  $\mu$ m-thick buried oxide (BOX) layer. The device is fabricated by a twostep patterning and etching process. A microring structure is patterned by 248 nm deep UV lithography and shallowly etched by reactive ion etching (RIE) process. Then, two crescents in the coupling regions and a circular shape inside the microring are patterned and another RIE dry etch of the silicon layer to BOX is performed. Such two-step patterning and etching process makes half-ridge waveguides, which can be found in detail in our previous work [18]. Two spot-size converters (SSC) are fabricated in input- and output- coupling facets in order to reduce coupling losses between fiber and waveguide. After the fabrication of the passive devices, 1- $\mu$ m high-density plasma (HDP) oxide is deposited, followed by 120 nm Titanium nitride (TiN) deposition for the thermal heater. Here, TiN is adopted rather than Ti due to its better chemical stability [19]. A 30 nm-thick silicon nitride is deposited for TiN etching protection. The width of heater line is 2  $\mu$ m and the length is ~327  $\mu$ m. After the formation of contact holes, 750 nm thick aluminum is deposited, followed by metal pad etching.



Fig. 1. (a) Optical micrograph of the microdisk integrated with thermal heater. (b) Optical micrograph of planar silicon ridge microdisk resonator. (c) Zoom-in SEM of the crescent-shaped converter between channel waveguide and ridge waveguide. (d) Zoom-in SEM of the directional coupler between two ridge waveguides. (e) TEM of the cross section in coupling region. (f) Optical micrograph of the cascaded crescent-shaped converter for cut-back measurement.

The optical micrograph of the final device is shown in Fig. 1(a). The upper yellow lines represent the thermal heater, while the passive add/drop microdisk is shown in Fig. 1(b). The heater is etched in concentric circles in order for uniform heat generation. Passive add/drop microdisk includes two crescent half-ridge waveguides and ridge disk. Both the crescent and microdisk have the radii of 20  $\mu$ m. Figure 1(c) shows the zoom-in SEM of the crescent-shaped transition section of the channel waveguide to the half-ridge waveguide. Such design is adopted in order to reduce the coupling loss. Figure 1(d) shows the zoom-in SEM of the ridge waveguide coupler. Cross-sectional view of the coupling region is shown in Fig. 1(e), with the slab thickness *h* and coupling gap *g*.

#### 2.2 Characterization and analysis

We employ the Photonic Dispersion and Loss Analyzer (Agilent 86038B PDLA) to characterize the fabricated microdisk add/drop filters. The laser output from PDLA is set to be quasi-TE polarized via a polarization controller (Agilent 8169A), then coupled into the input SSC via a polarization-maintaining (PM) single-mode lensed fiber. The output light from the device is collected by another PM fiber via output SSC and directly goes into the PDLA for analysis.

We first measure the propagation loss of the waveguide and the crescent-shaped converter using cut-back method. Figure 1(f) shows the microscopy of the cascaded crescent-shaped converters for the measurement. The measured propagation loss for 400 nm waveguide is  $\sim$ 2.4 dB/cm, and is  $\sim$ 0.025 dB/facet for the crescent-shaped converter with 100 nm slab thickness.

2.2.1 Optical modes dependence on the slab thickness



Fig. 2. Measured TE-polarized throughput and drop transmission spectra of a fabricated planar ridge microdisk with  $r = 20 \ \mu\text{m}$ ,  $h = 100 \ \text{nm}$ , and  $g = 250 \ \text{nm}$ . (a) The through and drop transmission spectra. (b) and (c) Zoon-in views of the two resonances spanning a FSR in linear scale with Lorentzian fittings.

Figure 2(a) shows the measured throughput and drop transmission spectra of a ridge microdisk resonator with h = 100 nm and g = 250 nm, which shows only one set of dominant modes with free spectral range (FSR) of ~4.96 nm. It is believed that the high-order modes are suppressed by the removal of the microdisk center region with only 100 nm slab. Figures 2(b) and 2(c) show the zoom-in views of the two resonances spanning a FSR, respectively. We observe that while the first resonance at ~1565.95 nm show a single peak with Q ~1.2 × 10<sup>5</sup>, the resonance at ~1570.9 nm splits into two peaks with Q ~1.48 × 10<sup>5</sup> and  $1.42 \times 10^{5}$ . We attribute this to the clockwise and counter-clockwise modes splitting due to the light scattering by the sidewall [6].

In order to investigate the optical modes dependence on the slab thickness, we fabricate planar ridge microdisk resonators with different slab thicknesses. Figure 3(a) show the

measured drop-port transmission spectra for  $r = 20 \mu m$ , g = 200 nm and h = 50, 100, and 150 nm. It clearly shows that as decreasing h, the number of the optical modes decreases. This is quite expected that as the decrease of the slab thickness, the microdisk gradually transforms to a microring resonator. Thus, the number of the optical modes and the optical mode quality factor decrease.

We compare the optical structure difference by calculate the effective refractive index. For microdisk resonator with small waveguide width w and large radius r, its cross-section can be considered as a rectangular waveguide structure, while for microring resonator, we can simply treat it as a three layer planar waveguide for the effective refractive index [20]. The calculating results are shown in Fig. 3(b). The upper insets (i) - (iv), respectively, show the calculated mode field distribution of the fundamental modes for the ridge waveguide structures with w = 400 nm, h = 0, 50, 100, and 150 nm (h = 0 corresponds to channel waveguide). As the structure changes from channel waveguide to different ridge waveguide, the mode profile evolves. For example, for h = 100 nm, the waveguide mode profile gradually evolves from channel waveguide mode to crescent waveguide mode, as indicated in insets (i) and (iii). For microdisk with thin slab, the optical mode is mainly confined inside the ridge waveguide. As the slab thickness increases, the optical mode gradually extends to the slab waveguide, and so the optical loss decreases. The bottom inset figure shows the calculation structure of the three-layer planar waveguide. The effective refractive indices for both structures also increase. For slab thickness closes to 150 nm, both structures have the same effective refractive indices, which suggest a microdisk structure for high-order modes. Such calculation is consistence with our measurements shown in Fig. 3(a).



Fig. 3. (a) Measured TE-polarized drop-port transmission spectra for  $r = 20 \mu m$ , g = 200 nm and h = 50, 100, and 150 nm. (b) Effective refractive indices comparison. Upper insets (i) – (iv) show the field distributions of the fundamental modes for the ridge waveguide structures with h = 0, 50, 100, and 150 nm. Lower inset shows three-layer waveguide structure.

#### 2.2.2 Quality factor dependence on the coupling gap and the slab thickness

We also investigate the Q-factor dependence on the waveguide-to-resonator coupling gaps and the slab thicknesses. Figure 4(a) show for example the drop-port transmission spectra of one set of devices with  $r = 20 \ \mu\text{m}$ ,  $h = 100 \ \text{nm}$  and varied coupling gap g = 200, 250, 300, and350 nm. We observe that as the coupling gap increases, the resonance peak intensity decreases in general and the resonance line width decreases. We also notice that for large coupling gap, for example,  $g > 250 \ \text{nm}$  in Fig. 4(a), the resonances split to two resonances. This is expected for high-Q microdisk resonators, which is induced by the clockwise and counter-clockwise modes splitting due to the light scattering by the sidewall [6].



Fig. 4. (a) Spectra of drop transmission with different coupling gaps. (b) Q-factor variations as functions of coupling gaps and slab thicknesses.

Figure 4(b) summarizes the Q-factor variations as functions of the coupling gaps upon different slab thicknesses. For the splitting resonance, we separately calculate the Q-factors from these two splitting resonances, denoted as Qs and Qc [6]. We obtain the Q-factors by fitting the optical resonance using Lorentzian function. The highest Q-factor achieved is  $\sim 4 \times 10^5$ . Due to the tunable laser resolution limitation of 1 pm, the maximum Q-factor measured is  $\sim 7 \times 10^5$ . For h = 150 nm and g = 350 nm, the Q-factor exceed this limit, which is not shown in the figure. As indicated in the transmission spectra (Fig. 4(a)), the resonance Q-factor increases as the coupling gap increases. The Q-factor also increases as the slab thickness increases, which have already shown in Fig. 3.

The Q-factor dependence on the coupling gap can be easily understood from the transmission spectra calculation. The light intensity from throughput (T) and drop (D) can be expressed as:

$$T = 1 - \frac{\kappa^2 \left(1 - t^2 \gamma^4\right)}{\left(1 - t^2 \gamma^2\right)^2 + 4t^2 \gamma^2 \sin^2(\theta)}$$
(1)

$$D = \frac{\kappa^4 \gamma^2}{\left(1 - t^2 \gamma^2\right)^2 + 4t^2 \gamma^2 \sin^2\left(\theta\right)}$$
(2)

where, t is the waveguide transmission coefficient, k is the coupling coefficient,  $\gamma$  and  $\theta$  are the loss coefficient and phase shift in *half* microdisk circumference. For lossless coupling,  $t^2 + \kappa^2 = 1$ , while for lossless propagation,  $\gamma = 1$ . Thus, we attain the relation of maximum of drop port as:

$$D_{max} = \frac{\kappa^4 \gamma^2}{\left(1 - t^2 \gamma^2\right)^2} \quad \text{and} \quad \frac{\partial}{\partial t} D_{max} = -\frac{4t \kappa^2 \gamma^2 \left(1 - \gamma^2\right)}{\left(1 - t^2 \gamma^2\right)^3} < 0.$$

 $D_{max}$  is smaller than the ideal case of 1, because of the loss,  $\gamma < 1$ . Also, the waveguide transmission coefficient *t* is a monotonic function of coupling gap *g*. Therefore, we have  $\partial D_{max}/\partial g < 0$ , which means the drop-port transmission intensity decreases with increasing *g*.

The full-width at half-maximum (FWHM) can be expressed as:

$$\Delta \theta_{3dB} = 2\sin^{-1} \left[ \frac{\sqrt{2}}{2} \frac{1 - t^2 \gamma^2}{\sqrt{1 + t^4 \gamma^4}} \right] \cong 2 \left( 1 - t^2 \gamma^2 \right)$$
(3)

The Q-factor relates with  $\Delta \theta_{3dB}$  as:

$$Q \cong \frac{2\pi\lambda_c}{FSR\Delta\theta_{_{3dB}}} \cong \frac{\pi\lambda_c}{FSR(1-t^2\gamma^2)}$$
(4)

where FSR is free space region, and  $\lambda_c$  is resonance wavelength.

As the coupling gap increases, the transmission coefficient *t* increases ( $\kappa$  decreases), resulting in the lower drop port transmission and narrow  $\Delta \theta_{3dB}$ . The corresponding Q-factors increase, as well.

# 2.2.3 Thermo-optical tuning of the microdisk resonator

As mentioned previously, thermo-optical tuning for microresonator devices plays two important roles: i) to trim the resonance wavelength due to fabrication imperfection, and ii) to switch the optical resonance for optical data routing. Here we show high-efficiency and high extinction ratio optical tuning using the demonstrated planar ridge microdisk resonator. Figures 5(a) shows the measured drop-port transmission spectra upon different voltage supplies. The optical resonance wavelength red-shifts due to thermo-optical effect. The resonance ER of the throughput is ~10 dB, while for drop-port is ~30 dB. The electric resistance of TiN heater is ~1677.8  $\Omega$ . The heater strip section is 120 nm × 2 µm, and total length is 327 µm. From Ohm's law, the electrical resistivity is 123 µ $\Omega$ ·cm. Figure 5(b) shows the resonance wavelengths as functions of the electric powers for the resonance at 1566 nm. The linear fitting suggests the tuning efficiency of ~66.5 pm/mW. Thus, for optical switching with on/off ratio of ~27 dB, the applied voltage is ~2 V, corresponding to an electrical power of ~2.4 mW.



Fig. 5. (a) Measured drop-port transmission spectra upon different voltage supplies. (b) Resonance wavelength shift as function of the electronic power. The demonstrated microdisk here is with  $r = 20 \ \mu\text{m}$ ,  $g = 250 \ \text{nm}$  and  $h = 100 \ \text{nm}$ .

By fixing the input light wavelength at 1572 nm, and scanning the supplied voltage from 0 V to 10 V (from 0 mW to 60 mW), the optical resonances of the microdisk resonator also increase as the refractive index change. The relationship between the thermal power and the wavelength change can be expressed as:

$$\lambda(nm) = 1572 - 0.067 V^2 / R(k\Omega)$$
(5)



Fig. 6. Comparing of drop-port transmission spectra between (a) wavelength scanning method, and (b) voltage scanning method. The voltage scale is converted to wavelength by using Eq. (5).

Figures 6(a) and 6(b) show the measured transmission spectrum using wavelengthscanning and voltage-scanning methods, respectively. According to Eq. (5), we have  $\Delta\lambda$  (pm)  $\approx 80V\Delta V$ . If the resolution of voltage supply is 1 mV, we obtain the wavelength resolution  $\Delta\lambda$ (pm)  $\approx 0.08V$ . This suggests that for voltage smaller than 1 V, the measurement accuracy for the optical transmission spectrum can be smaller than 0.1 pm. If we use nano-ampere current power supply, the measurement accuracy can go down to 0.2 fm. This is significant for high-Q resonance measurement, which usually requires high-resolution wavelength-scanning lasers. Furthermore, it is noticed that by using voltage-scanning method, the transmission spectrum is much clear with lower noise. Another application for such voltage-scanning method is to trace the wavelength shift of certain system. For instance, Fig. 6(b) can be considered as the voltage response of input wavelength 1572 nm. If the input wavelength shifts, we can easily determine the wavelength shift by scanning the voltage again and compare the voltage responses before and after the wavelength change.

Some of asymmetric Fano resonances are appear in Fig. 6(a), such as the resonance at ~1571.8 nm. We attribute the Fano resonance to the interaction between the microdisk mode and the modes generated inside the high slab crescent coupling region [21]. Its Q value is as high as ~ $1.6 \times 10^5$ . For the optical intensity changing from the maximum to the minimum via TO effect, the voltage change is only ~140 nm or 0.3 mW power change, with ER of ~24 dB. The potential application of such Fano resonance includes on chip spectra analyzer, optical switch and tunable filter.

#### 3. Conclusion

We have investigated the add/drop ridge microdisk resonators. We study the quality factor dependence on the microdisk slab thickness and the waveguide-to-microdisk coupling gap. For microdisk slab, the thicker it is, the more the optical modes and the higher the optical resonance quality factor. For coupling gap, the wider it is, the higher the quality factor. When it is used as thermo-optical tunable filter, we obtained a tuning efficiency of 66.5 pm/mW and extinction ratio of ~27 dB. We also propose and demonstrate the voltage-scanning method for the optical spectra measurement and compared with wavelength-scanning method, which show high resolution and low noise.

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