

Double-notch-shaped microdisk resonator devices with gapless coupling on a silicon chip

Invited Paper

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We propose novel double-notch-shaped microdisk resonator-based devices with gapless waveguide-to-microdisk and inter-cavity coupling via the two notches of the microdisk. Both finite-difference time-domain simulations and experimental demonstrations reveal the high-quality-factor multimode resonances in such microdisks. Using such double-notch microdisk resonators, we experimentally demonstrate the many-element linearly cascaded-microdisk resonator devices with up to 50 elements on a silicon chip.

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Microspiral resonators with the key merit of possessing a single notch for gapless coupling are widely investigated for unidirectional lasers^[1–4] since their initial demonstration in 2003 by Chern *et al.*^[1]. Thanks to their unique gapless coupling via the notch, such microspiral resonators have also been studied for multiple-element (three-element) cascaded-microdisk resonator-based devices that offer novel wavelength and intensity switching^[5,6].

Recently, our research group further demonstrated the microspiral resonators for passive wavelength-agile filter applications, leveraging the advantage that light can be directly in/out-coupled to the microspiral resonator via a waveguide that is seamlessly jointed to the microspiral notch^[7,8]. We have verified that such non-evanescent gapless waveguide-coupling via the notch preserves high-quality-factor (high-Q) whispering-gallery (WG) like multimode resonances^[7]. The shortcoming of microspiral resonators with the single-notch design is that an additional evanescently side-coupled waveguide is still imposed for optical input/output (I/O) devices, which are crucial building blocks for nascent photonic integrated circuit applications. In particular, microspiral resonators with a single-notch design are not favorable for many-element cascaded-microresonator devices such as optical delay lines^[9].

In this letter, we propose and experimentally demonstrate a novel double-notch-shaped microdisk resonator, with the key merit of gapless input- and output-coupling via two notches. Our two-dimensional (2D) finite-difference time-domain (FDTD) simulations indicate WG-like multimode resonances in such non-conventional microdisks. Our experimental demonstrations reveal a high-Q preserving microdisk of 50- μm radius in size with Q as high as 24000. Furthermore, we also demonstrate the many-element cascaded-microdisk resonator device with up to 50 elements using such double-notch microdisks in a SiN-on-silica substrate.

Figure 1(a) shows the schematic of the double-notch microdisk resonator-based channel notch filter. The

microdisk shape comprises two jointed non-identical semi-circles with radii of r_1 and r_2 . The mismatches between the two semi-circles on both sides along the diameter give two notches with widths of w_1 and w_2 . The notch widths are identical in the case that the two semi-circles are concentric. Each notch is seamlessly jointed to a waveguide of the same width. Thus, the light can be gaplessly in/out-coupled to the microdisk via these notch-waveguides without relying on the evanescent field which imposes sub-micrometer gap spacing. It is conceivable that the round-trip cavity light can be wavefront-matched with the in-coupled lightwave, and the resonance field is only partially out-coupled to the throughput port. This enables such single-input, single-output and gapless waveguides-coupled microdisk resonator to act as a channel rejection filter.

We numerically simulate the double-notch microdisk resonators using FDTD method. We adopt two semi-circles with radii of $r_1 = 10\ \mu\text{m}$ and $r_2 = 9.7\ \mu\text{m}$, giving identical notch size of $w_1 = w_2 = 0.3\ \mu\text{m}$. In order to account for the vertical dimension while using only 2D simulations, we use an effective refractive index contrast of 1.9/1.4 assuming a SiN-on-silica substrate.

Figure 1(b) shows the simulated TM-polarized throughput-port transmission spectrum of the double-notch microdisk-based filter. The free spectral range (FSR) of $\sim 24\ \text{nm}$ is consistent with the microdisk circumference. The calculated highest quality factor is ~ 5500 , which is high given by the FDTD spatial resolution. The inset of Fig. 1(b) shows the simulated steady-state mode-field pattern of mode A. We observe a WG-like resonance mode-field distribution, revealing cavity-enhanced intensity and lightwave directly in/out-coupled via the two notch-waveguides.

We fabricate the double-notch microdisk resonator-based filters in a SiN-on-silica substrate using standard complementary metal oxide semiconductor (CMOS) compatible silicon nanoelectronics fabrication processes. We adopt a 1.1- μm -thick SiN device layer on a 1.5- μm -thick silica under-cladding layer, each prepared by

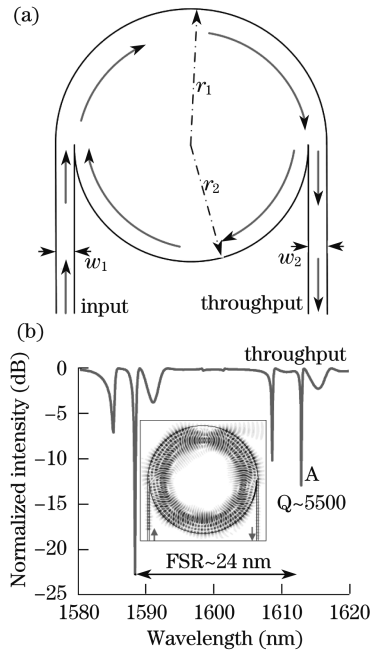


Fig. 1. (a) Schematic of the double-notch microdisk resonator. (b) 2D FDTD simulated TM-polarized throughput transmission spectrum of the microdisk resonator, showing high-Q and high-extinction-ratio resonances. The FSR is consistent with the cavity circumference. Inset: simulated resonance field patterns, displaying a WG-like mode-field distribution.

chemical vapor deposition (CVD) process on a 4" silicon wafer. The device structures are defined by i-line (365 nm) photolithography followed by CF₄-based reactive ion plasma etching (RIPE). The filters are air-clad ded. Figure 2(a) shows the top-view scanning electron micrograph (SEM) of the fabricated device. The measured radii are r_1 of $\sim 50 \mu\text{m}$ and r_2 of $\sim 49 \mu\text{m}$, giving a notch size of $\sim 1 \mu\text{m}$. The zoom-in view SEM shows the waveguide-to-microresonator gapless notch-coupling region. We note that the $1\text{-}\mu\text{m}$ -wide notch-waveguides remain single-mode based on our numerical simulations using beam-propagation method (BPM) (see the inset of Fig. 2(b)).

Figure 2(b) shows the measured TM-polarized throughput-port transmission spectrum of this device. The FSR is measured to be $\sim 3.5 \text{ nm}$, which is consistent with the microdisk circumference. This suggests that the resonances are WG-like. The measured highest Q is ~ 24000 , suggesting a high-Q preserving microcavity. However, the resonance extinction ratio is relatively small. We attribute this to the non-optimized design of the gapless waveguide-to-microdisk coupling.

Leveraging the gapless in/out-coupling, we propose and demonstrate many-element cascaded-microdisk resonator devices. All microdisks are directly coupled via gapless inter-cavity coupling. We fabricate such many-element devices on the same SiN chip, with the number of microdisks spanning 2, 10, 20, and 50.

Figure 3(a) shows the optical micrograph of our fabricated 50-element device with single input and single output. Figures 3(b)–(d) show the zoom-in view SEMs of the gapless in/out-coupling regions and the gapless inter-cavity coupling region. All the cascaded double-

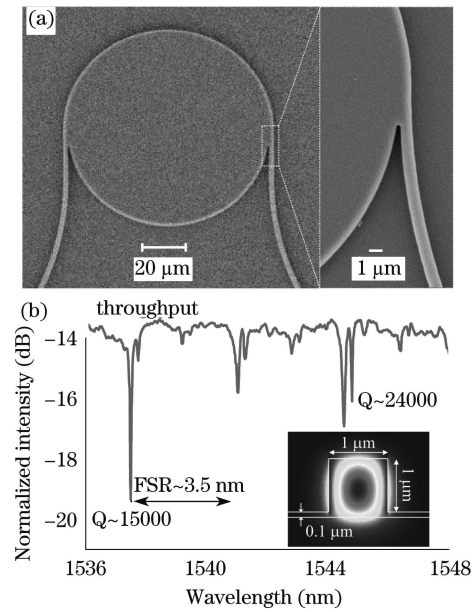


Fig. 2. (a) SEM of the fabricated double-notch microdisk resonator-based filter in SiN-on-silica substrate. Inset: zoom-in view of the notch junction. (b) Measured TM-polarized throughput transmission spectrum. Inset: BPM simulated mode-field distribution of a $1\text{-}\mu\text{m}$ -wide waveguide with the same cross-section of fabricated waveguide.

notch microdisks are with the same design of $r_1 = 20 \mu\text{m}$ and $r_2 = 19.2 \mu\text{m}$, with notches of $0.8 \mu\text{m}$ wide.

Light is directly input-coupled to the edge microdisk. At the inter-cavity coupling region, the cavity light is preferentially coupled from one microdisk to the next one in the forward propagation direction (gray solid arrow in Fig. 3(d)). Nonetheless, due to the structural asymmetry of the jointed notches, the cavity round-trip light from the onward disk is only weakly backward-coupled to the preceding disk (black dashed arrow in Fig. 3(d))^[10]. The light propagating to the other edge disk is output-coupled to the notch-waveguide. Compared with the coupled-resonator optical-waveguide devices using microring resonators^[9], the merit of our many-element device is that the gapless waveguide-to-cavity coupling and inter-cavity coupling impose no narrow gap spacing. This significantly relaxes the fabrication constraint which is often the key bottleneck for large-scale integration of microresonator arrays.

Figures 3(e)–3(h) show the measured TM-polarized throughput-port multimode transmission spectra of 2-, 10-, 20-, and 50-element devices. In each case, we observe a FSR of $\sim 9.4 \text{ nm}$, which is consistent with the single microdisk circumference. As the number of cascaded microdisks increases, some of the resonance lineshapes are inhomogeneously broadened. We attribute such lineshape broadening to possible size mismatches among the cascaded microdisks due to inevitable fabrication imperfections^[9].

For the 50-element device, the broadened lineshape results in periodic rejection bands with $\sim 5 \text{ nm}$ bandwidth and a flat baseline with $> 35 \text{ dB}$ extinction ratio. We note that the spectra from the different devices display common resonances that are only slightly shifted in

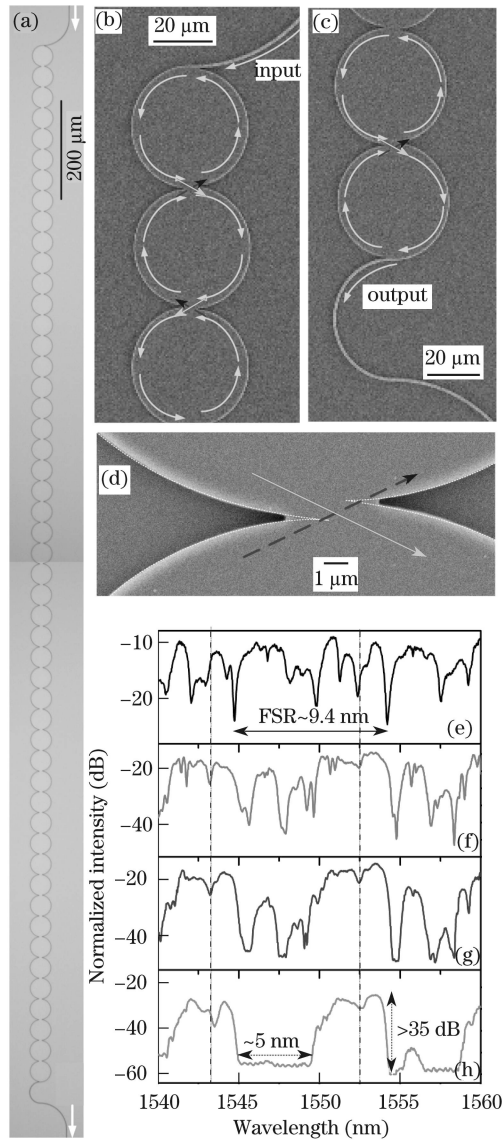


Fig. 3. (a) Optical micrograph of the fabricated 50-element cascaded-microdisk resonator device using double-notch microdisks. (b)–(d) Zoom-in SEMs of the in/out-coupling regions and the gapless inter-cavity coupling region. The white arrows illustrate the light propagation. The crossed white and black arrows illustrate the preferred forward-coupling and weak backward-coupling. (e)–(h) Measured TM-polarized throughput-port transmission spectra of many-element cascaded-microdisk resonator devices with disk numbers of 2, 10, 20, and 50.

wavelength (e.g, the vertical dotted lines highlight the common resonances that are separated by a FSR). From the on-resonance drop-port insertion losses, we estimate that the microdisk insertion loss is ~ 0.16 dB/disk. This is comparable to the previous demonstration using cascaded microring resonators which show ~ 0.13 dB/ring^[9].

In summary, we have proposed and demonstrated double-notch microdisk resonator-based devices with gapless in/out-coupling. Such building block is demonstrated to be high-Q preserving and is favorable for large-scale integration as many-element devices. The many-element cascaded-microdisk resonator devices with up to 50 elements are demonstrated. We therefore envision that such device should be good candidate for large-scale-integrated microresonator-based devices.

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