Variable bandwidth of dynamic add–drop filters based on coupling-controlled microdisk resonators

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Dynamic add–drop filters with variable bandwidth are demonstrated on microelectromechanical-system (MEMS)–actuated microdisk resonators for what is believed to be the first time. The tuning mechanism is based on a variable power coupling ratio that is controlled by varying the gap spacing between the waveguide and the microdisk through MEMS actuators. The results show wavelength switching with an extinction ratio of 20 dB and a tunable bandwidth ranging from 12 to 27 GHz. These dual functions were realized using the device with the operation voltage varying between 0 and 35 V. © 2006 Optical Society of America

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Dynamic add–drop filters are key elements in reconfigurable wavelength-division-multiplexing optical networks for routing individual wavelength channels. Integrated microresonators such as microrings and microdisks make it possible to realize large-scale add–drop multiplexing on a single chip.[1] To make the system reconfigurable, each filter has to be tunable by manipulating either the transmittance or the selective wavelength. Previously, we demonstrated a novel microelectromechanical-system (MEMS)–actuated microdisk resonator for switching a single wavelength between two waveguides.[2] Based on this design, promising hitless dynamic wavelength routing[3] is accomplished in planar light circuits. In this Letter, we further present a tunable spectral width of an add–drop filter based on this MEMS-actuated microdisk cavity.

Tunable bandwidth is useful for optical performance monitoring[4]; for example, measuring the group delay time between the upper and lower vestigial-sideband signals of the transmitted data. In addition, tunable bandwidth can be used in dynamic bandwidth allocation for optimal spectral utilization. However, tuning the bandwidth of an integrated optical filter is challenging, although other bulky devices such as mechanically stretched fiber Bragg gratings[5] and Gires–Tournois interferometers with movable micromirrors[6] have been demonstrated.

Directly tuning the power coupling ratios of a two-waveguide-coupled microdisk resonator is an effective way of implementing an integrated tunable filter not only in switching wavelength channels but also in engineering the filter bandwidth. However, the coupling ratio is extremely difficult to tune once the microdisk is fabricated. Employing MEMS actuators can control the gap spacing between the waveguide and the disk.[7,8] As a result, the power coupling ratio can be significantly modified. Figure 1 lists the coupling conditions of a microdisk resonator with variable gap spacing. As the waveguides are far from the disk, there is essentially no optical energy transferred since the coupled power is much less than the resonator loss. The optical wave propagates directly from the input port to the throughport. However, the coupling efficiency increases rapidly as the waveguide approaches the disk. Until the waveguide coupling greatly overcomes the resonator loss, the resonant wavelength could transfer from the input port to the drop port. A further increase of coupling does not affect the transmittance much, whereas the transmission bandwidth expands.

The optical filter is implemented by a fixed silicon microdisk with 20 μm radius and two vertically coupled deformable silicon waveguides with 0.8 μm width, as shown in Fig. 2. The waveguides and the

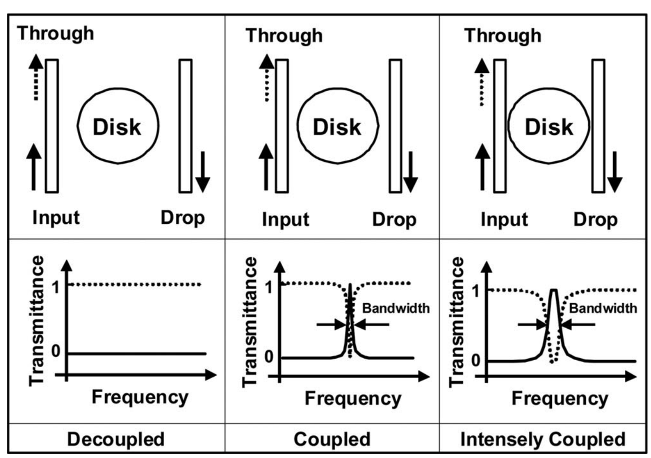
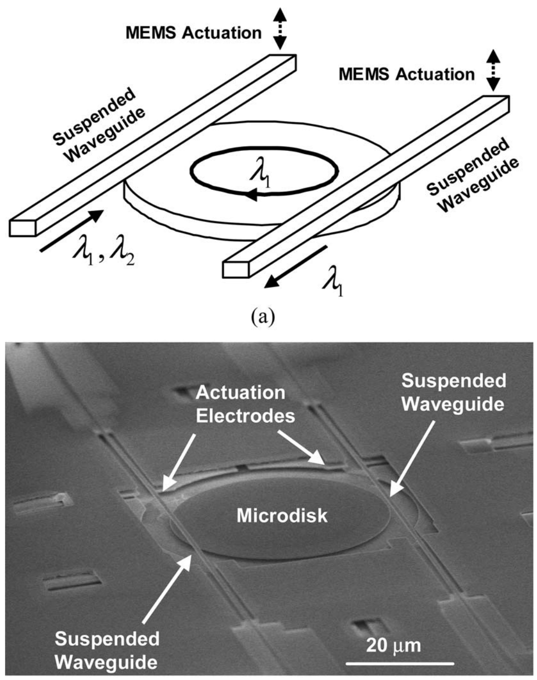


Fig. 1. Gap-controlled microdisk resonators and the transmission spectra at the throughport and the drop port.



(b)

Fig. 2. Vertically coupled microdisk resonator with MEMS actuators: (a) schematic illustration, (b) scanning electron micrograph of the fabricated devices.

microdisk are vertically separated by 1 μm gap spacing. These two waveguides are physically suspended and aligned with the disk edge. Electrostatic actuators, employed at the ends of the waveguides, pull the waveguide down as the bias voltage is applied to the electrodes. This deformation causes reduced gap spacing and excites the whispering gallery modes in the microdisk. Details of the fabrication processes were reported elsewhere.[2]

A quantitative analysis of waveguide transmission can refer to the time-domain coupling theory.[9] The optical transmission is expressed as a function of a resonant frequency ω_0, power coupling ratios of the input and output waveguides (κ_1 and κ_2, respectively), a round-trip propagation loss γ, and a round-trip propagation time T. The transmission from the input port to the throughport is given by

$$T_{\text{through}}(\omega) = \frac{j2T(\omega-\omega_0)+(\gamma+\kappa_1-\kappa_2)}{j2T(\omega-\omega_0)+(\gamma+\kappa_1+\kappa_2)}, \qquad (1)$$

and the transmission form the input port to the drop port is written as

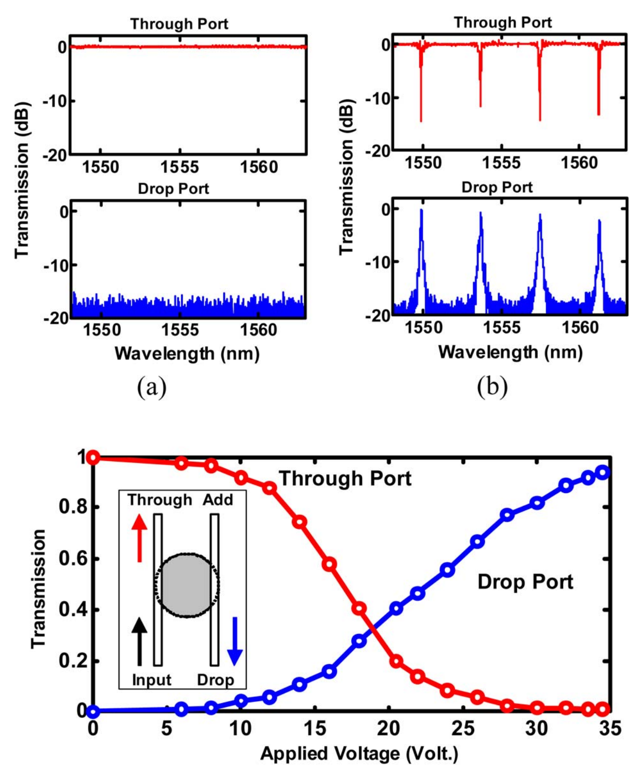
$$T_{\text{drop}}(\omega) = \frac{2\sqrt{\kappa_1\kappa_2}}{j2T(\omega-\omega_0)+(\gamma+\kappa_1+\kappa_2)}. \qquad (2)$$

When the power coupling ratios (κ_1 and κ_2) are equal for the two coupled waveguides, Eqs. (1) and (2) indicate that a complete optical power transfer at a resonant frequency occurs as long as the power coupling ratio is much larger than the round-trip resonator loss. On the other hand, no transfer happens as the power coupling ratio reduces to zero.

To examine this function, we launch a broadband light source into the input port and measure the optical power at the throughport and the drop port. Both waveguides are actuated with the same applied voltage. Figure 3(a) shows the spectral responses at the throughport and the drop port without bias. The power coupling ratio is minute for both waveguides due to a large gap spacing (1 μm). In such a case, all the power is transferred to the throughport. As the applied voltage increases to 30 V, the power decreases at the throughport as the signal is transferred to the drop port at the resonant wavelength. The results are shown in Fig. 3(b).

Figure 3(c) plots the optical transmission versus the applied voltage for both the throughport and the drop port at the resonant wavelength of 1555.46 nm. A 20 dB extinction ratio is observed when the bias is coupled from 0 V (decoupled) to 35 V (intensely coupled). At the threshold voltage of about 19 V, the sum of the power at the throughport and the drop port is not equal to the input power, as about 28% of the input power is consumed in the microdisk. This consumed power resulting from resonator loss emerges as the microdisk operates near the critical coupling condition ($\gamma=\kappa$), where the optical field intensity is maximal inside the disk. If the electrodes are switched between 0 and 35 V, this device can be utilized as a dynamic add–drop filter.

The quality factor (Q) and the bandwidth of the microdisk optical filter also vary with the power coupling ratio and the round-trip resonator loss. Accord-



(c)

Fig. 3. (Color online) Spectral response of transmission at the throughport and the drop port: (a) 0 V and (b) 30 V. (c) Power transfer curves at the resonant wavelength of 1555.46 nm .

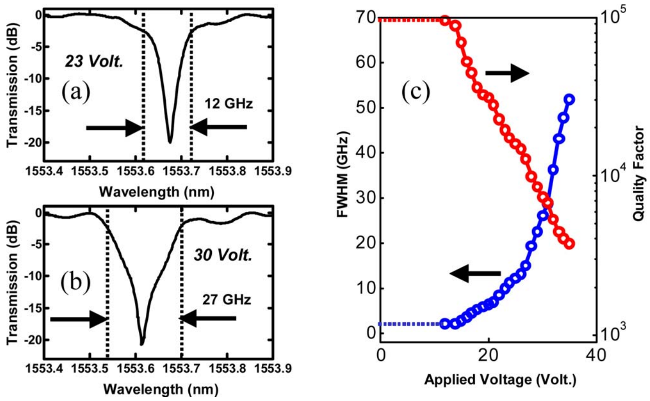


Fig. 4. (Color online) FWHM at the throughport with a bias of (a) 23 V and (b) 30 V. (c) Tuning ranges of the FWHM and Q.

ing to Eq. (2), the spectral response actually follows the Lorentzian-shaped function. Therefore, the quality factor is given by

$$Q^{-1} = \left(\frac{\kappa_1}{\gamma} + \frac{\kappa_2}{\gamma} + 1 \right) Q_0^{-1}, \tag{3}$$

where $Q_0 = \omega_0 T / \gamma$ represents the intrinsic quality factor. The full-width at half-maximum (FWHM) can be expressed as

$$\Delta\omega_{\mathrm{FWHM}} = \omega_0 \left(\frac{\kappa_1}{\gamma} + \frac{\kappa_2}{\gamma} + 1 \right) Q_0^{-1}, \tag{4}$$

which is based on the relation $Q = \omega_0 / \Delta\omega_{\mathrm{FWHM}}$. Equation (3) shows that Q decreases as the power coupling ratio increases. On the other hand, the maximum quality factor is ultimately limited by the intrinsic quality factor Q_0. The tuning range of Q or the bandwidth is approximately proportional to the value of $1/\gamma$. Therefore, a high-intrinsic-Q microdisk is desirable to have a wide tuning spectral range.

To demonstrate the tunable bandwidth of the microdisk resonator, we actuate both waveguides and measure the FWHM of spectral response at different electrode biases. Q can be obtained by curve fitting the Lorentzian-shaped spectral response. Figures 4(a) and 4(b) show the transmission spectra at the throughport with applied voltages of 23 and 30 V, respectively. The FWHM expands from 12 to 27 GHz without reducing the extinction ratio. The coupling-induced perturbation shifts the resonant wavelength from 1553.67 to 1553.62 nm as a result of phase mismatch of the waveguide and whispering gallery modes. This phase mismatch can be reduced by optimal design of the waveguide size. Figure 4(c) displays the tunable range of the variable quality factor and the FWHM, ranging from 3 to 53 GHz. The maximum Q is about 9.7×10^4, which approaches the intrinsic Q of our device, which was measured to be 100,000. These experimental results successfully demonstrate that a bandwidth-tunable optical filter can be realized by use of the MEMS-actuated microdisk resonator presented here.

In summary, we have shown bandwidth-tunable add–drop optical filtering by integrating MEMS actuators with a microdisk resonator. The power coupling ratio is tunable through gap-controlled MEMS actuation. Based on this tuning mechanism, a dynamic wavelength switching was presented with an extinction ratio of 20 dB and a tunable bandwidth range from 12 to 27 GHz. To our knowledge, this is the first time that a variable bandwidth has been realized with an integrated optical filter. More importantly, the results show that this coupling-controlled microdisk resonator could enable various tuning functions.

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