Vertically-Coupled MEMS Microdisks for Tunable Optical Delays and Dynamic Dispersion Compensation

Ming-Chang M. Lee
Electrical Engineering Department, University of California, Los Angeles
Phone: +1-310-825-7338, Fax: +1-310-794-5513, E-mail:marklee@icsl.ucla.edu

Ming C. Wu
Department of Electrical Engineering and Computer Sciences, University of California, Berkeley
Phone: +1-510-643-0808, E-mail:wu@eecs.berkeley.edu

Abstract: Rapidly tunable chromatic dispersion is realized by vertically-coupled microdisk resonators with MEMS-actuated deformable waveguides. Group delays (27 to 65 ps) and dispersions (185 to 1200 ps/nm) are continuously tuned by voltage (< 35V).

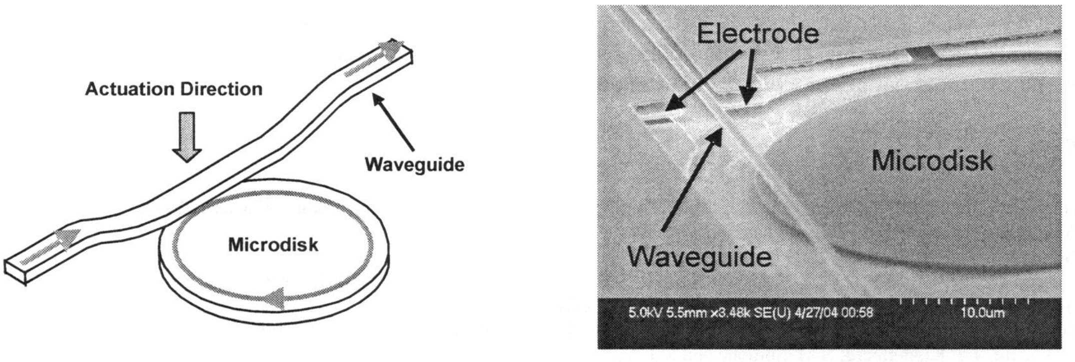
OCIS codes: (000.0000) General

Introduction

Dynamic dispersion compensation is essential for high bit rate reconfigurable optical networks. Tunable dispersion compensators using free-space Gires-Tournois interferometer [1], grating-based optical phase shifter [2], cascaded Mach-Zehnder interferometers [3], and waveguide ring resonators [4] have been demonstrated. Thermally tuned silica ring resonators have also been reported [5]. Thermal tuning, however, has high power consumption and slow response time. Semiconductor microdisk resonators are particularly attractive for this application because of their compactness, large free spectral range (FSR), and the ability to integrate with micro-electro-mechanical-system (MEMS) actuators. Previously, we have demonstrated a laterally coupled MEMS-tunable microdisk resonator [6]. The group delay was tuned by varying the power coupling ratio of the microdisk via a deformable waveguide. A variable negative group delay (0 to -400 ps/nm) was achieved.

The previous MEMS tunable microdisk can only operate in the under-coupled regime. In this paper, we report on a new, vertically coupled MEMS microdisk resonator. The improved design allows us to operate the integrated microresonator in all three coupling regimes (under-, critical, and over-coupling) for the first time. All-pass optical filters are realized by operating the microdisk in the over-coupling regime. Experimentally, a vertically coupled MEMS-actuated microdisk with positive tunable group delays (27 to 65 ps) and group velocity dispersions (185 to 1200 ps/nm) are achieved with tuning voltages less than 35V. [7]

Device Design, Simulation, and Fabrication



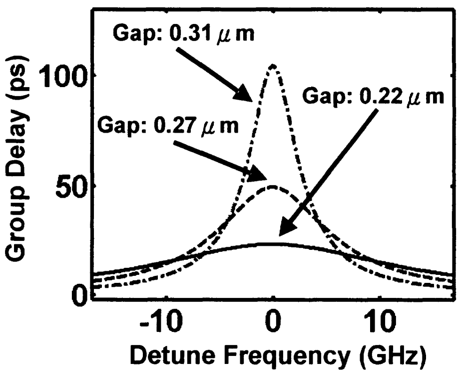
(a) (b)

Fig. 1 (a) Schematic and (b) scanning electron micrograph (SEM) of the tunable dispersion compensator comprising a vertically-coupled MEMS microdisk. The waveguide is suspended above the edge of the microdisk and can be pulled downward by electrostatic actuators.

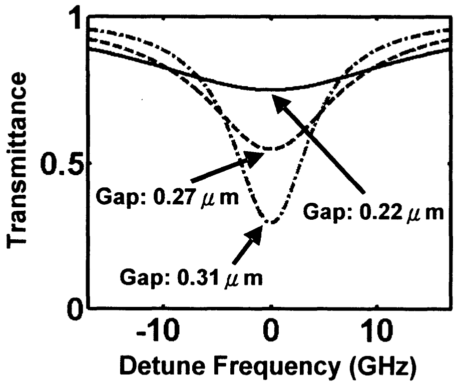
Figure 1(a) shows the schematic of the microdisk dynamic dispersion compensator. It comprises a fixed microdisk (20μm diameter) and a vertically coupled deformable optical waveguide (0.8μm wide). The waveguide is aligned to the edge of microdisk. Both the microdisk and the waveguide are made in 0.25-μm-thick single crystal silicon. The device is fabricated by thermally bonding two silicon-on-insulator (SOI) wafers with a 1-μm-thick SiO_2 in between. The microdisk and the electrodes for electrostatic actuators are fabricated on the bottom SOI layer, while the optical waveguide is fabricated on the top SOI layer. After released, the waveguides around the microdisks are suspended. The electrostatic actuator mimics that of a vertical comb-drive actuator with one movable finger and two fixed comb fingers. This design avoids the pull-in instability and permits the waveguide to be pulled down continuously from a gap spacing of 1μm (at 0V) to almost touching (at 35V). A novel hydrogen annealing process has been employed to reduce the sidewall roughness to less than 0.26nm. More detailed description of this process can be found in [7]. The scanning electron micrograph (SEM) of the fabricated device is shown in Fig. 1(b).

The vertically coupled device is favorable from both optical and MEMS point of view. The critical coupling gap is larger in the vertical direction. The operating voltage is also lower since the waveguide is easier to bend in the thinner dimension. This is indeed the case: the actuation voltage is 35V in the current device while it is > 70V in the laterally coupled device [6].

The mathematical expression of the group delay as a function of the power coupling ratio and the round-trip optical loss was introduced in our previous study [6]. In this analysis, we assume the resonator loss is fixed (unloaded Q= 10^5), and the power coupling ratio varies with the gap spacing according to the coupled-mode theory (CMT). Figure 2(a) shows the group delays versus the detuning frequency for three different gap spacing. A positive group delay indicates the resonator operates in the over-coupling regime. The maximum group delay increases with gap spacing as the power coupling ratios decreases. On the other hand, the transmission decreases as the gap spacing increases. This is because the operating condition is closer to critical coupling as the power coupling ratio reduces. The optical insertion loss can be minimized by increasing the quality factor (Q) of the microdisk.



(a)

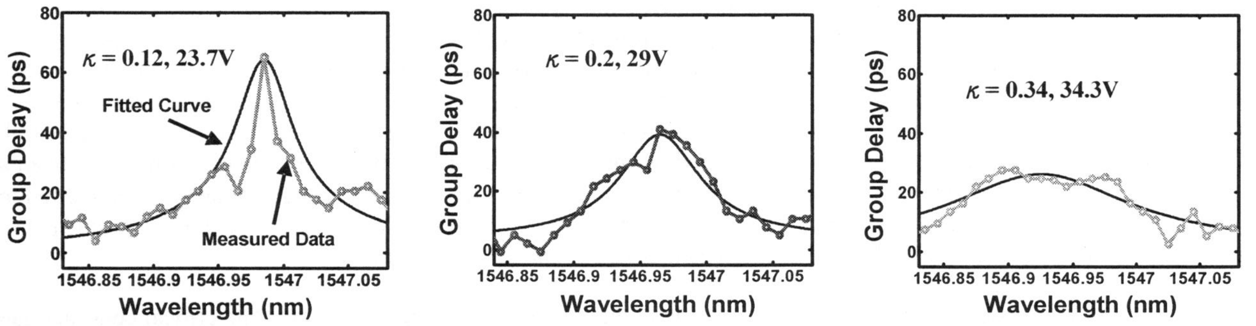


(b)

Fig. 2 (a) Calculated group delay versus detuning frequency for three different gap spacing: 0.31μm, 0.22μm, and 0.27μm, which correspond to power coupling ratios of 0.09, 0.17, and 0.3, respectively. (b) Calculated power transmission spectra for three different gap spacing.

Experimental Results

The group delay is measured with microwave modulation technique. An external cavity tunable laser is employed as the optical source. The optical carrier is modulated by a 500MHz sinusoidal signal. The microwave phase shift through the device is monitored while the optical wavelength is tuned across the resonance with a step size of 0.01 nm. Figure 3 shows the measured group delay at three different voltages. At 23.7V, a peak group delay of 65 ps is measured. At 34.3V, the peak delay reduces to 27 ps. By fitting the experimental data with the theoretical curve, the power coupling ratios are found to be 0.12 (at 23.7V), 0.2 (at 29V) and 0.34 (at 34.3V), respectively. The unloaded Q is estimated to be 70,000. The group velocity dispersion is varied from 185 ps/nm to 1200 ps/nm on the positive slope.



(a) (b) (c)

Fig. 3 Measured group delay versus wavelength at various bias voltages: (a) 23.7V, (b) 29V and (c) 34.3V. The power coupling ratios are extracted by fitting the experimental data to the theoretical curves.

Figure 4 shows the optical transmission spectra at various bias voltages. The full-width at half-maximum (FWHM) is 20GHz. The minimum optical insertion loss is 2 dB ($\kappa = 0.34$). As the coupling ratio reduces to 0.12, the transmittance drop at resonance is more pronounced (13 dB) because it is closer to the critical coupling condition ($\kappa = 0.065$). The optical insertion loss can be reduced by increasing the Q of the microdisk.

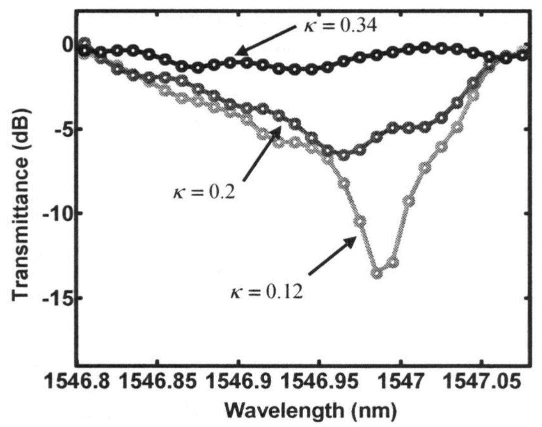


Fig. 4 Measured power transmission spectra at different applied voltages: (a) 23.7V, (b) 29V and (c) 34.3V.

Conclusion

Dynamic dispersion compensators using MEMS-actuated microdisks operating in the over-coupling regime have been demonstrated for the first time. The group velocity dispersion is tuned from 185 ps/nm to 1200 ps/nm, and the maximum group delay is tuned from 27 to 65ps. The minimum optical insertion loss of 2 dB is obtained at a power coupling ratio of $\kappa = 0.34$. The optical bandwidth is 20 GHz. Wider passband and larger dispersion range can be obtained by cascading multiple MEMS microdisks.

References

[1] K. Yu, O. Solgaard, "Tunable chromatic dispersion compensators using MEMS Gires-Tournois interferometers," 2002 IEEE/LEOS International Conf. Optical MEMS, pp. 181 -182, 2002

[2] D. T. Neilson, et al., "MEMS-Based Channelized Dispersion Compensator With Flat Passband", IEEE J. of Lightwave Tech., Vol. 22, No. 1, pp. 101-105, Jan. 2004.

[3] K. Takiguchi, S. Suzuki, T. Shibata, "Method for adjusting lattice-form optical devices and its use in realising low-loss variable chromatic dispersion compensator," Electronics Letters, vol. 39 pp.355 -356, 2003.

[4] G. Lenz et al., "Optical Delay Line Based on Optical Filters", IEEE J. of Quantum Electronics, Vol. 37, No. 4, pp. 525-532, Apr. 2001.

[5] C. K. Madsen, G. Lenz, A. J. Bruce, M. A. Cappuzzo, L. T. Gomez, T. N. Nielsen, L. E. Adams, and I. Brenner, "An All-Pass Filter Dispersion Compensator using Planar Waveguide Ring Resonators." OFC 1999, FE6-1

[6] Ming-Chang M. Lee, Sagi Mathai and Ming C. Wu, "Dynamic dispersion Compensator using MEMS-actuated microdisk resonators," CLEO 2004, Paper CThMM4.

[7] Ming-Chang Mark Lee, Jin Yao, and Ming C. Wu," Silicon Profile Transformation and Sidewall Roughness Reduction Using Hydrogen Annealing", 18th IEEE International Conference on Micro Electro Mechanical Systems MEMS 2005, accepted for publish