Transmission and group delay of microring coupled-resonator optical waveguides

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We measured the transmission and group delay of microring coupled-resonator optical waveguides (CROWs). The CROWs consisted of 12 weakly coupled, microring resonators fabricated in optical polymers (PMMA on Cytop). The intrinsic quality factor of the resonators was 18,000 and the interresonator coupling was 1%, resulting in a delay of 110–140 ps and a slowing factor of 23–29 over a 17 GHz bandwidth. © 2006 Optical Society of America

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Coupled-resonator optical waveguides (CROWs) are chains of weakly coupled resonators in which light propagates as a result of the coupling between the resonators.[1,2] Arising from the coupling between the resonators are dispersive properties unique to CROWs.[3–5] One of the most interesting properties is that optical pulses may propagate in CROWs with very low group velocities. As the resonators are weakly coupled, an optical signal in the structure effectively takes a longer time to tunnel from resonator to resonator and is thus slowed down.[6] Slowing light in a robust, chip-scale manner may open new avenues toward compact optical delay lines, interferometers, and optical buffers.[7,8]

A CROW, for the purpose of slowing light, must consist of a large number of weakly coupled resonators. However, the major challenge in realizing CROWs and other slow-light devices based on multiple resonators[9,10] has been the fabrication of nearly identical and relatively low-loss or high-Q resonators. The tolerance in the uniformity of the resonators becomes even stricter when the resonators are weakly coupled, since the linewidth of the coupled resonators is correspondingly narrower than when they are strongly coupled. Recently on-chip, high-order (>10) coupled microresonator chains have been realized by using microrings and photonic crystal defect cavities,[11–15] but an optical delay beyond ~ 1 ps has not been directly measured,[13] and the weak interresonator coupling has yet to be confirmed.

In this Letter we present amplitude and group-delay measurements of CROWs based on chains of high-order and weakly coupled (1%) microring resonators fabricated in polymer materials. The experiment is also the first demonstration of such high-order coupled resonators in optical polymers to our knowledge. Our results illustrate the possibility of achieving large optical delays (>100 ps) in CROWs.

The microring resonators were fabricated with electron-beam lithography in polymethylmethacrylate (PMMA, $n=1.49$, Microchem) with a perfluoropolymer, Cytop ($n=1.34$, Asahi Glass), as a lower cladding. Cytop was used because it provided sufficient index contrast for the fabrication of microrings. The combination of PMMA and Cytop has been used for polymer optical fibers[16] and planar waveguides,[17] though more complex waveguide structures have not been reported. Since a high degree of fabrication accuracy and uniformity is required, direct electron-beam writing of PMMA, one of the highest-resolution resists, without other processing steps that might add further deviations, is particularly well suited to the fabrication of CROWs.

We began by first depositing 5.2 μm of Cytop CTL-809M on a silicon substrate. After an oxygen plasma treatment, we spun a 2.6 μm thick layer of PMMA 950K C10 on the Cytop. The microring resonators were then patterned directly in the PMMA via electron-beam lithography by using a Leica EBPG 5000. Since PMMA is a positive resist, the electron-beam writing defined the cladding regions. The waveguides had a width of 2.9 μm and a height of 2.6 μm, and the cladding regions were 4 μm wide. The ring radius was 60 μm to keep the bend loss to <1 dB/cm. There was no gap between the resonators or between the resonators and the waveguides. Finally, we separated the devices by cleaving. Figure 1 shows an optical micrograph and a scanning electron micrograph of a fabricated device.

We have characterized the transmission and group-delay properties of CROWs with as many as 12 microring resonators. We coupled light into the device by butt coupling a single-mode fiber to the facet of the input waveguide. The light was collected at the facet of the output waveguide by a multimode fiber.

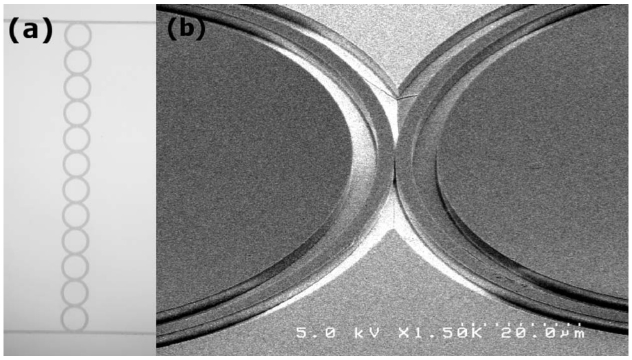

Fig. 1. (a) Optical micrograph of a CROW consisting of 12 microring resonators fabricated in PMMA on Cytop. (b) Scanning electron micrograph of the coupling region of the microring resonators. The radius of the microrings is 60 μm.

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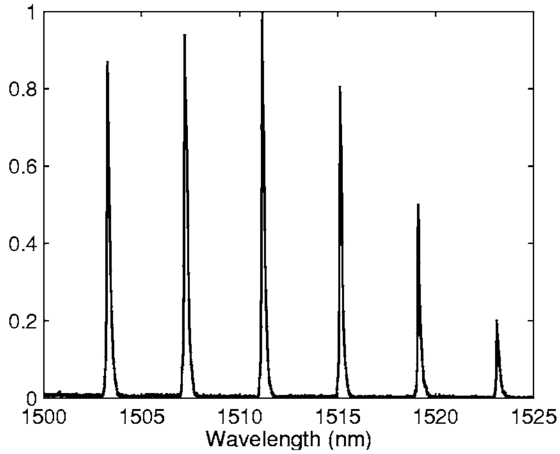

Fig. 2. Transmission spectrum through 12 microring resonators for TE-polarized light.

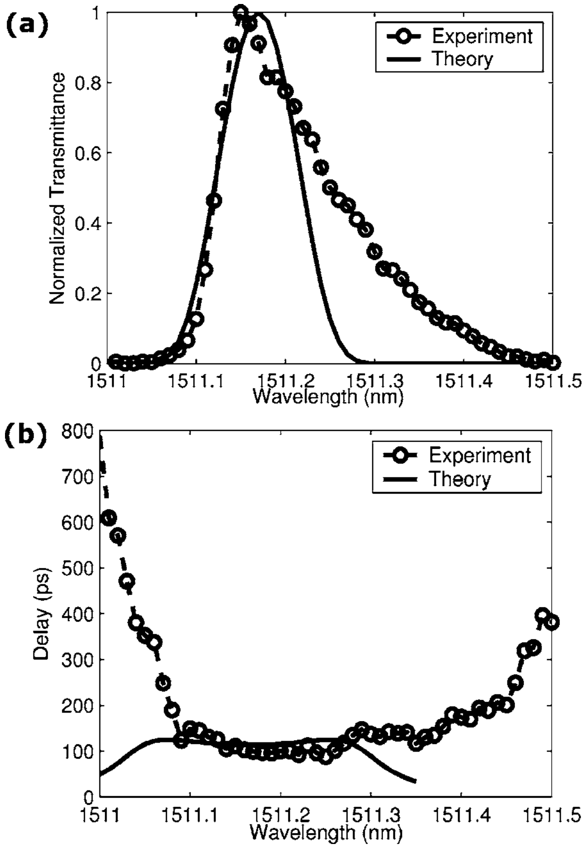

Fig. 3. (a) Normalized transmission amplitude and (b) group delay near 1551.16 nm through 12 microring resonators.

Figure 2 shows the transmission spectrum of TE-polarized light passing through the 12 microring resonators. The transmission spectrum does not possess spurious peaks, implying that the microring resonators were nearly identical. The narrow transmission peaks, with bandwidths at FWHM of 0.13 nm (17 GHz), are indicative of weak interresonator coupling. The free spectral range of the ring resonators was 3.97 nm, corresponding to a waveguide group index of 1.527. From the measurement of double-ring devices, we estimated the propagation loss in the microring to be 15 dB/cm, equivalent to an intrinsic quality factor of 1.8×10^4.

We measured the group delay by using a phase-shift technique with an RF lock-in amplifier[18] (SR 844). We modulated the optical output of a tunable laser at 200 MHz, and the output voltage of the detector at the output of the device was fed back to the lock-in amplifier, which measured the detected signal amplitude and its phase lag with respect to the modulation. By measuring the phase lag of a reference waveguide with a length equal to the input and output waveguides of the CROW and calibrating for any intrinsic system responses, we determined the group delay through the coupled microrings alone.

Figure 3 shows the measured amplitude and group delay over the wavelength range of the highest transmission peak in Fig. 2. The experimental results are compared against theoretically calculated results by using transfer matrices, assuming identical resonators with a loss of 15 dB/cm.[5] The asymmetry of the transmission peak in Fig. 3(a) may be due to slight polarization mixing and small deviations in the microring size and coupling in the presence of loss. Varying degrees of asymmetry were present in all of the devices measured. The interresonator intensity coupling coefficient, $|\kappa|^2$, from the numerical fitting of the amplitude and delay was approximately 1%. The group delay was 110 ± 7 ps at the transmission peak and increased to ~ 140 ps toward the edges of the transmission peak. The large group-delay values greater than 200 ps may not be physically accurate, since the transmission amplitude was nearly zero at those wavelengths. We define the slowing factor, S, as the ratio of the speed of light in vacuum, c, to the group velocity of light in the CROW, such that

$$S = c\tau/2NR, \tag{1}$$

where τ is the time delay, N is the number of resonators, and R is the radius. For the microring CROW, S is about 22.9 at the center of the transmission peak and about 29.2 at FWHM.

The insertion loss was 16 dB at the through port off resonance and 45 dB at the drop port on resonance. On resonance, approximately 25% of the power is coupled into the CROW from the input waveguide. Since the input and output waveguides are only several millimeters long, most of the loss at the through port is due to the input and output coupling between the device and the fibers. Assuming that the input and the output coupling losses were the same for the through and the drop ports, the ratio between the drop-port power and the difference in the on and off resonance through-port powers gives an equivalent loss of $\alpha_{\mathrm{res}} = 2.35$ dB per resonator. This is in close agreement with the theoretical prediction based on a chain of identical resonators[6]:

$$\alpha_{\mathrm{res}} = \alpha_l \pi R/|\kappa| = 2.8\ \mathrm{dB}, \tag{2}$$

where α_l is the per-length propagation loss in the resonators and $|\kappa|$ is the field coupling coefficient. The transmission spectrum (Fig. 2) and the losses attest to the uniformity of the microrings. Tuning of the individual resonators was not necessary.

In summary, we have measured in polymer microring CROWs optical delays of 110–140 ps and slowing factors of 23–29 with a FWHM bandwidth of 17 GHz. As we have demonstrated, a significant advantage of a CROW consisting of microrings rather than other types of resonator, such as spheres, disks, and photonic crystal defects, is that it possesses a clear and simple spectral response. The ultimate delay and number of coupled resonators that can be achieved in the polymer microring CROWs presented here will likely be limited by the propagation loss in the resonators and not by the fabrication accuracy.

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