Circular grating resonator-based microcavities make fast switches

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Integrated optical resonators with a small mode volume and a high quality factor hold promise for speedy data-transmission devices.

Future data communication bandwidth will require high-speed optical interconnections over short distances and ultimately, on-chip. The footprint of integrated components is important, but shrinking well-established device designs to dimensions of only a few optical wavelengths is difficult because electro-optical material properties do not scale well. Resonant structures compensate for this deficiency by creating an effectively longer propagation path for the light inside the active material. However, for mode volumes of only a few cubic wavelengths, commonly used ring or disc resonators are limited by bending losses. Alternatives such as photonic crystal-defect cavities and circular grating resonators (CGRs) enable ultra-small cavities to maintain very high quality factors (Q factors). CGRs consist of a central defect surrounded by Bragg mirrors in concentric circles. They do not require high-index contrast materials to achieve a complete band gap for radial wavevectors. In addition, fabricating devices with silicon-on-insulator (SOI) technology and taking advantage of CMOS-compatible processing enables very cost-efficient optical components.

We design and fabricate waveguide-coupled CGRs and explore their optical properties by performing linear transmission measurements to analyze CGR structures. Scanning near-field optical microscopy (SNOM) allows us to measure the intensity distribution in the selected mode. Our work has confirmed the operation of CGRs as fast, all-optical switches by performing pump and probe measurements.

By optimizing the dimensions of the concentric rings and maximizing the Bragg mirror’s band gap, we can achieve a large reflectivity. By varying the central defect’s radius, we can select resonance frequencies near the telecom wavelength of 1550nm. We fabricate CGRs on SOI substrates featuring a 2µm-thick buried oxide layer and a 340nm silicon device layer. The structures are defined by electron-beam lithography and transferred to the silicon by reactive-ion etching. The entire process flow minimizes the CGR’s side-wall roughness while maintaining the circular grating structures’ dimensional accuracy. Figure 1(a) shows the entire structure with in- and out-coupling waveguides. Figure 1(b) is a close-up of the rings highlighting the device’s fabrication precision. The CGR’s overall diameter is 10–20µm, depending on the central defect size and the number of Bragg rings.

Figure 1. Scanning electron microscope images of the circular grating resonator (CGR) structure. The dark lines are grating grooves. (a) Overview with in- and out-coupling waveguides. (b) Close-up of the circular grating, highlighting the fabrication precision. The width of the air gap is 118 nm and the silicon ridge is 282nm.

CGR transmission spectra reveal a large number of resonances. Applications such as ultrafast modulators require a subclass of resonances in which the mode is almost exclusively located in the central defect. Therefore, our work focuses on devices with a defect radius of 870nm, a resonance at 1562nm wavelength, and Q factor of about 1820.

We perform SNOM measurements to study details in the optical intensity distribution inside the CGR at a resolution of approximately 100nm (λ/15), which cannot be obtained by conventional far-field microscopy. Figure 2 shows a SNOM image of resonance overlaid with a CGR schematic design. The light enters from the bottom. There is scattering at the junction.

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Figure 2. Intensity distribution of the resonance at \( \lambda = 1562 \text{nm} \) measured with scanning near-field optical microscopy. The layout of the CGR is illustrated schematically. Intensity is in arbitrary units.

Figure 3. (a) Time-resolved transmission spectrum of a CGR after optical excitation with 0.21 nanojoule femtosecond pulses. The normalized intensity scale is colored in linear units. (b) Time-resolved wavelength shift of the CGR after optical excitation with 0.11–0.53 nanojoule pulse energies. Time delays are in picoseconds (ps) and wavelengths in nanometers (nm).

of the waveguides and the CGR due to mode-mismatch, a major source of transmission loss. However, there is good confinement in the central region, which enables the device to be used as a modulator with a very small active volume.

We investigated the spectral and temporal switching behavior using femtosecond pump-probe analysis. The transmission spectrum’s temporal evolution is shown in Figure 3(a). A clear wavelength shift that is dependent on the excitation pulse energy is seen with a rise time that reaches 10 picoseconds (ps) (see Figure 3(b)). The wavelength recovery time is mainly given by the free carrier lifetime (\( \sim 500 \text{ps} \)), which, in future work, we hope to reduce by actively sweeping out the charges or capturing them with implanted ions.\(^4\)

In summary, we have demonstrated the basic viability of waveguide-coupled CGRs as integrated optical resonators with a small mode volume of a few cubic wavelengths that still feature a Q factor of a few thousands. These are the first steps toward a novel waveguide-coupled, ultra-small footprint microcavity for fast switching devices. In future work, we will address the confinement of light within the defect. To increase the quality factor of the defect’s low-order azimuthal modes, vertical losses must be minimized. We also will study improved CGR designs.

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