Coupled-Resonator-Induced-Transparency in Cascaded Self-Coupled Optical Waveguide (SCOW) Resonators

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Abstract: We experimentally demonstrate coupled-resonator-induced-transparency (CRIT) in cascaded self-coupled optical waveguide (SCOW) resonators. CRIT tuning is realized by heating the inter-cavity connection waveguide using an intrinsic thermal resistor.
OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (230.4555) Coupled resonators

1. Introduction

Coupled resonator-induced transparency (CRIT) is a coherent resonance interference effect, analogous to electromagnetically induced transparency (EIT) in atomic systems [1, 2]. The CRIT is characterized by a sharp transparency peak between two resonant dips with a linear phase increase between two phase discontinuities. Due to its unique spectral characteristics, the CRIT can be used to implement various functions, including optical switch, optical buffer, biosensing, nonlinear optical signal processing, and quantum computing. Directly coupled microring resonators [3] or indirectly coupled microring resonators via two parallel bus waveguides [4] are the two common structures that can generate CRIT. In the former case, the transparency is produced by resonance splitting, which requires the mutual coupling coefficient between the two resonators be well set in order to get a suitable splitting separation. In the latter case, the transparency is produced by slightly detuning one of the resonators, which is challenging to implement in practice due to various fabrication errors.

Recently, we proposed and demonstrated novel self-coupled optical waveguide (SCOW) resonators, which exhibit unique optical characteristics and versatile optical functions [5-7]. The SCOW resonator is essentially a standing-wave resonator that can be configured to show split, broadened or enhanced resonance features as for a single resonator [7]. Here we experimentally investigate cascaded SCOW resonators and show that several types of CRIT resonance spectra can be generated dependent on the configuration of individual SCOW resonators.

2. Device structure and fabrication

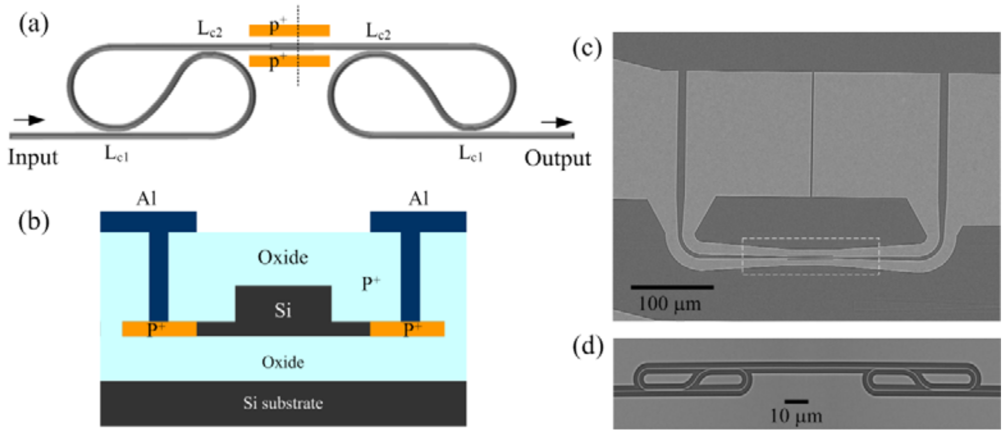

Fig. 1. (a) Schematic of the cascaded SCOW resonators. p-i-p thermal resistor is embedded in the inter-cavity connection waveguide. (b) Cross-sectional schematic of the thermal resistor. (c) SEM image of the device with electrodes. (d) SEM image of the device before electrode fabrication.

Fig. 1(a) shows the schematic drawing of the device comprising a pair of SCOW resonators connected by a thermal phase shifter in between. The phase shifter is composed by a lateral p-i-p junction as shown in Fig. 2(b). The rib waveguide width is 0.45 μm and the slab height is 60 nm. The central intrinsic region width is 1.65 μm. The length of the phase shifter is chosen such that the Fabry-Perot resonance (inter-cavity resonance) free spectral range (FSR) is double that of the SCOW resonance. The intrinsic region has a high resistivity and works as a micro-heater. Heat will be generated there when an electric current flows through the resistor. It should be noted that it is the waveguide itself that make up the thermal resistor (so called 'intrinsic' thermal resistor), and therefore, the generated heat directly interacts with the optical mode. There is no any diffusion process as in a conversional structure where a metal heater is put on top of the waveguide [8]. This type of intrinsic thermal resistor can potentially improve the power efficiency and switch speed, and moreover it is also compatible with CMOS processes.

The device fabrication process begins with a silicon-on-insulator (SOI) wafer with a top silicon layer of 220 nm thick and a buried oxide layer of 2 μm thick. The top silicon layer is p-type lightly doped with a resistivity of 10 to 15 Ohm·cm (corresponding to a hole concentration of ~10^{15} cm^{-3}). The waveguide was patterned with 248-nm deep ultra-violet (DUV) photolithography and then plasma dry etched. The etched depth is ~160 nm. The highly-doped P^+ regions were formed by Boron ion implantation with a concentration of ~10^{20} cm^{-3} for ohmic contact. After depositing a 1 μm thick silicon dioxide layer using plasma-enhanced chemical vapor deposition (PECVD) method as the waveguide upper-cladding, contact holes were etched through. Finally, aluminum was sputtered to cover the device surface and dry etched to form metal connection. Fig. 1(c) shows the final fabricated device. Metal connection lines and pads are clearly seen. The waveguides are buried inside the oxide cladding and can hardly be discerned. Fig. 1(d) shows the cascaded SCOW resonators without upper-cladding and electrodes to show the waveguide layer.

3. Experimental results

We characterize the device transmission performances using the Agilent loss and dispersion analyzer (86038B). Light is coupled into and out of the devices through on-chip waveguide invert tapers with a tip width of 180 nm. The active tuning of the device is performed by applying an external current source to the thermal resistor via a pair of metal probes.

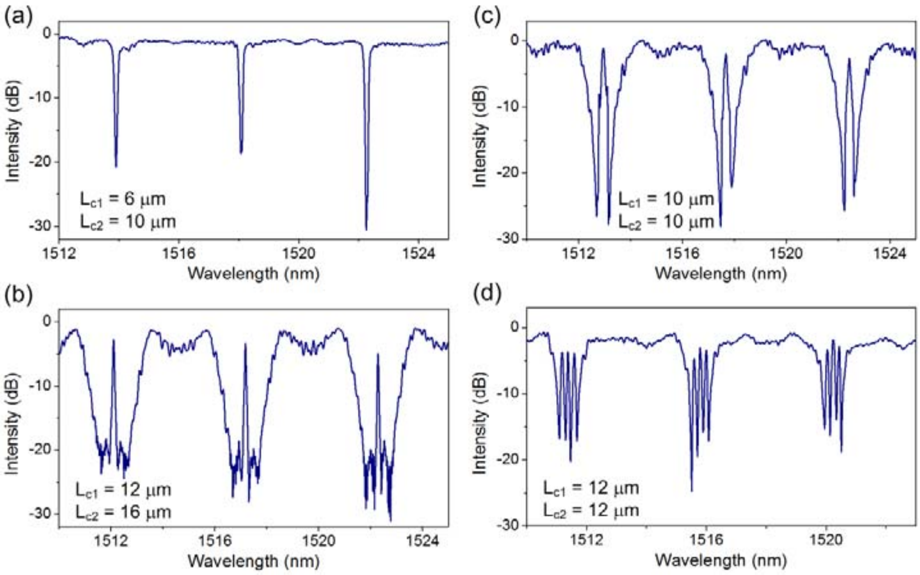

Fig. 2. Measured transmission spectra for cascaded SCOW resonators with various configurations showing (a) no transparency peak, (b) a single broad transparency peak in a narrow opaque valley, (c) a single narrow transparency peak in a broad opaque valley, and (d) three transparency peaks in a narrow opaque valley.

Fig. 2 shows the measured transmission spectra for various cascaded SCOW resonators without thermal tuning. The two SCOW resonators are identical and mirror-imaged from the central phase shifter. The coupling coefficients of SCOW resonators are varied by choosing different coupling lengths, as labeled in the figure. The optical characteristics of a single SCOW resonator are dependent on the coupling coefficients [7], and therefore when cascaded they can exhibit distinct optical performances when the coupling changes. When L_{c1} = 6 μm and L_{c2} = 10 μm, the resonance appears as a single sharp dip. The full-width-half-maximum (FWHM) width is 0.18 nm, corresponding to a quality (Q)-factor of 8400. Note that such a device can be used as a high-order filter. When L_{c1} = 12 μm and L_{c2} = 16 μm, the transmission spectrum exhibits a CRIT resonance with a 0.044 nm wide transparency peak in a 2.34 nm wide opaque valley. The CRIT peak has a Q-factor of 34,500 and an extinction ratio of ~20 dB. When L_{c1} = L_{c2} = 10 μm (symmetric couplers), and CRIT effect can also be observed, but the central transparency peak is broaden to 0.13 nm and the opaque valley is narrowed to 1.48 nm. Interestingly, if the length of the symmetric couplers is increased to $L_{c1} = L_{c2}$ = 12 μm, then the single CRIT peak is split into three with an almost equal separation of 0.2 nm. The extinction ratio for each peak is >10 dB.

To explore how the CRIT resonance changes with inter-cavity phase, we measured the transmission spectrum for various electric currents up to 1 mA as shown in Fig. 3. The device is the same as that in Fig. 2(b). The resistance is around 35 kΩ. It can be seen that with the increment of current, the broad opaque window is only slightly shifted due to the lateral diffusion of heat, while the CRIT peak shifts significantly first to the longer wavelength side and then returns back to the shorter wavelength side. It periodically moves inside the opaque wavelength window. Note that double peaks appear when the current is 0.2 mA and 1.0 mA due to the coherent interference between SCOW resonators.

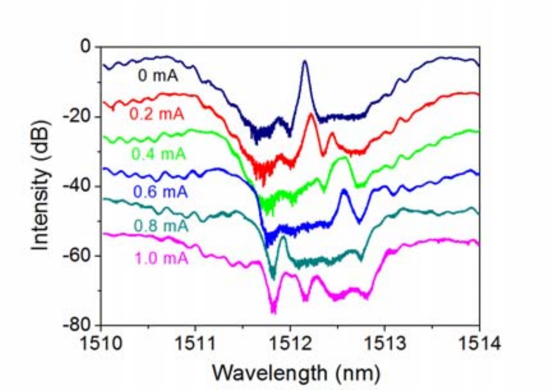

Fig. 3. CRIT resonance spectrum tuning under various currents from 0 to 1.0 mA with a step of 0.2 mA. The curves are vertically shifted for clarity.

4. Conclusion

We experimentally demonstrated cascaded SCOW resonators and CRIT phenomena were observed in the transmission spectra. The CRIT is dependent on the configuration of individual SCOW resonators, and in particular, one or thee transparency peaks can appear in a broad opaque wavelength window. We also performed thermal tuning experiments and found that the CRIT peak can be controlled by phase-shifting the interconnection waveguide while keeping the opaque window fixed.

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