Experimental Demonstration of Self-coupled Optical Waveguide (SCOW)-Based Resonators

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Abstract—We experimentally demonstrate a self-coupled optical waveguide (SCOW)-based optical resonator. Transmission spectra reveal the resonators can exhibit split, broadened, or enhanced resonance dips. The SCOW resonators can be used for second-order optical filters.

I. INTRODUCTION

With the advances in on-chip optical signal processing and inter-/intra-chip optical interconnects, silicon photonics is becoming one of the most promising candidates for highly compact nano-photonic integrated chips. Due to the high-index contrast, silicon photonic devices are very compact, making it possible for very large scale photonic integration (VLSI photonics). A key building block for VLSI photonic circuits is the micro-resonators, which have been applied in many optical devices including filters [1, 2], switches [3], modulators [4], on-chip optical interconnects [5], and detectors [6]. Spectral filtering is a basic function for optical signal processing in frequency domain. Of the various micro-resonators, microring resonators are very attractive as they have a small footprint and their resonance wavelengths and spectra can be easily tailored. Generally, a single microring resonator only exhibits a single resonance mode which limits their use in many important applications like high-order optical filters. Cascaded microring resonators can be used to build high-order filters with flat top and sharp roll-off. However, the resonance frequencies for all resonators have to be accurately aligned, which is practically difficult to achieve due to various fabrication errors.

In our previous paper [7], we proposed and analyzed a novel self-coupled optical waveguide (SCOW)-based resonator to generate unique resonance features. Unlike conventional coupled microring resonators, SCOW-based resonators have their clockwise and counter-clockwise resonance modes co-excited, with no need for strict alignment of different resonance modes. Here, we present an experimental demonstration of the SCOW-based resonator. The dependence of the resonance performance on various design parameters is characterized. In particular, high-order resonance features such as split, broadened, and enhanced resonance dips are observed. The SCOW resonators can be used for second-order optical filters in VLSI optical signal processing.

II. DEVICE FABRICATION AND CHARACTERIZATION

A. Device Fabrication and Experimental Setup

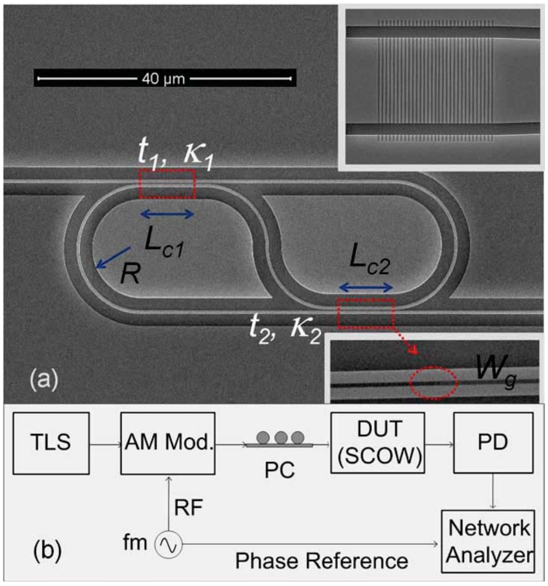

Fig. 1. (a) SEM image of the fabricated SCOW-based resonator. The bottom zoom-in inset shows the coupling region and the upper inset shows the waveguide grating coupler. (b) Schematic diagram of the experimental setup. TLS: tunable laser source, AM Mod: amplitude modulator, PC: polarization controller, RF: radio frequency signal.

Our devices were fabricated on a silicon-on-insulator (SOI) wafer with the top silicon layer thickness of 220 nm and the buried oxide (BOX) layer of 3 μm. First, the wafer was coated with 300-nm-thick ZEP520 positive photoresist and patterned by electron beam lithography (EBL). Then, the devices were etched by inductively coupled plasma (ICP) etching. Fig. 1(a) shows the scanning electron microscope (SEM) images of one of the fabricated SCOW-based resonators. The cross-sectional dimension of the silicon waveguide is 450 nm × 220 nm. The upper inset shows the SEM image of the waveguide grating coupler used for input and output coupling with optical fibers. The grating is 19-μm-long and 12-μm-wide. The grating period is 620 nm and the etch depth is 100 nm.

Fig. 1(b) shows the experimental setup based on an Agilent loss and dispersion analyzer (86038B), which comprises a

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tunable laser, an amplitude modulator, and a network analyzer. The modulated light passes through the device under test (DUT) and its transmission is compared with the reference signal to extract the loss and dispersion information. A polarization controller is used to adjust the polarization state. Light is coupled into and out of the devices through the on-chip grating couplers with the fibers tilted 8° from the normal direction.

B. Experimental Results

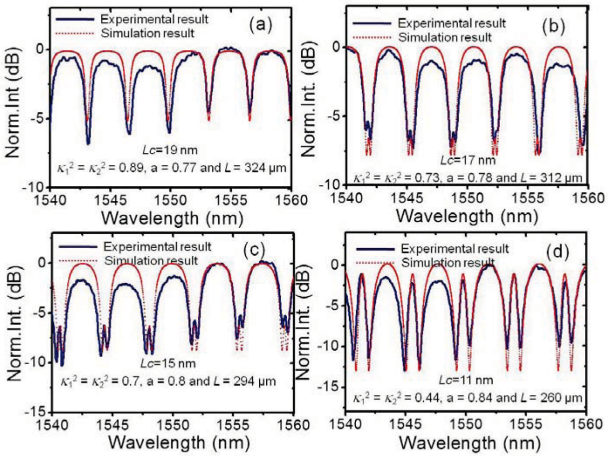

Fig. 2. Transmission spectra of the symmetric SCOW resonators with various coupling lengths of (a) $L_c = 19$ nm, (b) $L_c = 17$ nm, (c) $L_c = 15$ nm, and (d) $L_c = 11$ nm. The solid curves are the experimental results and the dotted curves are theoretical fitting. κ_1 and κ_2 are the coupling coefficients, *a* is the loss factor, and *L* is the circumference of the SCOW resonator. The spectra are all normalized to a reference waveguide.

Figs. 2(a)-2(d) show the experimental and theoretical transmission spectra of the SCOW-based resonators with symmetric couplers having an equal coupling length ($L_{c1} = L_{c2} = L_c$). The coupler gap size is 0.18 μm. The bending radii of the outer ring and the inner bridge waveguides are 6 μm and 12 μm respectively. The theoretical fitting based on the transfer matrix method [7] agree qualitatively well with the experimental results. For the symmetric SCOW-based resonator, the output spectrum is determined by the coupling coefficient (or equivalently L_c for a certain gap) and the waveguide loss. From Fig. 2, we can see that as L_c decreased from 19 μm to 11 μm, the spectrum changes gradually from a single resonance to a dual-channel split-resonance, and meanwhile, the channel separation and the extinction ratio increase. This is because with a decrease in L_c, the coupling to resonance is enhanced, resulting in a more strong interference between two inherent resonance paths [7]. Note that waveguide loss also affects the resonance spectral profile. If there is no loss, the resonance is always split into two. The resonance free spectral range (FSR) in Fig. 2(d) is ~4.25 nm, the extinction ratio is ~12 dB, and the dual-channel separation is ~1.1 nm. From the theoretical fitting, the device parameters (κ_1, κ_2, α, and L) are deduced as shown in the figure.

SCOW-based resonators with asymmetric couplers ($L_{c1} \neq L_{c2}$) were also experimentally demonstrated. Fig. 3(a) shows the transmission spectrum. Here, L_{c1} = 13μm, L_{c2} = 24 μm, and the other parameters are the same with the previous case. The spectrum shows a high resonance extinction ratio of ~24 dB and a FSR of ~3.4 nm. The deep single dips indicate that the critical coupling is nearly reached at the resonant wavelengths.

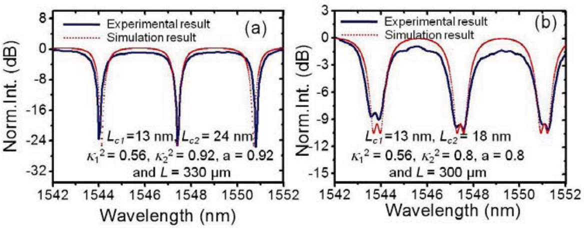

Fig. 3. Transmission spectra of the asymmetric SCOW resonators with various coupling lengths of (a) L_{c1} = 13 nm, L_{c2} = 24 nm and (b) L_{c1}= 13 nm, L_{c2} = 18 nm.

Fig. 3(b) shows the device spectrum when L_{c1} = 13 μm and L_{c2} = 18 μm. In this case, the extinction ratio is ~10 dB and the FSR is ~3.7 nm. The resonance has a bandwidth of >1nm and the bottom ripple is ~1 dB. It suggests that a single SCOW resonator can exhibit a second-order filter performance with a flat rejection band and a sharp roll-off, similar to coupled microring resonators.

III. CONCLUSIONS

In conclusion, we experimentally demonstrated a novel SCOW-based resonator. The transmission characteristics of SCOW-based resonators with various coupling strengths were investigated, showing split, broadened, and enhanced resonance features, suitable for multiple filtering applications. Compared with conventional coupled microring resonators, our SCOW-based resonator utilize two degenerate modes to generate the high-order resonance features, and hence it is more compact and robust to fabrication errors. It can be used as a basic building block for on-chip optical signal processing.

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