Demonstration of Wavelength Multicasting Using a Silicon Mode-split Microring Resonator

Fangfei Liu, Tao Wang, Ziyang Zhang, Min Qiu, *Member, IEEE*, Yikai Su, *Senior Member, IEEE*

***Abstract*—We experimentally demonstrate wavelength multicasting based on free carrier dispersion effect in a silicon mode-split microring resonator with a radius of ~10 µm. The mode-split of the resonator is caused by mutual coupling between the co-propagating and counter-propagating modes inside the microring resonator, which is induced by the periodic grating-like roughness of the sidewalls. The free carriers are generated through the two photon absorption (TPA) effect and blue shift the resonance spectrum. 1.25-Gb/s data carried by the pump is simultaneously converted to two probe channels placed in the split resonances separated by ~0.326 nm.**

***Index Terms*—Optical communication, Optical signal processing, Optical filter.**

I. Introduction

Silicon-on-insulator (SOI) structure provides an excellent platform to realize photonic integrated circuit (PIC)-based on-chip networks due to its compatibility with the standard complementary metal oxide semiconductor (CMOS) fabrication process. Silicon microring resonator is one of the building blocks for all-optical signal processing such as passive filtering, wavelength conversion and all-optical switching [1-2]. Recently, we observed mode-splitting in a microring resonator, where the resonance is split into two sub-resonances due to the mutual coupling between the co-propagating and counter-propagating modes induced by the periodic grating-like roughness of the sidewalls [3]. The split resonances enable more channels for wavelength division multiplexing (WDM) application and the channel spacing can be tuned to satisfy the WDM requirements.

In this paper, we experimentally demonstrate wavelength multicasting based on the free carrier dispersion (FCD) effect in a silicon mode-split microring resonator. Wavelength multicasting is a process where a single data packet is converted into packets at multiple wavelengths, which is promising in application scenarios like IPTV and video conferencing [4]. Previous wavelength multicasting approaches mainly used discrete devices such as semiconductor optical amplifier (SOA) [5] and highly nonlinear fiber [4]. Recently, we demonstrated dense wavelength conversion using a silicon microring resonator with mode split and presented a preliminary result of dual-channel wavelength multicasting [6]. Here, we provide a thorough investigation of wavelength multicasting using a silicon mode-split microring resonator in both time and wavelength domains. In our experiment, a 1.25-Gb/s non-return-to-zero (NRZ) data carried by a pump signal is converted to two probes located at the two resonance splits spaced by ~0.326 nm simultaneously. When the pump power is high, free carriers are generated through the two photon absorption (TPA) effect and give rise to the change of the effective refractive index. This free carrier dispersion (FCD) effect blue shifts the resonance spectrum and induces the change of the transmission at the wavelengths of the two probes, thus the information carried by the pump is converted to the probes simultaneously.

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II. Principle

The basic structure of the silicon microring resonator used in the experiment is a ring evanescently coupled to a single straight waveguide as shown in Fig. 1. The incident wave si generates the clockwise travelling mode a, which in turn generates the counter-propagating mode b due to the periodic grating-like roughness along the sidewalls of the ring. According to the coupled mode theory, we define the mutual coupling quality factor as Qu and the transfer function of the microring resonator with mode-split can be expressed as [6]:

$$\frac{s_o}{s_i}=1-\frac{\omega_0}{\sqrt{2}Q_e}\left(\frac{1}{j(\omega-\omega_0+\frac{\omega_0}{2Q_u})+\frac{\omega_0}{2Q_i}}+\frac{1}{j(\omega-\omega_0-\frac{\omega_0}{2Q_u})+\frac{\omega_0}{2Q_i}}\right) \quad (1)$$

where ω_0 is the resonance frequency, Q_e and Q_i are the coupling quality factor and intrinsic quality factor, respectively.

It can be seen that the resonance at frequency ω_0 is split into two sub-resonance frequencies $\omega_0-\omega_0/(2Q_u)$ and $\omega_0+\omega_0/(2Q_u)$. In addition, the separation between the two sub-resonances is determined by the mutual coupling quality factor Q_u.

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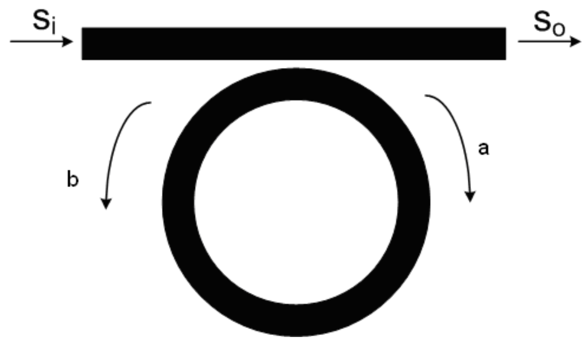

Fig. 1. Schematic of a microring resonator

III. FABRICATION AND CHARACTERIZATION OF THE DEVICE

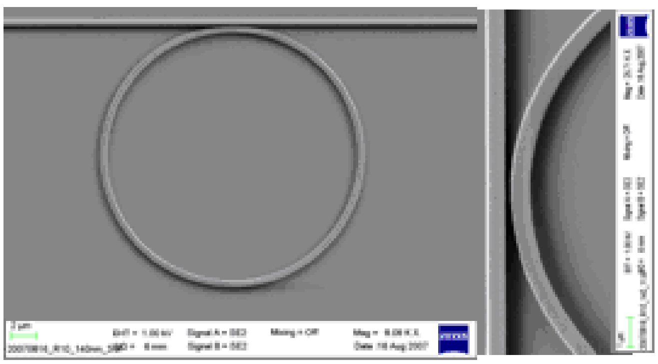

Fig. 2. SEM photo of the silicon mode-split microring resonator

The device used in the experiment is a silicon microring resonator with a radius of 10 μm, and an air gap of 140 nm between the ring and the straight waveguide. The silicon waveguide is 250 nm in height and 450 nm in width, fabricated on a 3-μm silica buffer layer. The scanning electron microscope (SEM) photos of the devices are provided in Fig. 2. As studied in Ref. [3], the mode-split is caused by the periodic grating-like roughness on the sidewall of the ring, which results from the pseudo-circular scan mode in electron beam (E-beam) lithography. The separation of the mode-split can be tuned by changing the E-beam scan step size and the exposure dose. Gold gratings with a period of 590 nm, a filling factor of 34% and a thickness of 25 nm are added at each end of the straight waveguide to couple light near-vertically from single mode fibers (SMF). The grating couplers only support transverse electrical (TE) mode with a fiber-to-fiber loss of ~20 dB.

The appearance of the mode-split is dependent on the resonance wavelength. For the fabricated device, there is obvious mode-splitting for the resonance at ~1555.5 nm and there is no mode-splitting for the resonance at ~1564 nm. The spectra are shown in Fig. 3. The two split resonances are separated by ~0.326 nm. The left split resonance has a notch depth of ~13.3 dB and a 3-dB bandwidth of ~0.048 nm; the notch depth of the right split resonance is ~17.8 dB with a 3-dB bandwidth of ~-0.056 nm. The resonance at ~1564 nm shows a notch depth of ~25 dB and a 3-dB bandwidth of ~0.075 nm.

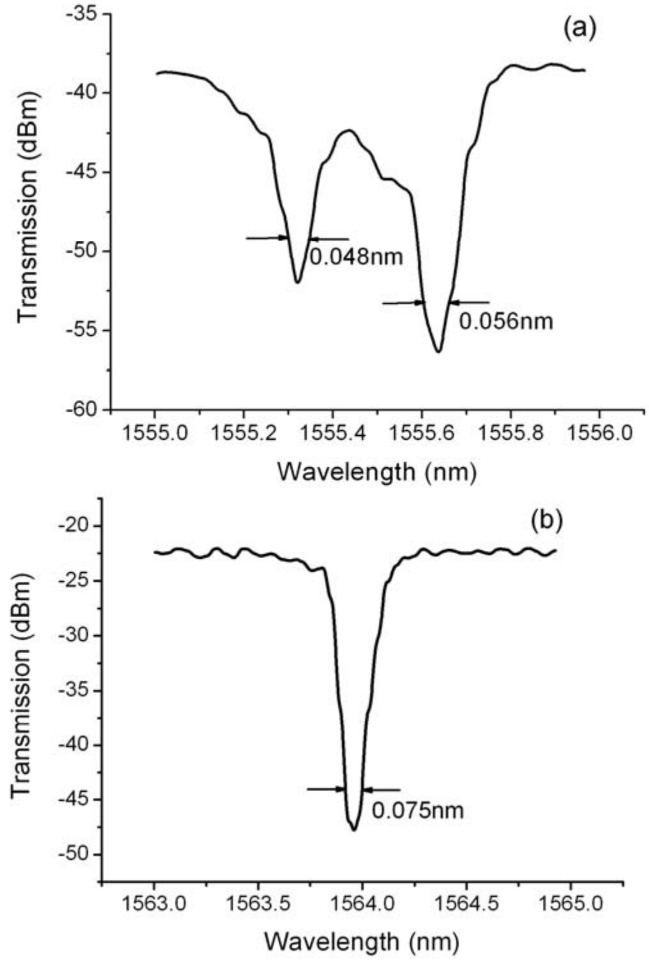

Fig. 3. Spectra of the resonances of the device at (a) ~1555.5 nm and (b) ~1564 nm.

IV. EXPERIMENT

A. Experimental setup

The experimental setup is shown is Fig. 4. Two continuous wave (CW) probe lights located at the vicinity of the two split resonances are combined using a 50:50 coupler and then amplified using an Erbium doped fiber amplifier (EDFA). The NRZ pump light is modulated using a Mach-Zehnder modulator (MZM) driven by a 1.25-Gb/s pseudo random bit sequence (PRBS) signal with a pattern length of 2^7-1. Three polarization controllers (PCs) are used to adjust the polarization of the pump and two probes respectively to guarantee the polarization is TE mode. The pump signal and two probes are combined using a 90:10 coupler so that the pump power is sufficiently high and the optical signal-to-noise ratio (OSNR) of the signal carried by the probe light is only slightly degraded. The 95:5 coupler is used as a tap to monitor the output power of the microring resonator in order to ease the alignment of the wavelength to the resonance wavelength. The two converted probes are separated using a tunable bandpass filter (BPF) with a 3-dB bandwidth of 0.3 nm. The pump power measured at the input fiber is ~18 dBm and the one for the two probes is ~5 dBm.

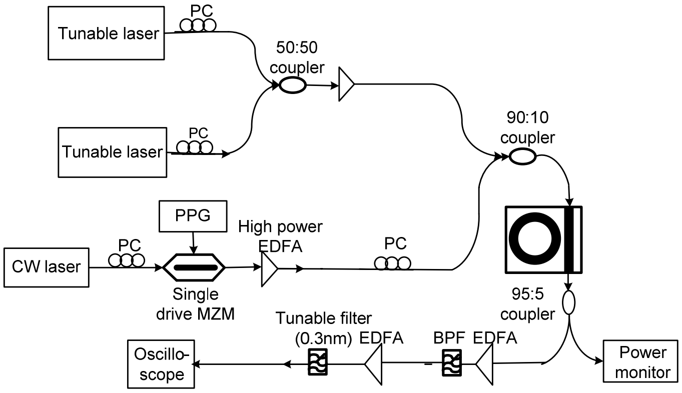

Fig. 4. Experimental setup for the demonstration of wavelength multicasting in silicon mode-split microring resonator

B. Experimental results

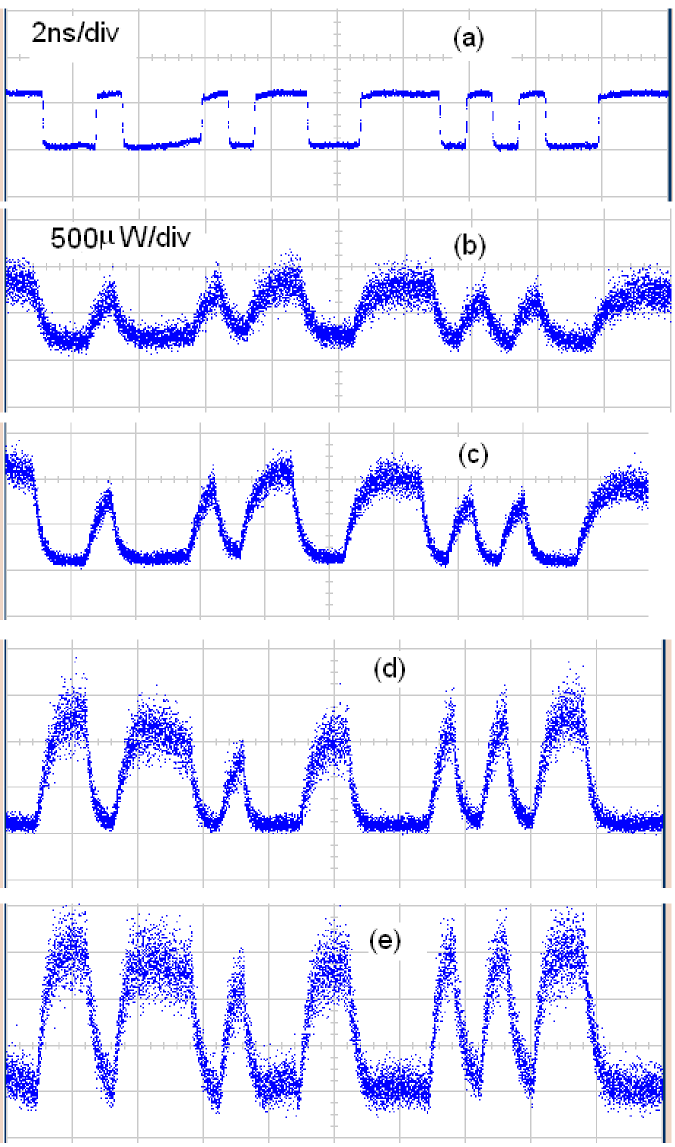

Fig. 5. Waveforms for (a) NRZ pump signal; converted probe signal at (b) left resonance split and (c) right resonance split; converted probe signal with inversion of '0' and '1' at (d) left resonance split and (e) right resonance split.

The measured waveforms are shown in Fig. 5. Fig. 5(b) (c) represent the non-inverted wavelength multicasting for the input signal shown in Fig. 5(a), in which the probes are placed at the right edge of the resonance; Fig. 5(d) (e) show the case with the inversion of the '0' and '1' of the pump signal, in which the probes are placed at the left edge of the resonance. In both cases, there is little interference between the two channels. There are some pattern effects with the converted signals, in which the height of a single '1' is different from that of the consecutive '1's. This is due to the limited carrier lifetime of ~500 ps [1]. There is an accumulation of the number of the free carriers along with the consecutive '1's, thus it would induce a continuous blue shift of the spectrum; similarly, it cannot return to zero immediately when the pump signal becomes '0' due to the slow recombination of free carriers.

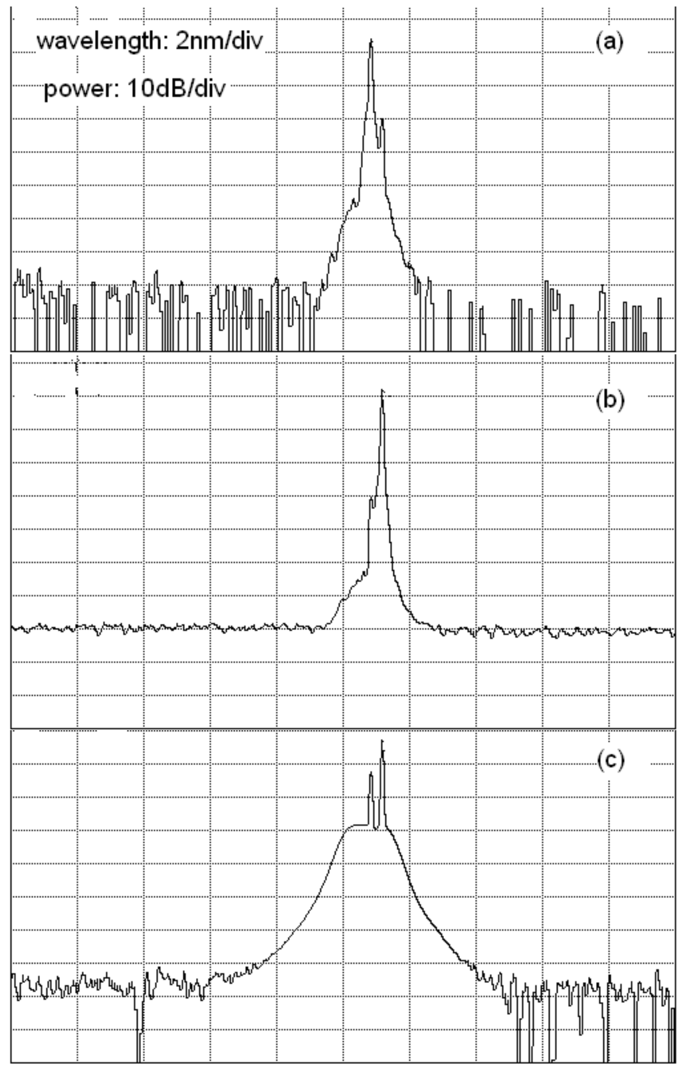

Fig. 6. Spectra of converted probes (a) at the left resonance split, (b) at the right resonance split, (c) before the 0.3-nm filter

The optical spectra of the two probe signals after the non-inverted conversion are provided in Fig. 6, which are obtained by tuning the 0.3-nm filter. The relatively poor OSNR of the converted signal is due to the large coupling loss (~20 dB) and the deep notch of the resonances. It should be mentioned that the slight difference between the OSNR of the two probes is caused by the different input power of the two probes.

V. Conclusions

We have experimentally demonstrated multi-channel wavelength conversion for 1.25-Gb/s NRZ signal in a mode-split silicon microring resonator, both in the inverted and non-inverted cases. There is little interference between the probe channels. By carefully designing the radius of the ring and the separation of the mode split, it is possible to convert signal to more channels with WDM specifications.

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