Micrometer-scale optical up-converter using a resonance-split silicon microring resonator in radio over fiber systems

Qingjiang Chang (1), Qiang Li (2), Ziyang Zhang (2), Min Qiu (2), and Yikai Su (1)
1. State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering
Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai 200240, China, yikaisu@sjtu.edu.cn

2. Department of Microelectronics and Applied Physics, Royal Institute of Technology, Electrum 229, 16440, Kista, Sweden

Abstract: We propose and demonstrate a novel micrometer-scale optical up-converter for converting 1-Gb/s data to 40-GHz milimeter-wave. This scheme utilizes the free-carrier dispersion effect in a resonance-split silicon microring resonator.

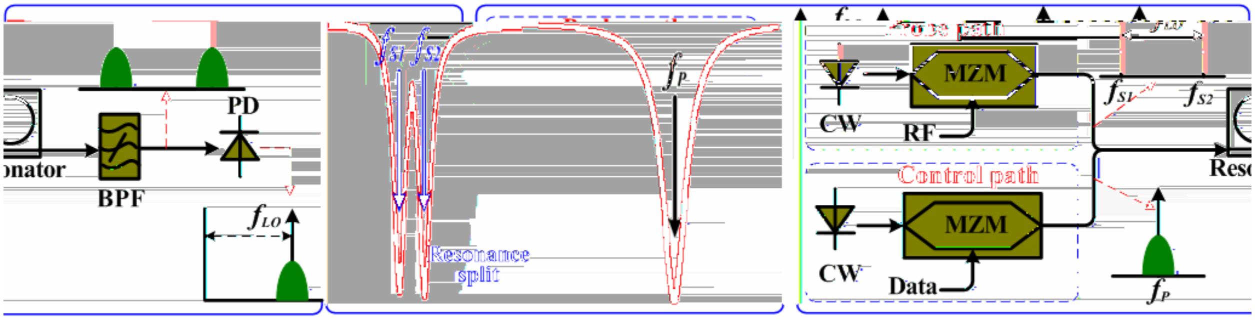
OCIS codes: (060.4510) Optical communications; (060.5625) Radio frequency photonics; (130.3120) Integrated optics; (230.1150), All-optical devices.

1. Introduction

The convergence of wireless communication and optical fiber systems in an integrated platform has become a promising technique for providing broadband wireless access services with increased mobility and reduced cost [1]. In order to meet the requirement of high bandwidth and overcome the spectral congestion at low frequency, future radio over fiber (RoF) systems would utilize millimeter-wave (MMW) frequency for high-speed wireless access [2, 3]. In this situation, the optical up-conversion of baseband data to MMW is a key technique. Recently, several optical up-converters for baseband data up-conversion have been reported, which used four-wave mixing in highly nonlinear fiber [4], or cross gain modulation in semiconductor optical amplifier [5]. However, there remain challenges in compact-size, low-cost, highly integrated applications.

In this paper, we propose and demonstrate a novel micrometer-scale optical up-converter in RoF systems. The scheme is based on free-carrier dispersion (FCD) effect in a resonance-split silicon microring resonator. A prototype of optical up-converter is experimentally demonstrated for up-converting 1-Gb/s baseband data to 40-GHz MMW. Comparing with the previous approaches, the proposed scheme uses a 20-μm-radius silicon microring resonator, which features compact footprint, and easy integration.

2. Principle



(a) Transmission Spectrum (b) Schematic diagram

Fig. 1. (a) Transmission spectrum of resonance splitting; (b) Schematic diagram of the proposed optical up-conversion system

For a ring resonator side coupled to a waveguide, if periodic roughness (grating) on the sidewall of the ring is introduced [6], both propagating and counter-propagating modes can be excited. The two coupled modes result in resonance-splitting, i.e., single resonance is split into two resonances, as shown in Fig. 1(a). Figure 1(b) shows the schematic diagram of the proposed optical up-conversion systems based on the FCD effect [7] in a resonance-split silicon ring resonator. In a probe path, a Mach-Zehnder modulator (MZM) is driven by an RF signal to generate an optical carrier suppression (OCS) signal. The generated OCS signal consists of two continuous wave with a frequency spacing equal to that of the two split resonances. While in a control path, a pump light is modulated by a baseband data. The modulated pump light works at one resonance and the two tones of the probe signal are located at the split resonances. The pump signal and the probe signal are combined by a coupler and then injected into a resonance-split microring resonator. When the pump power is high (logic 1), free carriers are generated inside the ring resonator from two-photon absorption (TPA) [8]. The free carriers give rise to a refractive index change through FCD effect and cause the blue-shift of the resonances. The transmission of the signal is therefore changed. When the pump power is low (logic 0), these carriers recombine mainly due to surface recombination in the case of submicron structures. Therefore, the resonant wavelength and the transmission of the signal relax back [9]. In this way, the information carried at the pump light is transferred to the two tones of the probe signal, thus one can obtain an up-converted optical signal. The output signal of the microring resonator is launched into a bandpass filter (BPF) to separate the probe signal. On beating in a photo-detector (PD), the probe signal is converted into an electrical wireless signal. Since the frequency spacing of the split resonances can be adjusted by changing the E-beam scam step size and the exposure dose, the resonance-split scheme can provide large and flexible frequency for the baseband data up-conversion.

3. Experimental Setup and Results

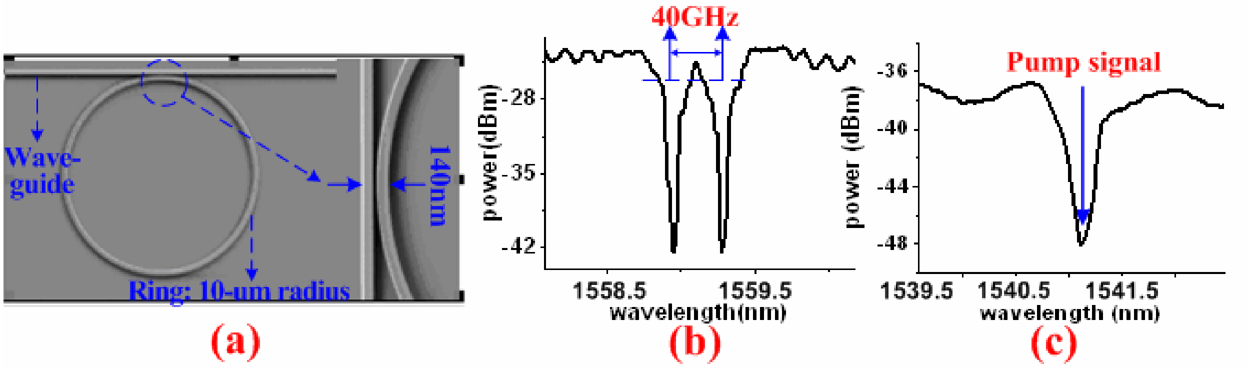


Fig. 2. (a) The SEM photo of the microring resonator; (b) Spectrum of the device at 1559.1 nm; (c) Spectrum of the device at 1540.8 nm.

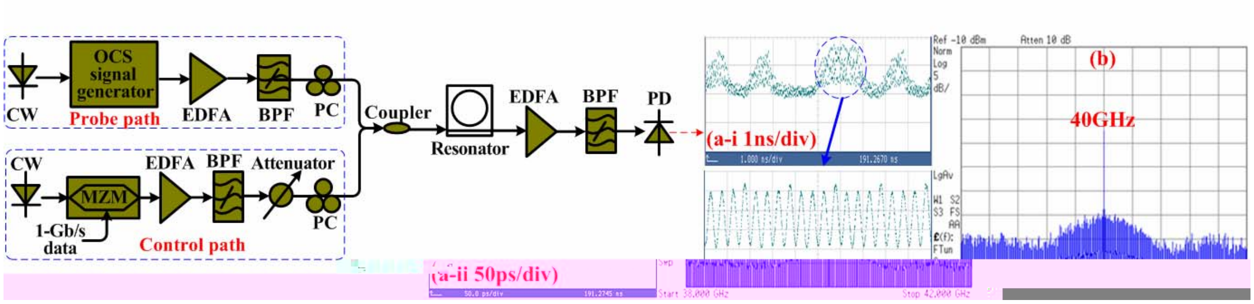


Fig. 3. Experimental setup of the proposed scheme. (a-i) Waveform of the up-converted 1-Gb/s data at 40-GHz MMW. (a-ii) Magnified picture of the RF carrier in the blue circle in (a-i); (b) Electrical spectrum of the up-converted signal.

In this experiment, a 10-μm radius silicon microring resonator is used, which is fabricated on a 3-μm silica buffer layer. The cross section of the silicon waveguide is 250×450 nm. The microring is side-coupled to a straight waveguide with an air gap of 140 nm between the ring and the straight waveguide. The scanning electron microscope (SEM) photos of the devices are provided in Fig. 1. For the fabricated device, there is obvious resonance-splitting at ~1559.1 nm and there exists no resonance-splitting at ~1540.8 nm. Their spectral responses are shown in Fig. 2(b) and (c), respectively. The two split resonances have the same notch depth of ~17dB with a 3-dB bandwidth of ~0.048 nm and their frequency spacing is ~0.32 nm (40 GHz). The resonance at ~1540.8 nm shows a notch depth of ~14 dB and a bandwidth of ~0.075 nm.

Figure 3 illustrates the experimental setup of the proposed scheme. To demonstrate a broadband optical up-converter, we employ OCS technology [10] to generate an optical MMW with two tones of 40-GHz frequency spacing. The pump light is modulated by a 1-Gb/s baseband data to generate a non-return-to-zero (NRZ) format, with its waveform shown in Fig. 4(a). The obtained NRZ data is amplified by a high power erbium doped fiber amplifier (EDFA) followed by an attenuator to adjust the pump power. The pump light and the probe signal are coupled through a 3-dB coupler to the microring resonator by a vertical coupling system. As the gold grating coupler of the microring is polarization dependent, two polarization controllers (PCs) are inserted before the coupler to ensure the probe signal and the control light are in TE mode. Based on the FCD effect, when the pump power is ~10 dBm and probe signal power is ~ -2 dBm, the 1-Gb/s NRZ data carried by the pump light is converted to two tones of the OCS signal located at the two split resonances. The optical spectrum of the OCS signal is provided in Fig. 4(b). Figure. 4(c) and (d) show the optical spectrum and the waveform of the converted probe signal at the left sideband, respectively, while those for the right sideband are also provided in Fig. 4(e) and 4(f), respectively. The output signals of the microring resonator is amplified using an EDFA, and a BPF is used to separate the probe signal, which is sent to a 40-GHz PD for detection. The waveforms of the up-converted 1-Gb/s data at 40-GHz are shown in insets of Fig. 3(a-i). The electrical spectrum is indicated in inset of Fig. 3(b).

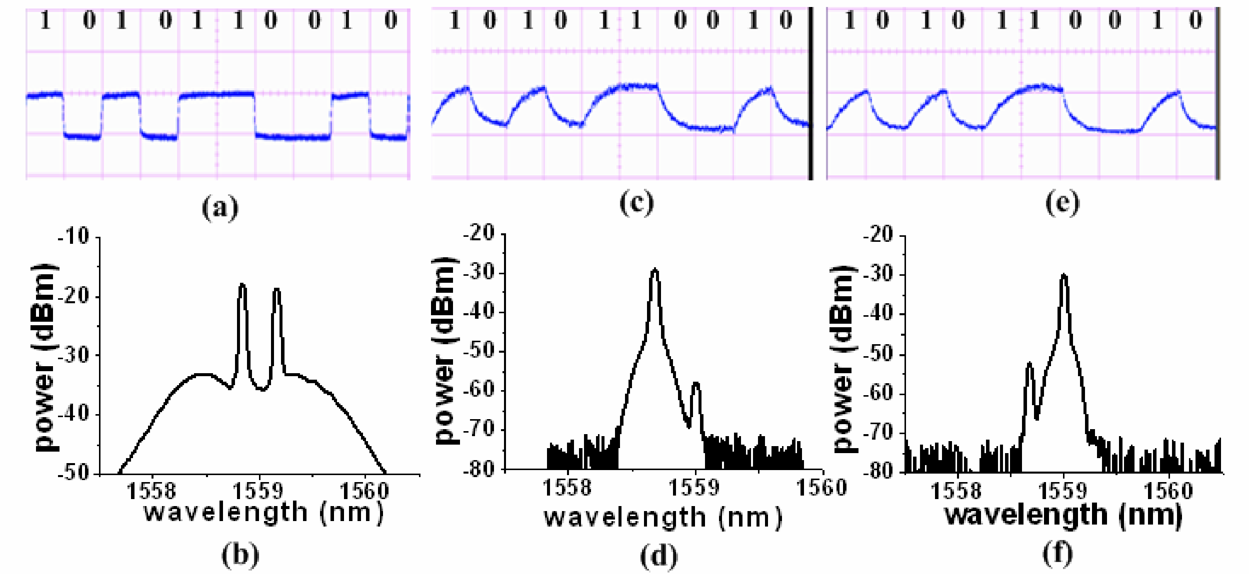


Fig. 4. (a) Waveform of the NRZ pump signal; (b) Spectrum of the OCS signal; (c) Waveform of the converted signal at the left sideband; (d) Spectrum of the left sideband; (e) Waveform of the converted signal at the right sideband; (f) Spectrum of the right sideband.

4. Conclusion

We have proposed and demonstrated a novel scheme to optically up-convert 1-Gb/s baseband data to 40-GHz MMW using a mode-split silicon microring resonator. The proposed scheme opens up opportunities to integrate the silicon waveguide devices into RoF systems.

Acknowledgement: This work was supported by the NSFC (60777040), Shanghai Rising Star Program Phase II (07QH14008), Swedish Foundation for Strategic Research (SSF) through the Future Research Leaders program, the SSF Strategic Research Center in Photonics, and the Swedish Research Council (VR).

References:

[1] D. Wake, "Radio over fiber for mobile communications," in *IEEE Int. Topical Meeting Microwave Photonics (MWP 2004)*, pp. 157-160, (2004).
[2] Z. Jia, "A full-duplex radio-over-fiber system based on optical carrier suppression and reuse," *IEEE Photon. Technol.Lett.*, vol. 18, no. 16, pp. 1726–1728(2006).
[3] Q. Chang, "Simultaneous generation and transmission multi-band signals and upstream data in a bidirectional radio over fiber system," *IEEE Photon. Technol. Lett.*, vol. 20, no. 3, pp. 181–183(2008).
[4] J. Yu, "Seamless integration of an 8x2.5Gb/s WDM-PON and radio over fiber using all-optical up-conversion based on Raman-assisted FWM," *IEEE Photon. Technol. Lett.*, vol. 17, pp. 1986-1988(2005).
[5] J-H. Seo, "1.244-Gb/s data distribution in 60-GHz remote optical frequency up-conversion systems," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1389-1391(2006).
[6] Z. Zhang, "Resonance-splitting and enhance notch depth in SOI ring resonators with mutual mode coupling," *Opt. Express*, vol. 16, pp. 4621-4630(2008)
[7] Q. Xu, "Micrometer-scale all-optical wavelength converter on silicon", *Opt. Lett*. vol. 30, pp. 2733-2735(2005).
[8] M. Dinu, "Third-order nonlinearities in silicon at telecom wavelengths," *Appl. Phys. Lett.* vol. 82, pp. 2954-2956(2003).
[9] Q. Li, "Dense wavelength conversion and multicasting in a resonance-split silicon microring,"*Appl. Phys. Lett.*, vol. 93, no. 8, 2008.
[10] T. Kawanishi, "Quadruple frequency double sideband carrier suppressed modulation using high extinction ratio optical modulators for photonic local oscillators," in *Proc. IEEE Microwave Photonics 2005*, paper PDP-03