Optical frequency comb generation and microwave synthesis with integrated cascaded silicon modulators

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Abstract: Optical frequency comb with 15 lines, 5 GHz spacing and 6 dB flatness is generated by two cascaded silicon Mach-Zehnder modulator and phase modulator. 5-20 GHz microwave synthesis is also demonstrated using the generated comb.

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Optical frequency combs (OFCs) are widely utilized in the applications of microwave photonics, frequency metrology and optical communications. To obtain OFC with large frequency spacing and tunability, lots of researches have been conducted on generating OFC by electro-optical modulators. This approach has been proved to be a success in generating highly stable, laser-wavelength-tunable and energy efficient OFCs [1,2]. OFC generation on a silicon photonic platform is very attractive because other than the advantages mentioned above, it can be integrated with complementary metal-oxide-semiconductor (CMOS) technology to obtain high-density integrated photonic chips.

In this work, we demonstrate OFC generation by modulating two cascaded silicon single-drive push-pull Mach-Zehnder modulator (MZM) and PN-junction based phase modulator (PM). The silicon modulators generate 15 OFC lines with 5 GHz comb spacing and 6 dB flatness by optimizing the applied DC voltages and microwave power. 5 GHz – 20 GHz microwave synthesis is also achieved with the generated OFC. The maximum microwave frequency can be extended to 70 GHz by using a high-speed photodetector and a wideband microwave amplifier.

Figure 1(a) shows the structure of the cascaded silicon MZM and PM for OFC generation. Both the MZM and the PM are integrated with a high-speed travelling-wave electrode (TWE) [3,4]. The MZM is designed with a single-drive push-pull TWE to provide large-bandwidth intensity modulation. The PN junctions are doped to form an L-shape cross-sectional profile to achieve a low half-wave voltage. The measured half-wave voltages of the 3-mm-long MZM and PM are both less than 3V. An optical microscope image of the device is shown in Fig. 1(b). The MZM and the PM are put side by side so that the two modulators can share a single GSGSG microwave probe. On-chip 50Ω TiN resistors are wire-bonded to the other end of the TWE to absorb the remained microwave signal.

The experiment setup is shown in Fig. 1(c). A tunable laser generates light at 1550 nm as light source. The light is adjusted to the transverse electric (TE) mode by a polarization controller (PC) and then coupled to the MZM on the chip. A 15 GHz sinusoidal signal is applied onto the MZM and a 5 GHz sinusoidal signal is applied onto the PM. By tuning the amplitude V_{RF1} of the 15 GHz microwave signal, the DC bias voltage V_1 and the DC voltage V_2, the MZM alone can produce 5 OFC lines with 15 GHz frequency spacing. Similarly, by tuning the amplitude V_{RF2} of the 5 GHz microwave signal and the DC bias voltage V_3, the PM alone can output 3 OFC lines with 5 GHz frequency spacing. The two cascaded modulators eventually produce 15 OFC lines with 15 GHz frequency spacing. The OFC lines are characterized by an optical spectrum analyzer (OSA).

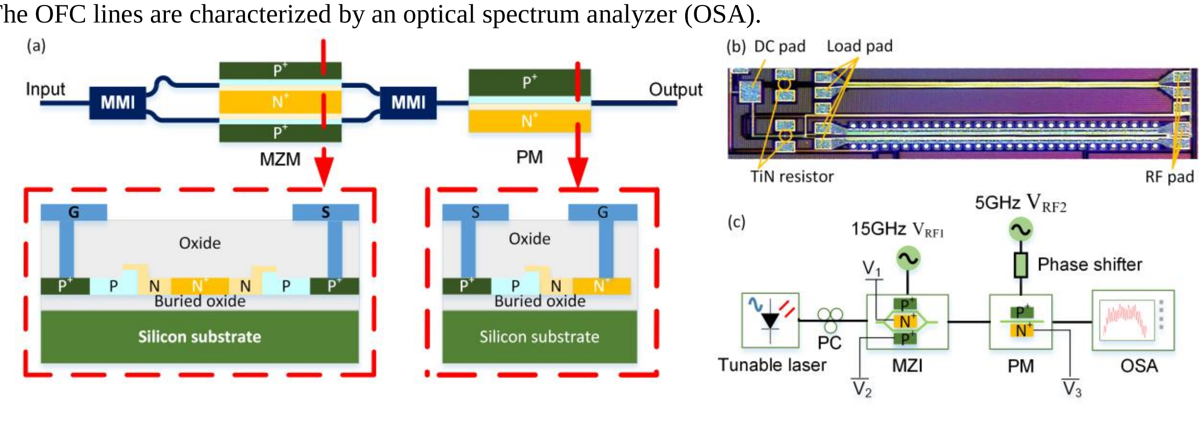

Figure 1. (a) Schematic drawing of the cascaded modulators for OFC generation. Insets show the cross-sectional views of the MZM and the PM separately. (b) Optical microscope image of the device. (c) Experimental setup for OFC generation.

Figure 2(a) shows that the MZI alone produces 5 OFC lines with 15 GHz frequency spacing and 2.4 dB flatness when driven by a 15 GHz sinusoidal microwave signal with ~18 dBm power. A bias voltage V_1 of 6V is used to set the PN junction inside the MZM in the carrier-depletion mode. Another DC voltage V_2 of 0.48V is also applied onto the MZM. Figure 2(b) shows that the PM alone produces 3 OFC lines with 5 GHz spacing frequency and 1.7 dB flatness when driven by a 5 GHz sinusoidal microwave signal with ~16 dBm power. A bias voltage V_3 of 3V is used to set the PN junction inside the PM in the carrier-depletion mode. When the two modulators are cascaded and work simultaneously, they generate 15 OFC lines with 5 GHz frequency spacing, 6 dB flatness and a total microwave signal power of ~20 dBm, as shown in Fig. 2(c).

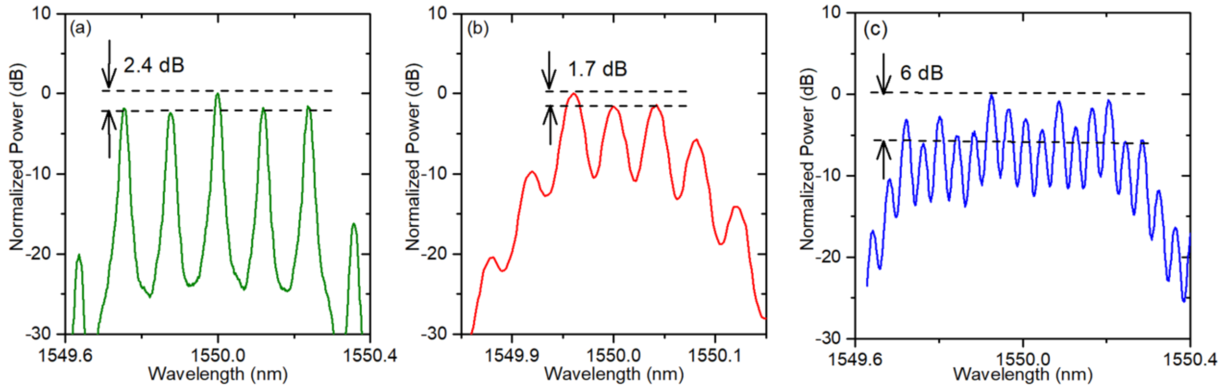

Figure 2. (a) OFC generated by MZM alone. (b) OFC generated by PM alone. (c) OFC generated by cascaded MZM and PM.

To demonstrate the capability for microwave synthesis with the generated OFC, the OFC signal is detected by a 50 GHz photodiode and amplified by a 20 GHz microwave amplifier. The generated microwave signals are characterized by an electrical spectrum analyzer as shown in Fig. 3. Figure 3(a)-3(d) shows the microwave signals of 5 GHz with 60 dB extinction ratio (ER), 10 GHz with 60 dB ER, 15 GHz with 62 dB ER and 20 GHz with 60 dB ER, respectively.

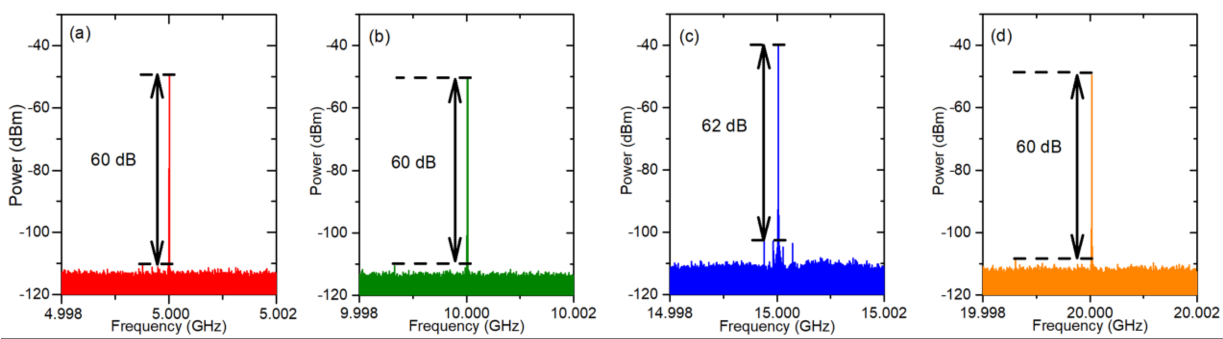

Figure 3. Generated microwave signals at (a) 5 GHz, (b) 10 GHz, (c) 15 GHz, and (d) 20 GHz measured by an electrical spectrum analyzer with a resolution bandwidth of 10 Hz.

In conclusion, we have demonstrated OFC generation by modulating two cascaded silicon MZM and PM. When the two modulators are driven with proper microwave power and DC bias voltages, they generate 15 OFC lines with 15 GHz comb spacing and 6 dB flatness. We have also demonstrated microwave synthesis from 5 GHz to 20 GHz with the generated OFC. The microwave frequency can be further extended to 70 GHz with wideband photodetector and microwave amplifier.

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