Optical Frequency Comb Generation Using CMOS Compatible Cascaded Mach-Zehnder Modulators

Student Paper

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ABSTRACT

We demonstrate flexible optical frequency comb generation using two cascaded push-pull Mach-Zehnder modulators fabricated using a CMOS-compatible process. The optical comb has nine phase-locked frequency lines spaced at 5 GHz or 6 GHz with a signal-to-noise ratio of 40 dB after optical amplification and filtering. The envelope of the comb has a rectangular-shape and the corresponding time-domain waveform fits well with sinc-shaped Nyquist pulses having pulse widths of 17 ps or 20 ps.

Keywords: optical frequency comb generation, cascaded Mach-Zehnder modulators, silicon-on-insulator.

1. INTRODUCTION

Optical frequency combs (OFCs) providing a series of equidistant spectral comb lines with correlated phase have been used extensively in a diverse range of applications, including optical communications, spectroscopy, and sensing [1]. In general, three methods are employed to obtain an OFC. First, a mode-lock laser assisted by an internal or external reference can generate very broadband bandwidth OFCs, but the tunability is very limited [2]. Second, OFCs can be obtained by pumping a microresonator with a single-frequency pump laser and exploiting Kerr nonlinearity [3]. However, a continuously tunable comb spacing and flat comb output is hard to achieve. Third, electro-optic modulation can be used; it provides flexibility in tuning the center frequency, comb spacing, and number of comb lines [1], [4]-[6]. In [5], an OFC with 20 GHz spacing was obtained using a dual-drive Mach-Zehnder modulator (MZM) fabricated in silicon-on-insulator (SOI) using a CMOS-compatible process. However, there were only 5 comb lines that exhibited significant power variation without spectral shaping. In [6], cascaded $LiNbO_3$ intensity MZMs were used to generate rectangular-shaped combs with 9 to 10 lines and bandwidths up to 156 GHz. In this paper, we demonstrate the generation of an electro-optic OFC using cascaded push-pull MZMs in SOI. By precisely controlling the amplitude of the driving RF signals, bias and thermal heating, an OFC with 9 lines and bandwidths up to 54 GHz are produced.

2. DESIGN AND FABRICATION OF CASCADED MZMS

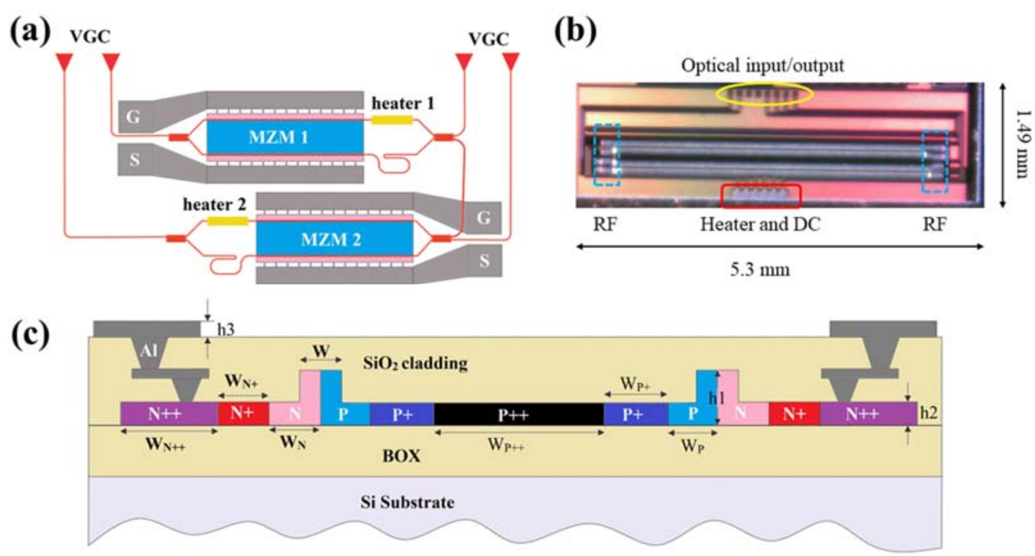

Figure 1. (a) Device schematic, (b) photo of fabricated device, and (c) cross section of push-pull MZM. The dimensions are: h1=500 nm, h2=90 nm, h3= 2 μm, W=500 nm, W_{N++} = 5.2 μm, W_{N+} = 0.81 μm, W_N = 0.39 μm, W_{P++} = 28 μm, W_{P+} = 0.83 μm, W_P = 0.37 μm.

Figs. 1 (a) and 1((b) show the schematic of our cascaded MZMs and a picture of the fabricated device. The devices are fabricated on a 220 nm SOI wafer with a 750 $\Omega - cm$ silicon substrate using a CMOS-compatible foundry process available at IME A*STAR. Rib waveguides having a width of 500 nm, a height of 220 nm, and a slab height of 90 nm are doped to form diode waveguides, see the cross section in Fig. 1 (c). The modulators are designed based on the parameters in [7]. Each modulator has a path imbalance of 100 μm; a heater is overlaid on the upper arm for fine-tuning the phase. The length of each modulator is 4.55 mm and the net p-n junction loading is 4.2 mm. The half-wave voltage of each MZM is around 10 V. Two MZMs are connected in series using 2×2 MMI couplers and additional taps are connected to vertical grating couplers (VGCs) designed for TE mode operation over the C band for input and output coupling and testing. The total loss is ~ 24 dB with a coupling loss of ~ 15 dB between two VGCs coupled to a fiber array. The total size of the device is 1.49 mm × 5.3 mm. We characterize the *S* parameters of both MZMs using a 50 GHz lightwave component analyzer; the results are summarized in Fig. 2. The bandwidths of MZM 1 and MZM 2 are 13.1 GHz and 10.9 GHz, respectively, for a reverse bias of -3 V. The S_{11} value is below -10 dB for frequencies up to 50 GHz, indicating good 50 Ω matching.

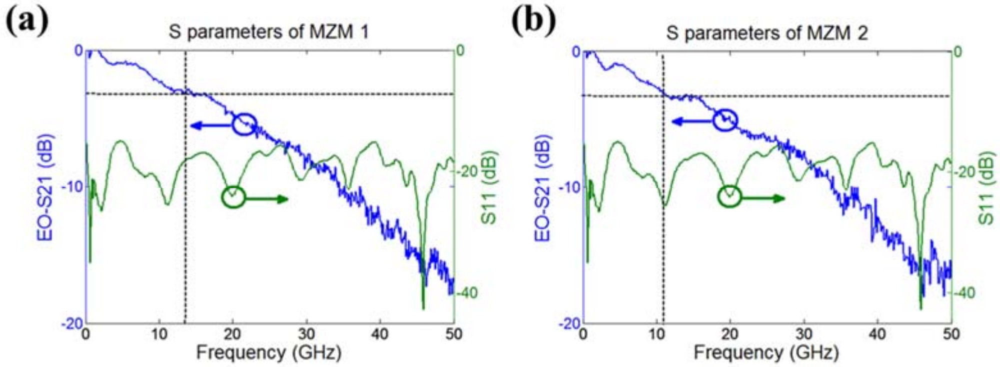

Figure 2. Measured S_{11} and S_{21} parameters of (a) MZM1 and (b) MZM 2.

3. EXPERIMENT AND RESULTS

The principle of OFC generation is detailed in [6] and our experimental setup is shown in Fig 3. A continuous wave (CW) laser tuned to 1546.7 nm with a power of 5 dBm is launched into the chip as a seed carrier for MZM 1. By tuning the amplitude of the RF signal (RF1), as well as the bias and voltage of the heater of MZM 1, we obtain two first-order sidebands with the same power level as the seed carrier while suppressing the second-order sidebands. The frequency spacing is equal to the frequency of RF1. These three spectral lines are then injected into MZM 2 (driven by a second RF signal, RF2) as new seed carriers to generate new first-order sidebands. Therefore, 9 comb lines are achieved. In order to get an equidistant OFC, the frequency of RF2 should be 1/3 that of RF1. The output OFC is then amplified by an EDFA and filtered to suppress out-of-band amplified spontaneous emission noise. The spectral and temporal responses are measured using a high resolution optical spectrum analyser (20 MHz) and a high-speed optical sampling oscilloscope. RF1 signal has a power level of 13 dBm and RF2 has 20 dBm; the two RF signals are combined with bias voltages via bias-tees. Due to the limited bandwidth of the MZMs, we set the frequencies of the two RF signals as 15 GHz/5 GHz or 18GHz/6 GHz. Therefore, the total bandwidth of our combs is 45 GHz or 54 GHz. In principle, the center frequency, comb spacing, bandwidth, and even the number of comb lines can be continuously tuned by changing the center wavelength of the CW laser, the frequency of the RF signals, and the amplitude and bias of the MZMs.

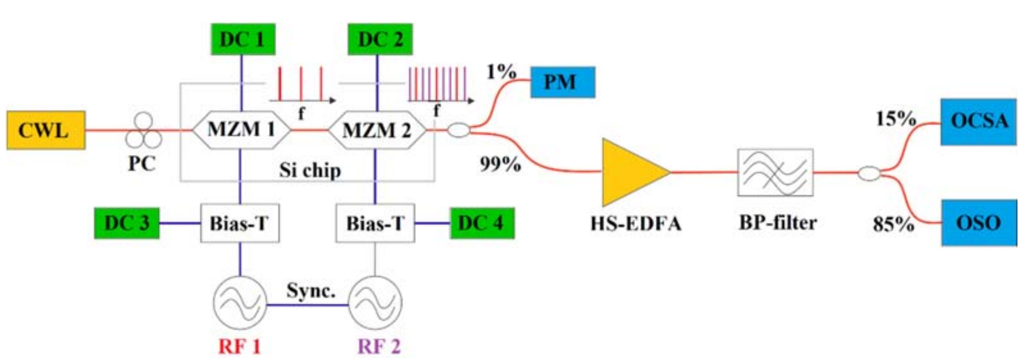

Figure 3. Experimental setup of on-chip OFC generation. CWL: continuous wave laser, PC: polarization controller, RF: radio frequency, DC: direct current, PM: power meter, HS-EDFFA: highly sensitive Erbium doped fiber amplifier, BP-filter: bandpass filter, OCSA: optical complex spectral analyzer, OSO: optical sampling oscilloscope.

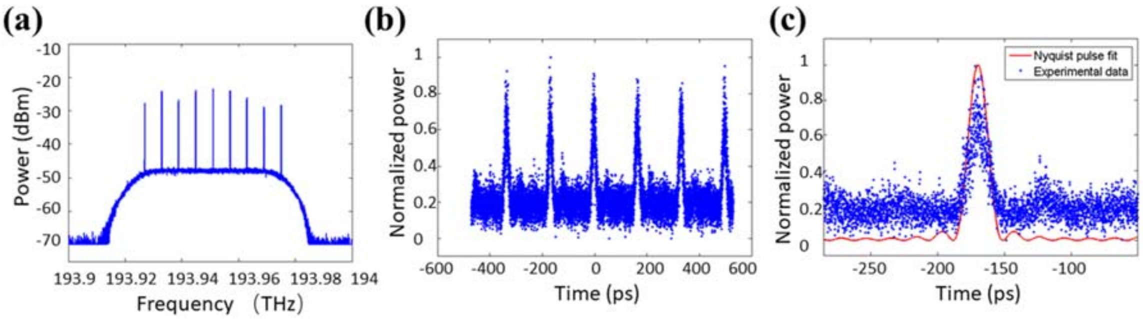

Figure 4. Measured spectrum (a) and time-domain waveform (b) of a comb with 9 lines and a spectral separation of 6 GHz; (c) curve fit of measured time-domain waveform using sinc-shaped Nyquist pulse.

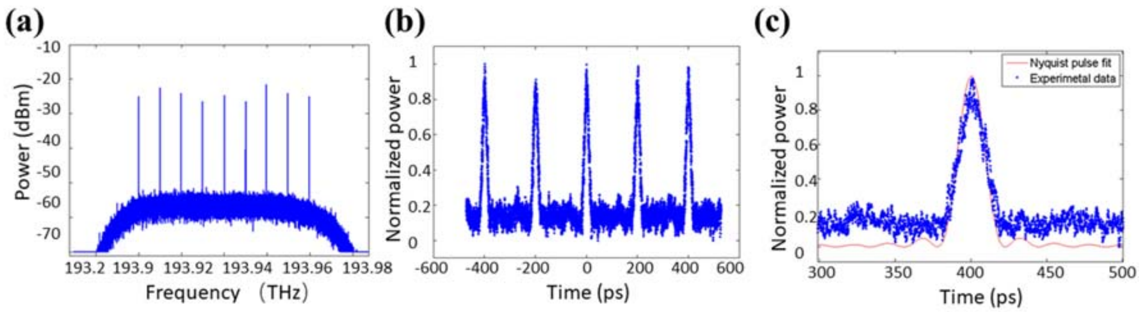

Figure 5. Measured spectrum (a) and time-domain waveform (b) of a comb with 9 lines and a spectral separation of 5 GHz; (c) curve fit of measured time-domain waveform using sinc-shaped Nyquist pulse.

The results are summarized in Figs. 4 and 5 for OFCs with a line spacing of 6 GHz and 5 GHz, respectively. We observe very stable optical spectra with a signal-to-noise ratio of more than 40 dB and power variation in the comb lines of 5 dB. The envelope of the comb has an approximate rectangular-shape; the corresponding temporal waveform is a sinc-shaped Nyquist pulse. The measured waveforms have a good fit with the simulated Nyquist pulses and the pulse widths are 17 ps and 20 ps.

4. CONCLUSIONS

We have demonstrated the use of two cascaded unbalanced series push-pull MZMs in SOI for OFC generation. We believe that such an OFC can be used for seeding a chip-scale optical transmitter for both orthogonal frequency division multiplexing or super-channel Nyquist wavelength-division multiplexing to achieve high overall spectral efficiency.

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