Silicon-Organic Hybrid (SOH) Frequency Comb Source for Data Transmission at 784 Gbit/s

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Abstract *We demonstrate a frequency comb generator using silicon-organic hybrid (SOH) electro-optic modulators to obtain flat-top comb spectra. This is the first demonstration of a modulator-based frequency comb generator on silicon. The viability of the device is confirmed in a data transmission experiment achieving an aggregate data rate of 784 Gbit/s.*

Introduction

Frequency combs enable a wide range of attractive applications such as optical metrology, arbitrary-waveform generation[1] or high-speed data communications at Tbit/s aggregate transmission rates[2]. A particularly versatile and flexible approach to generate frequency combs is based on modulation of a continuous-wave (cw) laser with an appropriate arrangement of electro-optic phase shifters, each of which is driven with a periodic signal of distinct amplitude and phase[3]. This results in a precisely adjustable line spacing, tunable center wavelength, and narrow linewidth. A key figure of the associated phase shifters is the achievable modulation bandwidth and the modulation depth. Experimental demonstrations have been performed on the basis of conventional lithium niobate devices[4] or InP-based photonic integrated circuits[5]. For advanced transmitter systems, it would be highly desirable to co-integrate frequency comb generators with the wealth of devices offered by silicon photonics. However, electro-optic modulation on silicon currently relies on depletion-type pn phase shifters. These devices are characterized by a low efficiency, which impedes broadband frequency comb generation. In this paper we demonstrate a novel concept for silicon-based comb generators that are based on silicon organic hybrid (SOH) integration[6]. The SOH approach combines silicon nanophotonic waveguides with organic cladding materials to realize highly efficient broadband phase shifters. Using a single dual-drive Mach-Zehnder interferometer (MZI) modulator with a $U_\pi L$ product of 2 V mm, we demonstrate generation of 7 lines within a power range of 2 dB. The device enables data transmission of 28 GBd QPSK signals on 7 adjacent carriers. Using polarization multiplexing, this results in an aggregate rate of 784 Gbit/s. This is to the best of our knowledge the first demonstration of a modulator-based frequency comb source on silicon.

Silicon-organic hybrid (SOH) frequency comb generator

The frequency comb generator consists of a dual drive MZI modulator exploiting SOH phase modulators[6,7] as depicted in Fig. 1(a). The phase modulator consists of a slot waveguide electrically connected to a coplanar transmission line through 60 nm thick doped silicon strips. The waveguide is covered with the electro-optic chromophore DLD164, which entirely fills the slot. The voltage applied to the transmission line drops across the narrow slot, resulting in a high electric field that strongly overlaps with the optical mode. Silicon waveguides are fabricated in IMEC by 193 nm deep-UV lithography on an SOI wafer with a 2 µm thick buried oxide and a 220 nm thick device layer. The dual drive Mach-Zehnder modulator (MZM), Fig. 1(b), consists of two identical 2 mm long phase-modulators. The phase modulators are driven individually by two coplanar copper slotlines. The electro-optic cladding is applied by spin coating and poled at elevated temperatures by applying a DC voltage across the slotline electrodes. The voltage-length product of each phase modulator was measured at DC to be $U_\pi L = 2$ V mm. The experimental setup for comb generation is depicted in Fig.1(b): The high bandwidth and low $U_\pi L$ product of the phase shifters allow for efficient generation of higher-order optical
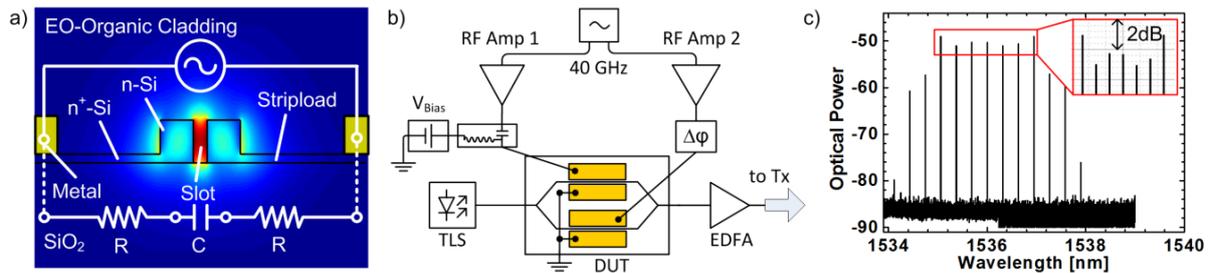
Fig. 1: a) Schematic and simulated optical mode of a silicon-organic hybrid (SOH) phase-modulator. The two rails of a silicon slot waveguide are electrically connected to metal electrodes by 60 nm high *n*-doped silicon slabs. The waveguide is covered by an electro-optic cladding material (DLD164), which entirely fills the slot. **b)** Integrated frequency comb generator: A tunable laser source (TLS) is coupled to a dual-drive SOH Mach-Zehnder modulator (MZM) via grating couplers. The arms are driven by two sinusoidal 40 GHz signals. Flat combs are obtained by carefully adjusting the signal powers and phases along with the bias voltage V_{Bias}. Fiber-chip coupling losses are compensated by an erbium-doped fiber amplifier (EDFA). **c)** Flat-top spectrum obtained for electrical drive powers of 28 dBm and 23 dBm, showing 7 lines within 2 dB flatness. The lines are spaced by 40 GHz.
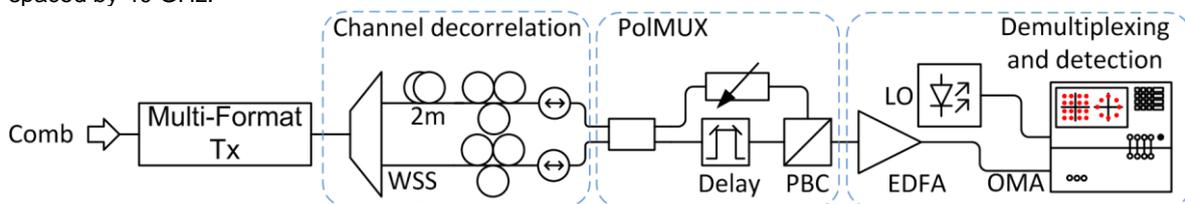
Fig. 2: Data transmission setup: Each comb line is modulated with a 28 GBd QPSK signal. Even and odd channels are separated with a wavelength-selective switch (WSS) to decorrelate neighboring channels. Both data streams are merged and are polarization multiplexed (PolMUX). After amplification, the channels are demultiplexed and detected by an optical modulation analyzer (OMA) and a tunable laser acting as a local oscillator (LO).

sidebands, see Fig. 1c). By carefully adjusting the drive parameters[3], we achieve a spectral flatness of 7 lines within 2 dB. The line spacing amounts to 40 GHz.

WDM data transmission

We have performed a proof-of-principle data transmission experiment using the setup depicted in Fig. 2. We use a single Multi-Format transmitter to modulate each line with the same QPSK NRZ signal at a symbol rate of 28 GBd. For decorrelation of the data signals, even and odd channels are separated by a wavelength-selective switch (Finisar WaveShaper, WSS), delayed with respect to each other, and recombined in a fiber-based 2×2 coupler. Polarization division multiplexing (PDM) is emulated in a similar manner by splitting the data stream, delaying one part with respect to the other, and recombining them in a polarization beam combiner.

To characterize the signal quality at the receiver side, we use an optical modulation analyzer (OMA, Agilent N4391A) along with a tunable laser acting as a local oscillator. Digital signal processing is performed for polarization demultiplexing and equalization. We record the

constellation diagrams and extract the error vector magnitude (EVM) as a measure for signal quality, Fig. 3. Note that the comb generator used for the data transmission experiment had a slightly worse performance and a higher voltage-length product of $U_\pi L = 3.2$ V mm than the device discussed in the previous section. As a consequence, the spectral flatness of the comb was worse with a power variations of 7 dB for 7 spectral lines. In addition, we used 28 GBd NRZ QPSK and fairly narrow carrier spacing of 40 GHz. This leads to an overlap of the data spectra and hence to significant inter-channel interference (ICI) and signal quality impairments. The different channels show EVM values between 20.7% and 37.0% and measured bit error ratios (BER) are better than 4×10^{-3}, which is still below the hard-decision FEC threshold[8] of 4.5×10^{-3}. Using 28 GBd PDM-QPSK signals on 7 adjacent carriers we hence obtain a gross aggregate data rate of 784 Gbit/s. In future experiments, ICI can be avoided by using advanced multiplexing schemes such as OFDM or band-limited Nyquist pulse shaping techniques. This will enable chip-scale multi-channel transceivers providing aggregate data rates beyond 1 Tbit/s.
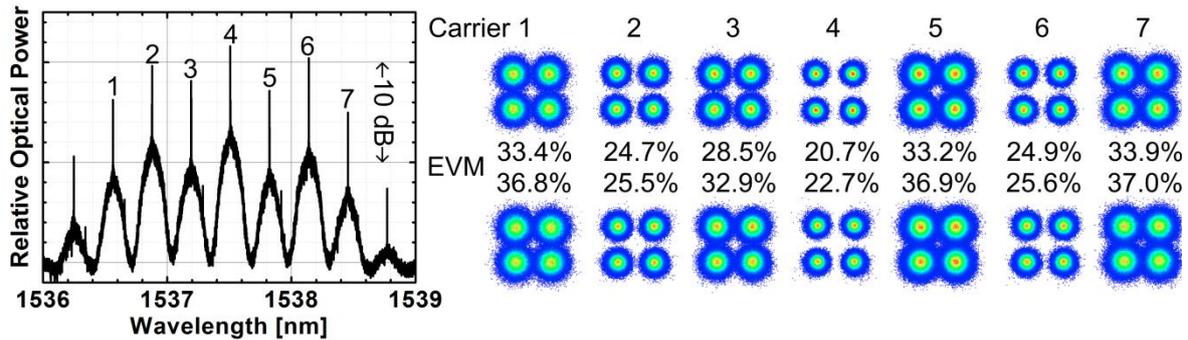
Fig. 3: Data transmission results: Data transmission of 784 Gbit/s using QPSK signals on 7 carriers generated by an integrated SOH comb source. Comb spectrum (left) and constellation diagrams for all channels and both polarization are depicted along with measured EVM values. BER below hard-decision threshold are achieved for all signals.

Conclusions

We have demonstrated a modulator-based frequency comb generator based on silicon-organic hybrid (SOH) integration. The device can generate flat-top frequency comb spectra with 7 lines within a 2 dB power range. Data transmission was demonstrated with gross data rates of 784 Gbit/s and BER values below hard-decision FEC.

Acknowledgements

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