Data Transmission at Terabit/s Data Rates Using Silicon-Organic Hybrid (SOH) Frequency Combs

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Abstract: We demonstrate frequency comb generation using silicon-organic hybrid (SOH) electro-optic modulators. The frequency combs are used for WDM data transmission at terabit/s data rates and distances of up to 300 km.

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1. Introduction

Optical frequency combs are key elements for a multitude of applications such as optical metrology, arbitrary-waveform generation, and terabit/s communications [1]. On the technology side, it is highly desirable to co-integrate these devices along with other components on large-area silicon-on-insulator (SOI) substrates. A particularly suitable and versatile approach for integrated frequency comb sources is based on modulation of a continuous-wave (cw) laser with an appropriate arrangement of electro-optic phase shifters driven with sinusoidal signals [2]. Modulator-based comb generators offer precisely adjustable line spacing, tunable center wavelength, along with narrow linewidth and do not require resonant structures. For data transmission using wavelength division multiplexing (WDM), broadband frequency combs with tens of GHz of linespacing are essential. This requires phase shifters with appropriate modulation bandwidth and large modulation depth. Experimental demonstrations of this scheme have been realized using conventional lithium niobate modulators [3] or InP-based photonic integrated circuits [4]. However, electro-optic comb generation on the SOI platform was so far impeded by the relatively low modulation efficiency of commonly used depletion-type pn phase shifters. We have recently demonstrated that silicon-organic hybrid (SOH) integration is well suited for broadband frequency comb generation on silicon substrates. In a first proof-of-principle experiment, we have generated a 784 Gbit/s data stream comprising 7 channels, spaced by 40 GHz and modulated with 28 GBd NRZ QPSK signals [5]. Larger data rates were impeded by the limited spectral efficiency and by the available optical bandwidth obtained from the 2 mm long SOH comb generator. Moreover, signal quality was not sufficient to demonstrate data transmission over noteworthy distances.

In this paper we demonstrate the first terabit/s data transmission using a modulator-based comb generator on silicon. We use a 1 mm long SOH modulator to generate 9 lines with adjustable free spectral range. Using a combination of 16 QAM and QPSK modulation along with a symbol rate of 18 GBd and Nyquist pulse shaping, we generate a total data stream of 1.152 Tbit/s. Given a channel spacing of 25 GHz, this results in a net spectral efficiency of 4.9 bit/s/Hz. In addition, we demonstrate data transmission over a distance of up to 300 km, using NRZ QPSK signals at a symbol rate of 28 GBd on 9 channels with a spacing of 40 GHz, amounting to a total data rate of 1.008 Tbit/s.

2. SOH modulator for frequency comb generation

The frequency comb is generated by using two SOH phase shifters [6, 7], Fig 1(a) in a Mach Zehnder modulator (MZM) as depicted in Fig. 1(b). Each 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 [8], which entirely fills the slot. A schematic cross section and simulated mode profile of the waveguide is depicted in Fig. 1(a). 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, resulting in highly efficient electro-optic interaction which is essential for a low $V_\pi L$ product. The MZM has a length of 1 mm and is driven by a single coplanar transmission line (GSG – ground, signal, ground). The electro-optic cladding is applied by spin coating and poled at elevated temperatures by applying a DC voltage across the ground electrodes of the transmission line [9]. The π-voltage V_π of the MZM in push-pull operation was measured to be 1 V at DC, the 6 dB electrical-optical-electrical bandwidth is measured to be 23 GHz. The experimental setup for comb generation is depicted in Fig.1(b):

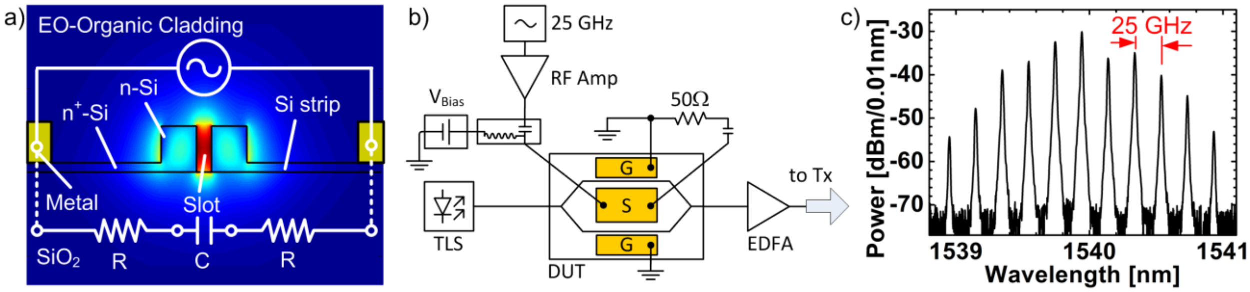

Fig. 1: (a) Schematic cross-section and simulated optical mode of a silicon-organic hybrid (SOH) phase-modulator. The two rails of a silicon slot waveguide are electrically connected to metal electrodes by 60 nm high n-doped silicon slabs. The waveguide is covered by an electro-optic cladding material (DLD164), which entirely fills the slot. (b) Frequency comb generator: A tunable laser source (TLS) is coupled to the SOH MZM via grating couplers. The device is driven by sinusoidal signals of 25 GHz or 40 GHz. The operation point can be chosen with the bias voltage V_{Bias}. The electrodes are terminated with 50 Ω. Fiber-chip coupling losses are compensated by an erbium-doped fiber amplifier (EDFA). (c) Resulting optical spectrum using an electrical drive signal of 25 GHz and a RF power of 23 dBm.

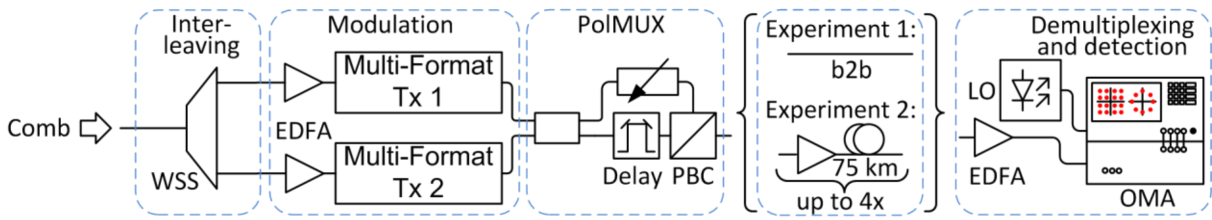

Fig. 2: Data transmission setup: A wavelength-selective switch (WSS) interleaves the comb lines into even and odd carriers which are modulated independently at a symbol rate of 18 GBd using QPSK and 16QAM in combination with Nyquist pulse shaping in a multi-format transmitter. Both data streams are merged and are polarization multiplexed (PolMUX). **Experiment 1:** In a first experiment, the data is fed directly into the receiver (back-to-back configuration). **Experiment 2:** Here NRZ QPSK signals at a symbol rate of 28 GBd are used for modulation of comb lines spaced by 40 GHz. Up to 4 spans of 75 km SMF are used for transmission over up to 300 km. After amplification, the channels are demultiplexed and detected by an optical modulation analyzer (OMA) and a tunable laser acting as a local oscillator (LO).

A tunable laser source (TLS) is coupled to the chip via grating couplers, the electrodes for the sinusoidal driving signal and termination are contacted with RF probes. The high bandwidth and low $V_{\pi}L$ product of the phase shifters allow for efficient generation of higher-order optical sidebands, see Fig. 1(c). The line spacing of 25 GHz is determined by the modulation frequency.

3. Nyquist-WDM Tbit/s data generation with generated frequency combs

Using the carriers generated by the SOH comb source, we generated a WDM data stream. The experimental setup is shown in Fig. 2: A wavelength-selective switch (Finisar WaveShaper, WSS) interleaves even and odd carriers, which are then modulated independently by multi-format transmitters with a symbol rate of 18 GBd using independent pseudo-random bit sequences (PRBS) of length 2^9-1. Nyquist pulse shaping [10] enables a spectrally efficient channel spacing of 25 GHz. After combination of the two signals in a fiber-based 2 × 2 coupler, polarization division multiplexing (PDM) is emulated by splitting the data stream, delaying one part with respect to the other, and recombining them in a polarization beam combiner on orthogonal polarizations. The data stream is then transmitted either directly into the receiver (back-to-back) or over up to 4 spans of 75 km of SMF. For transmission experiments, erbium-doped fiber amplifiers (EDFA) are used to maintain a constant input power of 8 dBm into the fiber span.

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 for each channel and polarization.

In a first experiment, the data was fed directly into the receiver. The results can be seen in Fig. 3: The 7 strongest carriers were used for 18 GBd PDM-16QAM signals, two weaker higher-order sidebands were modulated with 18 GBd PDM-QPSK. All channels show measured bit error ratios (BER) better than 4.3×10^{-3}, staying below the hard-decision forward-error correction (FEC) threshold [11] of 4.5×10^{-3}. This amounts to a gross data rate of 1.152 Tbit/s, the highest data rate achieved with a silicon modulator-based frequency comb generator so far. Taking into account a 6.7% overhead for the hard-decision FEC, we obtain a net spectral efficiency of 4.9 bit/s/Hz. The spectral efficiency can be further optimized by increasing the symbol rate of the Nyquist pulse stream to 25 GBd, adapted to the channel spacing. Transmission of the signal over noteworthy distances was not possible due to insufficient BER margin.

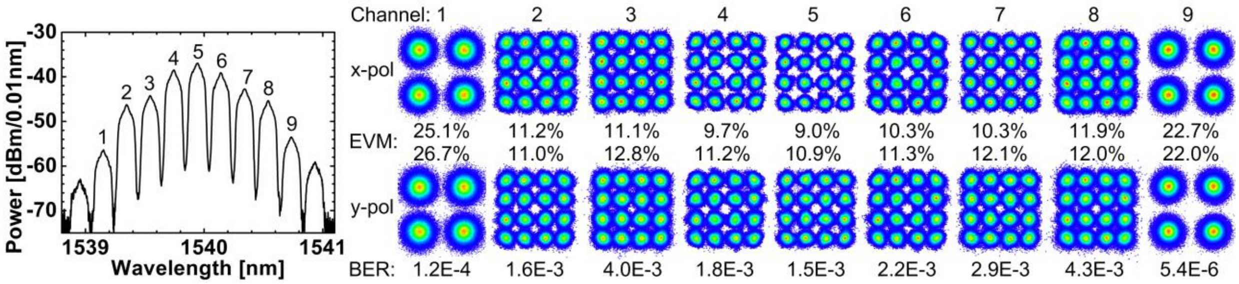

Fig. 3: Results of back-to-back data transmission: A total of 9 carriers spaced by 25 GHz were generated by an integrated SOH comb source. Optical spectrum of the modulated carriers (left) and constellation diagrams (right) for all channels and both polarization are depicted along with measured EVM values. The 7 strongest carriers were modulated with Nyquist pulse-shaped 16 QAM signals, weaker carriers 1 and 9 were modulated with Nyquist pulse-shaped QPSK signals. Symbol rate for all channels is 18 GBd. BER below hard-decision threshold are achieved for all channels, yielding a gross data rate of 1.152 Tbit/s.

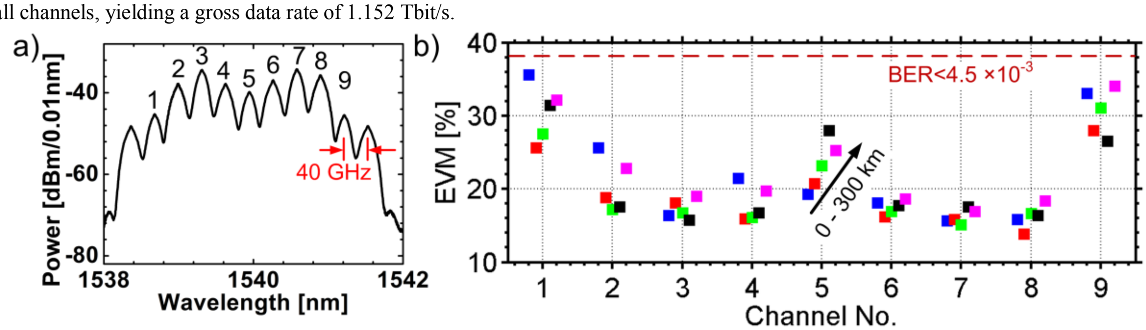

Fig. 4: Results for data transmission of NRZ QPSK signals: a) Optical spectrum of the modulated carriers with 40 GHz spacing and 29 dBm of RF power driving the comb generator. b) The average EVM of both polarizations over channel number are shown color-coded (and slightly offset for clarity of presentation) for each length of fiber span (0 km, 75 km, 150 km, 225 km, 300 km). Drift of the operation point of the integrated comb source leads to some deviations from equal optical power for each channel. Nonetheless, BER values below 4.5×10^{-3} are achieved for all channels.

4. NRZ-WDM Tbit/s data transmission over 300 km

In a second experiment, we demonstrate data transmission over up to 300 km using more simple NRZ QPSK signals. The modulator also exhibits a π-voltage V_π of 1.0 V at DC. It is operated with a drive signal of 40 GHz and 29 dBm of RF power, resulting in 9 lines that were usable for data transmission, Fig.4(a). All carriers were modulated with 28 GBd NRZ PDM-QPSK signals. The operation point of the device was not stabilized thermally nor electronically, leaving some residual drift, which lead to variations in channel performance during the measurements. Fig. 4(b) depicts the average EVM of both polarizations for all channels and various transmission distances (0 km, 75 km, 150 km, 225 km, 300 km). The EVM of all channels are below the threshold for hard-decision FEC, which corresponds to a BER of 4.5×10^{-3} and is represented by the red line in Fig. 4(b) [12]. We thus demonstrate error-free transmission of a gross data rate of 1.008 TBit/s over 300 km.

5. Summary

We have demonstrated an integrated silicon-based frequency comb generator using SOH modulators. With a channel spacing of 25 GHz and Nyquist pulse shaping, we demonstrate generation of PDM-QPSK and PDM-16QAM signals at 18 GBd, achieving aggregate data rates of up to 1.152 Tbit/s with a net spectral efficiency of 4.9 bit/s/Hz. Transmission over up to 300 km is demonstrated using NRZ QPSK signals at a symbol rate of 28 GBd on 9 channels with a spacing of 40 GHz, amounting to a total data rate of 1.008 Tbit/s.

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