300 Gb/s Net-Rate Intra-Datacenter Interconnects with a Silicon Integrated Optical Frequency Comb Modulator

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Abstract: We propose and demonstrate intra-datacenter interconnects based on a silicon optical frequency comb modulator consisting of four cascaded microring modulators. The generated 4×50 Gbaud WDM-PAM4 signals exhibit BERs below 33% HD-FEC threshold after 2-km transmission.

1. Introduction

Emerging Internet applications like virtual reality, contents streaming, social networking, and cloud computing have spawned a digital explosion. All these Internet services will become impossible without extremely powerful warehouse-scale datacenters. Pulse-amplitude modulation (PAM) has been widely studied to support the growing demand for communication bandwidth of intra-datacenter interconnects. The objective of this research is to seek for scalable high-capacity interconnects with low power consumption, low cost, and superior capacity scalability. Silicon photonics (SiP) modulators have become an attractive solution to intra-datacenter interconnects due to small footprint, low power consumption, and complementary metal-oxide-semiconductor (CMOS) compatibility. Recent demonstrations based on SiP Mach-Zehnder modulators show a capacity of over 100 Gb/s with discrete multitone modulation [1], and PAM signaling [2, 3]. Proposals to achieve a capacity to 400 Gb/s or even higher have been concentrated on either to increase the single-lane bitrate [2] or the number of parallel lanes [3]. However, it might not be a sustainable solution to increase the number of lanes considering the cost and interconnect efficiency. Therefore, novel sustainable approaches should be introduced for higher bitrate intra-datacenter interconnects. One possible solution is wavelength-division multiplexing (WDM) in a single transmitter. Yet WDM would create new problems. Firstly, WDM usually requires multiple light sources and active wavelength controls, which consumes extra energy and increases the cost. Secondly, dense WDM requires multiplexers and demultiplexers with a sharp roll-off, which can further increase the complexity of the system.

In this paper, we propose and explore intra-datacenter interconnects at 400 Gb/s line rate with a single silicon optical frequency comb modulator consisting of cascaded microring modulators (MRMs), as well as a single distributed-feedback (DFB)-laser based electro-optical frequency comb. Silicon MRM features several unique advantages. First and foremost, the strong wavelength-selectivity makes MRMs a perfect match with the energy-efficient electro-optical frequency comb, which shows great potential to be integrated on a single chip [4, 5]. Here, demultiplexing, modulating, and multiplexing WDM signals can be done using only cascaded microrings in a single integrated device [6]. Second, it has ultra-compact size, ultra-low modulation power and total power penalty [7]. Thirdly, the wavelength tunability and cascade ability make it highly flexible for elastic optical interconnects. For comb source, the single-laser-based electro-optical frequency comb requires only one active laser wavelength control unit and can potentially reduce the energy consumption to tens of milliwatts if integrated on-chip [5]. Combining these two techniques, we demonstrate the generation of up to 4×50 Gbaud WDM-PAM4 signals. Bit-error ratio (BER) performance below 33% hard-decision forward error correction (HD-FEC) threshold was achieved for all four WDM channels after 2-km transmission with a net rate of 300.75 Gb/s. With 40 Gbaud modulation, a net rate of 299.06 Gb/s is achieved, assuming 7% HD-FEC. To the best of our knowledge, this is the first WDM modulation demonstration using a single SiP integrated circuit with an electro-optical frequency comb source, paving a way for future single-chip solution with heterogeneous silicon/III-V technology.

2. The SiP optical frequency comb modulator and experimental setups

We designed a silicon optical frequency comb modulator consisting of 20 cascaded MRMs (only four rings are used in the current experiment). The ring radius is 7.5 μm, and each ring has a microheater sitting on top of it to adjust the resonant wavelengths. The high-speed modulation is based on a reverse-biased P-N junction in the middle of the ring waveguide [6, 7]. The PIC was fabricated on an 8” silicon-on-insulator wafer with a top silicon thickness of 220 nm. We packaged the chip with two fibers, a printed circuit board (PCB) with 20 RF transmission lines to drive the modulators, and a second PCB with DC lines to control the heaters, shown in Fig. 1. The packaged ring modulators have an estimated bandwidth of around 15 GHz, from our previously measured devices with a similar design.

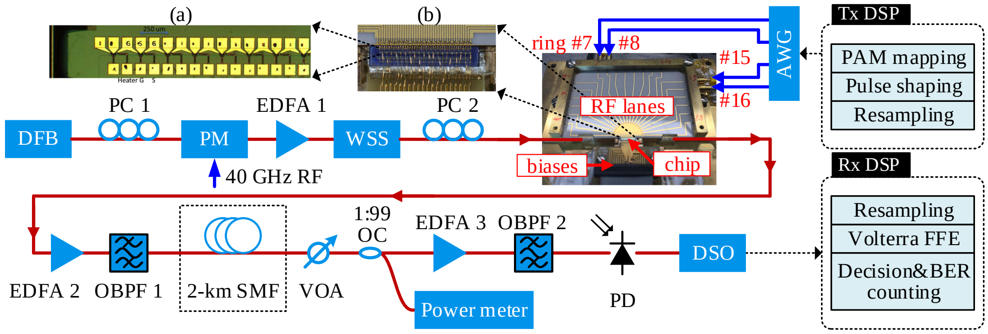

Fig. 1. Experimental setup.

Figure 1 shows the experimental setup. A DFB laser working at 1551.88 nm with an output optical power of 13 dBm is used. It is phase-modulated at 40 GHz through a phase modulator (PM). The generated 40-GHz spaced optical frequency comb is amplified through an EDFA (EDFA 1) and then line-by-line filtered and equalized by a wavelength-selective switch (WSS) to an 80-GHz spaced optical frequency comb with 4 comb lines located at 1550.91 nm, 1551.55 nm, 1552.19 nm, and 1552.83 nm, respectively. The 4 comb lines are used as WDM sources and launched into the optical frequency comb modulator. In this experiment, we used MRM 7, 8, 15, and 16 to implement the WDM transmitter. It should be noted that the WSS used in this proof-of-concept experiment is used to equalize the optical frequency comb, which might not be preferred in intra-datacenter interconnect. However, the flat optical frequency comb generation can be replaced by other electro-optical frequency comb generation schemes which do not need the costly WSS [8-10]. The electro-optical comb source can potentially be integrated on SiP [4].

The electrical PAM-4 signals are generated using an arbitrary waveform generator (AWG) with 65 GSa/s sampling rate from a pseudo-random binary sequence with a length of 215-1. A roll-off factor of 0.01 is used for the electrical pulse shaping. Four broadband electrical amplifiers and four electrical bias tees are used to amplify the electrical PAM 4 signals to a peak-to-peak voltage around 5 volts with non-negative amplitudes and drive the MRMs on-chip (partially shown in Fig. 1, inset (a)) through packaged RF connectors. The MRMs are thermally tuned to match the wavelengths of the WDM source using DC lines wired with heater pads (shown in Fig. 1, inset (b)). The total optical input power to the transmitter is 4 dBm. The optical insertion loss for the whole device is 19 dB. The output of the transmitter is amplified by an optical preamplifier (EDFA 2) to 13 dBm and filtered through an optical bandpass filter (OBPF 1). A 2-km SMF is inserted to evaluate the transmission performance.

A preamplified optical receiver is used to evaluate the BER performance of the interconnect system. The receiver consists of a variable optical attenuator (VOA), a 1:99 optical coupler (OC) with a power meter, an optical preamplifier (EDFA 3), OBPF 2, and a 70-GHz bandwidth photodiode (PD). The detected signal is then sampled by a digital sampling oscilloscope (DSO) with an analogue bandwidth of 63 GHz, and a sampling rate of 160 GSa/s. Two 4-million-sample records for each received power of each WDM channel is used for the offline digital signal processing (DSP), including resampling, Volterra-based feed-forward equalization (Volterra FFE), and decision and BER count. The equalizer lengths for 1st, 2nd, and 3rd kernels of the Volterra FFE are 101, 29, and 9, respectively. To reduce computation complexity, we adopt the simplified method proposed in [11], where kernels with large interval product terms are truncated since they have negligible contribution to signal distortions.

4. Results and discussions

Figure 2(a) shows the optical spectra out of the optical frequency comb modulator with the input of ASE noise, as well as the equalized 80-GHz spaced optical frequency comb source. The MRMs have been thermally tuned to match the frequency comb. The power variation of the equalized comb lines is within 1 dB. Figure 2(b) gives the optical spectra of the modulated PAM 4 signals from each MRM, as well as the WDM signal. All four channels are generated simultaneously. Figure 2(c) shows the detected electrical spectrum of 50 Gbaud PAM 4 signal from MRM 16 at the back-to-back scenario. More than 10 dB amplitude drop can be observed within the signal bandwidth. This indicates that our system is limited by the overall bandwidth of all devices, mainly from the packaged MRM.

Figure 3(a) and 3(b) give the back-to-back BER performance of the 4×40 Gbaud and 4×50 Gbaud WDM-PAM4 signals, respectively. Figure 3(c)-d) show the BER performance after 2-km fiber transmission. The 4×40 Gbaud WDM-PAM4 signals show a BER performance below 7% HD-FEC threshold (BER=3.8×10^{-3}). The achieved net rate is calculated to be 299.06 Gb/s. BER below 33% HD-FEC threshold (BER=2.12×10^{-2}, staircase codes [12]) is observed for the 4×50 Gbaud WDM-PAM4 signals. The corresponding achieved net rate is 300.75 Gb/s. The four WDM channels have shown some performance variations. We attribute this mainly to the fabrication deviations of the MRMs, which result in different electro-optical response and extinction ratios. We also observed crosstalk between adjacent MRMs. The crosstalk may result from the dense microstrip lines on the RF PCB. Better arrangement of these microstrip lines and bending designs are therefore required to improve the performance.

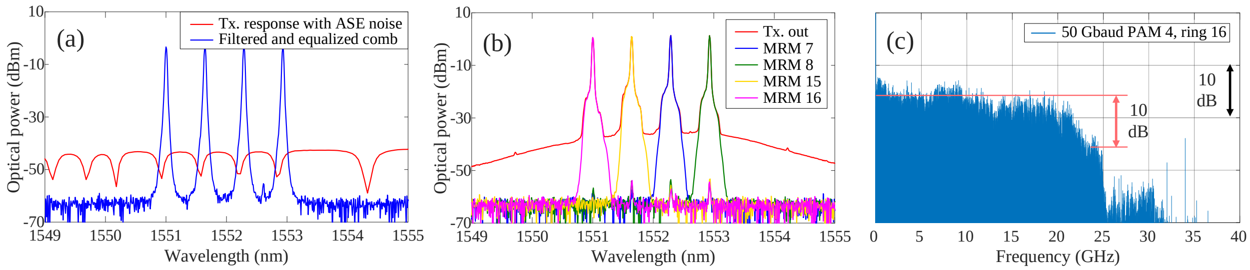

Fig. 2. (a) Optical spectra of the transmitter response with ASE noise and the equalized optical frequency comb; (b) Optical spectra of outputs from each MRM and output of the transmitter; (c) Electrical spectrum of the detected 50 Gbaud PAM4 signal from microring 16.

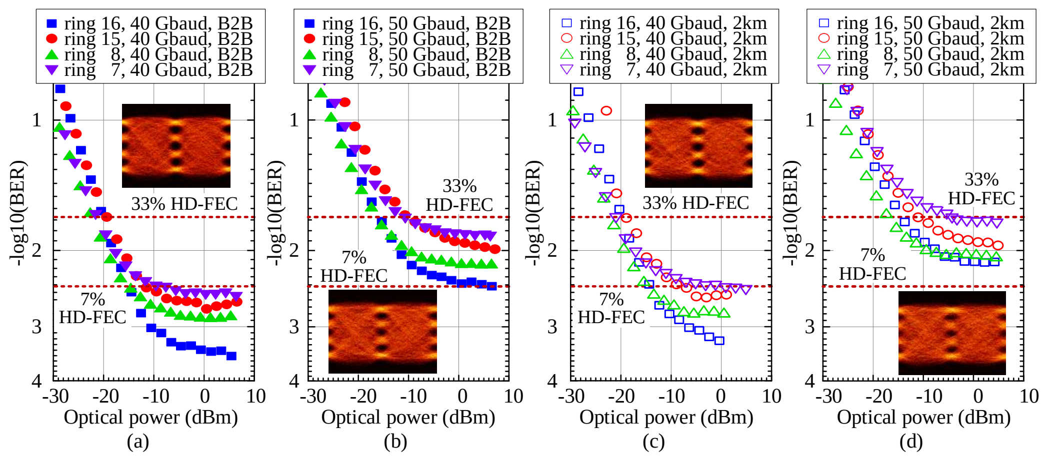

Fig. 3. (a)-(b) BER performance of the 4×40 Gbaud and 4×50 Gbaud WDM-PAM4 signals at back-to-back scenario; (c)-(d) BER performance of the 4×40 Gbaud and 4×50 Gbaud WDM-PAM4 signals after 2-km fiber transmission.

5. Conclusion

We have demonstrated 300 Gb/s net-rate intra-datacenter interconnects using a single optical frequency comb modulator based on cascaded MRMs. Taking advantage of the strong wavelength-selectivity of the MRMs, a single DFB-laser-based 80-GHz spaced optical frequency comb has been used as WDM sources and simultaneously modulated. 4×40 Gbaud and 4×50 Gbaud WDM-PAM4 signals have been generated and transmitted through a 2-km SMF, with BER performance below 7% and 33% HD-FEC thresholds, respectively. The resulting net rates for the 40 Gbaud and 50 Gbaud WDM signals are 299.06 Gb/s and 300.75 Gb/s. Given the cascade ability of the MRMs and the large bandwidth of the optical frequency comb, this scheme has the potential for higher capacity intra-datacenter interconnects with low power consumption.

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6. References

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