230-Gb/s on-chip optical interconnection based on GeSi transceiver

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Abstract *230-Gb/s on-chip optical interconnection is experimentally demonstrated using GeSi electro-absorption modulator and photodetector. The demonstrated results indicate that GeSi-based integration transceiver chip are promising solutions for low cost and high-speed on-chip optical interconnection.*

Introduction

Since 2022, ChatGPT has sparked the first global Artificial Intelligence (AI) usage boom, which is supported by of the total computing power of 3640PF-day. This computing power is made possible by the high-performance computer network composed of thousands of Nvidia's strongest H100 graphics cards and faster InfiniBand network interconnection technology [1]. However, with the computing power demand increasing, we have to face the bottleneck in the short distance interconnection of electronic chips in system construction. Chip-scale optical interconnection provided an effective solution. Compared to electrical interconnection, optical interconnection has advantages such as large bandwidth, low latency, and low power consumption. Chip-scale optical interconnection can further enhance system integration and reduce system power consumption, which is considered as the next generation high-performance interconnect technology.

Due to the inherent characteristics of silicon materials, the speed of devices based on silicon technology has approached the physical limit. Improving device speed and maintaining linear characteristics has become very difficult. To address this contradiction, the germanium silicon (GeSi) process has been proposed. Its direct bandgap can provide high conversion efficiency for photonic devices and is compatible with silicon technology. Important components related to optoelectronic integration can even be integrated on the same chip in the same active layer, providing another new technological development path for high-speed devices [2].

In this paper, we experimentally demonstrate an on-chip optical interconnection of 230-Gb/s probabilistic shaping pulse amplitude modulation-6 (PS-PAM-6) using GeSi-based integration transceiver. Based on the same sidewall-doped GeSi structure, high bandwidth (>110 GHz), high modulation efficiency, and low power consumption GeSi electro-absorption modulator (EAM), and high bandwidth and high sensitivity GeSi photodetector (PD) are integrated in a single chip, which are fabricated based on the commercial 90-nm silicon photonics platform. Finally, the on-chip optical interconnection of a 230-Gb/s PS-PAM-6 signals are successfully achieved using GeSi-based transceiver with the bit error rate (BER) below the 20% overhead soft-decision forward error correction (SD-FEC) limit of 2.4×10^{-2}.

Design and fabrication of GeSi transceiver

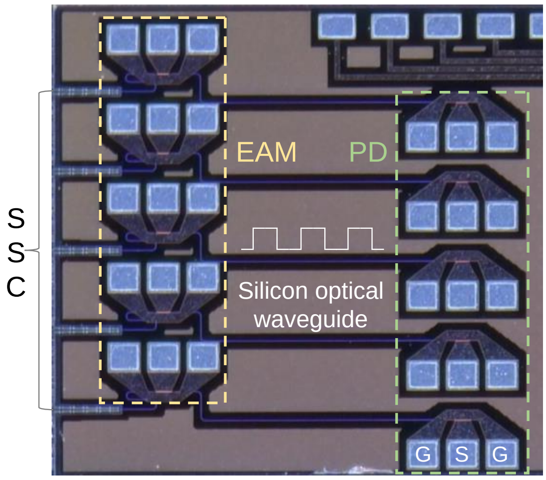

Fig. 1: Optical micrograph of the integrated optical interconnect link with GeSi electro-optical modulators (EAMs), silicon waveguides, and germanium silicon (GeSi) photodetectors (PDs). SSC: spot size convert.

Figure 1 shows the optical micrograph of monolithic integration of GeSi EAM, silicon waveguide, and GeSi PD. The designed GeSi EAMs and PDs are fabricated in a commercial 90-nm silicon photonics platform with simple fabrication processes. The EAMs and PDs are based on the same Ge sidewall-doped structure, which is reported in our previously works [3-5].

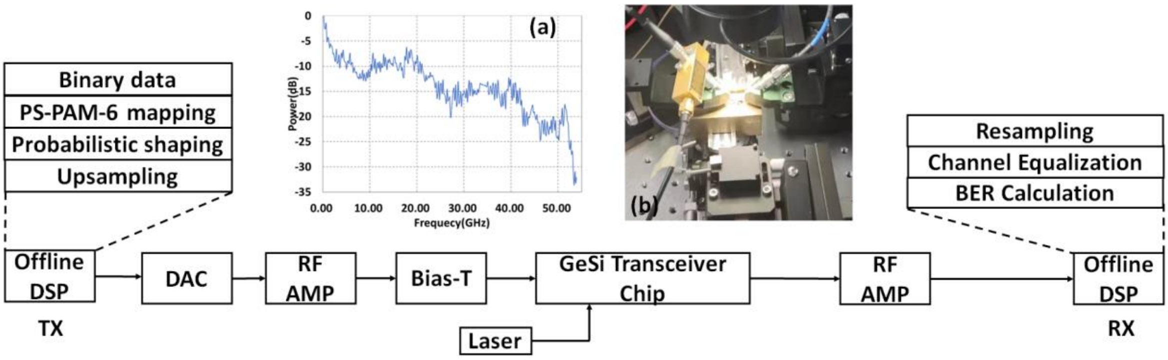

Fig. 2: Experimental setup for the on-chip optical interconnection of 230-Gb/s PS-PAM-6 signal based on GeSi transceiver at L-band; (a) Measured amplitude response; (b) Experimental chip and probe platform;

The typical p++, p+, p, n++, n+, and n implants for the modulators and PDs are performed on the exposed silicon and Ge. The overlaps of the optical field and electric field are very high, which helps to enhance the bandwidth and responsivity. The width and the height of the epitaxial Ge on Si layer are 1-μm and 400-nm, respectively. The length of the Ge varied from 40 to 60-μm. The electro-optic (EO) 3-dB bandwidth of EAM is beyond 110-GHz, while the optoelectrical (OE) 3-dB bandwidth of PD is only about 50-GHz, which is limited by carrier transit time. The light is coupled via Si-based suspended spot size convert (SSC) edge coupler with approximately 3.6-dB/facet coupling loss at 1600-nm.

The Franz-Keldysh (FK) effect of Ge can be used to realize the electro-absorption modulation at L band with operation spectrum width of >25 nm. When the width of Ge is reduced to sub-micrometer scale, the absorption coefficient can be improved by the FK effect under strong electric field [6]. This will break through the quantum efficiency (QE) of about 60% limitation in the L band. Therefore, the GeSi structure can be used for high efficiency optical modulation and photodetection simultaneously at L band.

Experimental Setup

Fig. 2 depicts the experimental setup for the on-chip optical interconnection of 230-Gb/s PS-PAM-6 signals based on GeSi transceiver at L-band. At the transmitter, signal probabilistic shaping method is used to map original binary data into PS-PAM-6 symbols. The probability distribution PS-PAM-6 signal conforms to the Maxwell-Boltzmann distribution with net entropy of 2.19, while the transmitted baud rate is 105-GBaud with bit rate of 230-Gbit/s. The signal is then unsampled to 256-GSa/s, which is converted into analogue signal employing an Keysight arbitrary waveform generator (AWG) M8199A, running at 256-GSa/s. The output of the AWG is amplified by a 67-GHz bandwidth RF amplifier. The signal is then applied to the EAM in the chip using a 110-GHz RF probe. An external cavity laser (ECL) is used as the optical source, whose operation wavelength is set to L-band. The optical signal injects into the EAM of the chip through SSC-based edge coupler with the power of 8-dBm. The modulated light is transmitted within the chip by the single mode silicon waveguide. After propagating in chip at a distance of about 1000-um, the signal is converted into electrical signal by the on-chip GeSi photodetector (PD), as shown in Fig. 1. The output electrical signal of the GeSi PD is detected via a 110-GHz RF probe, it is then sampled by a 256-GSa/s oscilloscope with 70 GHz analog bandwidth, and the signals is processed offline.

In the receiver digital signal processing (DSP), the resampling is first implemented, which allow the sampling rate to be twice of the baud rate of the transmitted signal. Then, only a feed-forward equalizer is employed for signal equalization. Finally, PS-PAM-6 are passed through the decoder to recover the original binary stream, and BER calculation is finally performed.

Results and Discussion

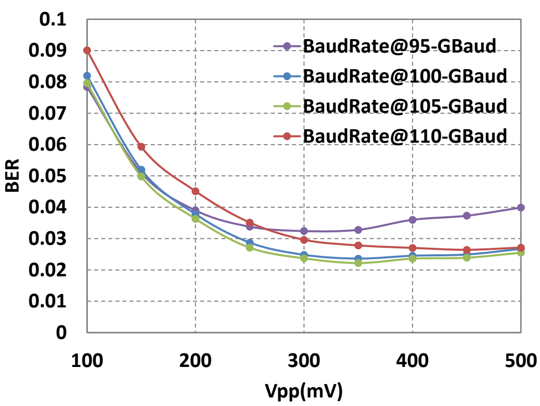

Fig. 3: 230-Gb/s PS-PAM-6 BER versus Vpp with different baud rate.

For measurement process, the selected length of EAM and PD are 40-um and 50-μm, respectively, and the bias voltage of PD is fixed at -5-V. Firstly, the performance of transceiver is investigated in the optical back-to-back (OBTB) case, where the driver, AWG, EAM, PD and DSO are involved. Fig. 3 shows the measured curve of 230-Gb/s PS-PAM-6 BER versus voltage-peak-to-peak (Vpp) of the AWG, with different baud rate. It is observed that the optimum BER with the baud rate of 105-GBaud is around 2.2×10^{-2}, corresponding to 350-mV Vpp. The 105-GBaud and 100-GBaud signals almost have the similar BER performance, which are much better than that of 95-GBaud and 110-GBaud signals.

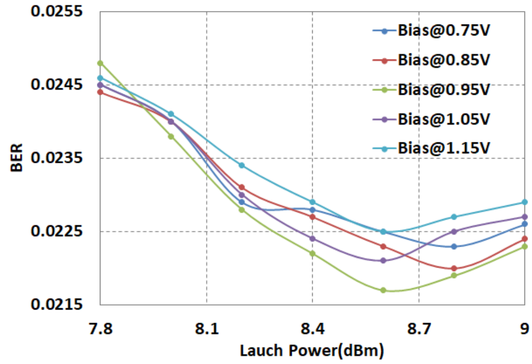

Fig. 4: 230-Gb/s PS-PAM-6 BER versus different launch power and bias voltage.

Secondly, we investigate the impact of bias voltage and launch power on the performance of the system. Fig. 4 shows the performances of BER versus launch power for different bias voltage. It is observed that the optimal bias voltage and launch power are 8.6-dBm and 0.95-V, respectively. Further increasing the optical power (>8.6-dBm) will lead to the space charge screening (SCS) effect on Ge region, which will reduce the quality of generated signal. The 0.95-V bias is the highest modulation efficiency region for the measured EAM.

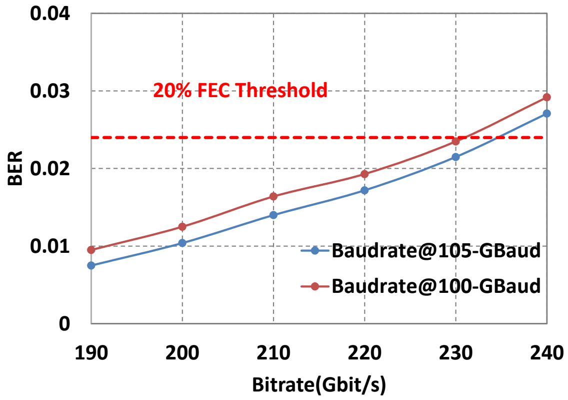

Fig. 5: BER versus different bitrate of PS-PAM-6 signal.

Figure 5 shows the BER versus different bitrate of PS-PAM-6 signal with 100-GBaud and 105-GBaud. We change the bitrate of the signal by changing the net entropy while keeping the baud rate constant under the optimal bias and launch power condition. We can see that 105-GBaud signal has better performance. The maximum bit rate for the 20% FEC threshold of 2.4×10^{-2} is around 235-Gbit/s.

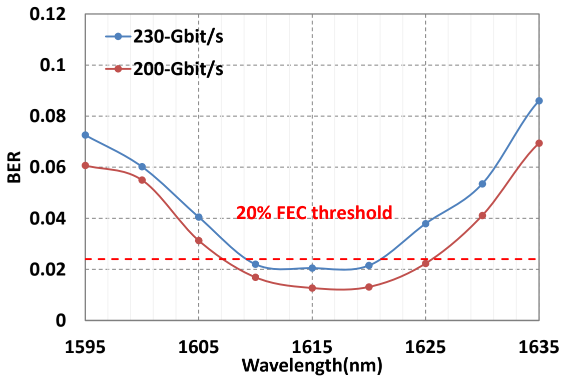

Fig. 6: Measured curve of BER versus wavelength with different bitrate.

Finally, we study the effective wavelength range of optical interconnection. It can be seen from the Fig. 6 that the effective operating wavelength ranges of 200-Gbit/s and 230-Gbit/s optical interconnections at the 20% FEC threshold are 18 and 11-nm, respectively.

Conclusions

Based on the available 90-nm silicon photonics foundry, the monolithic integration of GeSi EAMs, silicon waveguides, and GeSi PDs are designed and fabricated. The active regions of EAM and PD are ultra-compact, which are less than 100-μm^2. Using this GeSi transceiver, we successfully experimentally demonstrate the on-chip optical interconnection of 230-Gb/s PS-PAM-6 signal at L-band. The effective operating wavelength ranges of 200-Gbit/s and 230-Gbit/s optical interconnections are approximatively 18 and 11-nm, respectively. We believe that the proposed GeSi-based transceiver possess have great potential to achieve low-cost, low complexity, high-density, and high-speed on-chip optical link. It can offer a promising upgrade path to higher data rate from electrical interconnection to optical interconnection.

Acknowledgements

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