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High-Bandwidth Photodiodes on Silicon Nitride Supporting Net Bitrates in Excess of 350 Gbit/s

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Abstract *Silicon-nitride-based integrated photonic platforms currently lack fast photodiodes, limiting its adoption for high-speed optical transceivers. We show uni-traveling-carrier (UTC) photodiodes heterogeneously integrated by means of micro-transfer-printing and demonstrate their excellent bandwidth performance at 1550 nm, achieving net bit rates in excess of 350 Gbit/s. ©2022 The Authors*

Introduction

Inter- and intra-data center interconnects are facing great challenge to support exponential increase in data traffic. To meet future demand for data, high-speed optical transceivers are required to support the next generation 1.6T and faster data center interconnects. Silicon photonics (SiPh) is a widely adopted technology for high-speed integrated transceivers. Multiple flavours of silicon-photonic platforms exist, such as silicon on insulator (SOI), or silicon nitride (SiN). The former can already be found in commercial transceivers, but SiN offers distinct benefits. The advantages include, but are not limited to, a wider transparency window, no two-photon absorption – which greatly improves power handling, a much lower thermo-optic coefficient – beneficial for stability of filters, and lower propagation losses. As such, they offer the best high-Q resonators and filters, providing the much-desired high-extension ratio filters and arrayed waveguide gratings (AWG) for wavelength-division multiplexing (WDM)[1].

However, no active devices can be grown directly on SiN. Amplifiers, modulators and detectors need to be integrated heterogeneously. This can be done using, for example, wafer-bonding a III-V wafer, or micro-transfer-printing III-V chiplets, on SiN waveguides. The latter approach offers the benefit of allowing diverse material stacks to be integrated closely together and simplifies manufacturing of the active components. Recently, first lasers and amplifiers integrated on SiN have been demonstrated[2]. However, the bandwidth performance of detectors demonstrated so far was inferior compared to their SOI counterparts[3].

In this work, we show the versatility and benefits of micro-transfer-printed uni-travelling-carrier (UTC) photodiodes (PDs), which are integrated on a SiN platform. We also demonstrate a 200 m optical interconnect, enabled by this PD. Here, net bit rates on the order of 350 Gbit/s are achieved at a symbol rate of 140 GBd with 8-level pulse amplitude modulation (PAM-8), i.e. a line rate of 420 Gbit/s.

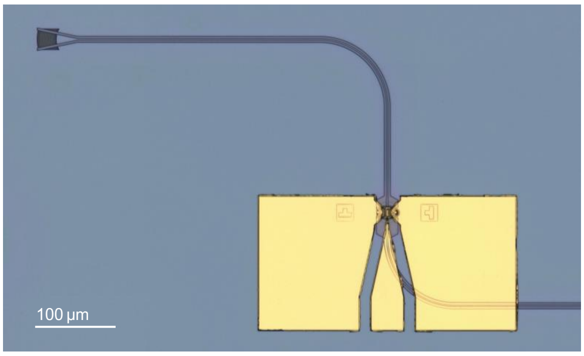

Fig. 1: The transfer-printed UTC photodiode on a SiN PIC.

Photodiode fabrication and performance

Waveguide-coupled UTC PDs on a SiN circuit were made by means of micro-transfer-printing. To this end, pickable chiplets, coupons, were first fabricated on the III-V source wafer. SiN tethers support the coupon, and prevent it from col-

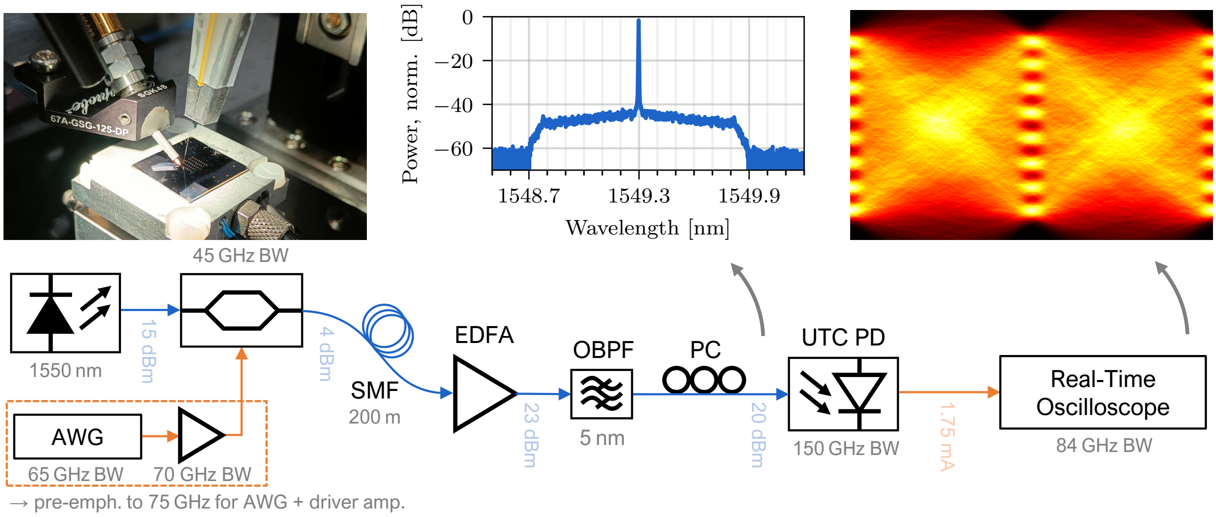

Fig. 2: The experimental setup consists of a MZM and AWG at the transmit side. After transmission over a 200 m-long SMF, this signal is amplified at the receiver side, passed through a polarization controller and bandpass filter, before coupling into the PIC containing the UTC PD. The electrical signal is directly fed into the real-time oscilloscope after opto-electric conversion. The PIC is probed both optically and electrically (top left). The optical spectrum of the signal fed to the PD (top middle) and eye diagram (top right) of a 144 GBd PAM-8 signal are shown.

lapsing on the substrate. These chiplets are then made pickable by under-etching a release layer in between the coupon and substrate. A more detailed description of the fabrication can be found in our previous work[4].

The design of this proof-of-concept PIC consists of a vertical grating coupler, short waveguide, and ground-signal-ground (GSG)-contact pads for electrical probing (Figure 1). These contacts were deposited on top of the PD coupon after opening the electrodes on the transfer-printed device. The waveguides were verified to have low losses ($<$1 dB/cm), and the simple vertical grating coupler shows a coupling efficiency of -9 dB. All further values for responsivity will consider the on-chip power, corrected for grating-coupler losses.

Multiple PDs were fabricated, with sizes varying from $2\times12\,\mu m^2$ to $2\times20\,\mu m^2$. The characteristics of these PDs were measured and show a low dark current of 10 nA at -1 V bias, a responsivity up to 0.45 A/W and high 3-dB bandwidth of 155 GHz at -1 V bias, eight times higher the current state of the art[5]. Also at zero bias the PDs show a very high bandwidth of 135 GHz, making them even faster than their counterparts on silicon[3]. All further results are for a $2\times16\,\mu m^2$ PD with a responsivity of 0.3 A/W.

Experimental setup

To demonstrate the performance of the waveguide-integrated PD, a short-reach intensity modulation and direct detection (IM/DD) system is set up (Figure 2). At the transmitter, a 1550 nm continuous laser signal at a power of 15 dBm is modulated using a Mach-Zehnder Modulator (MZM) biased at quadrature point. The MZM has a 6-dB bandwidth of 45 GHz and a smooth frequency response roll-off. The electrical signal fed into the MZM is generated by an arbitrary waveform generator (AWG) with a 3 dB bandwidth of 65 GHz, and amplified by an 11 dB driver amplifier with 70 GHz 3-dB bandwidth. Pre-emphasis is applied up to 75 GHz, de-embedding the frequency response of the AWG and driver amplifier, while the frequency response of the MZM is left uncompensated. The optical power at the output of the MZM is 4 dBm. The modulated optical signal is then transmitted over 200 m single-mode fiber (SMF). At the receiver side, the optical signal is amplified to 23 dBm and passed through a 5 nm bandpass filter to suppress amplified spontaneous emission (ASE) noise. A polarization controller is placed at the input of the UTC PD due to the polarization dependence of the grating coupler. The optical power is 20 dBm at the input of the PIC containing the UTC PD. The grating coupler contributes to 9 dB insertion loss, yielding 11 dBm optical power at the PD. 1.75 mA photocurrent is obtained from the PD, which is then converted to voltage by the 50 Ω termination of a real-time oscilloscope with 84 GHz bandwidth (Figure 2). To evaluate the capability of the UTC PD to support high-speed optical signal detection, PAM signals with 2, 4 and 8 amplitude levels are transmitted at various symbol rates. In this work, the same transmitter and receiver digital signal processing (DSP) stacks as described in[6] are employed. Figure 2 shows the optical spectrum at the input of the PIC and the eye diagram obtained at the output of the receiver equalizer when a 144 GBd PAM-8 signal is transmitted.

Experimental results

To determine the achievable net bitrate, normalized generalized mutual information (NGMI) is first computed based on the histogram of the equalized signal[6]. The obtained NGMI as a function of symbol rate is shown in Figure 3(a). For practical forward error correction (FEC) schemes, NGMI thresholds exist, which indicate the lowest NGMI values required from a channel to ensure proper operation of the FEC scheme. In this work, we consider the same FEC scheme as described in[6], namely soft-decision tail-biting spatially-coupled low-density parity check codes concatenated with hard-decision Bose-Chaudhuri-Hocquenghem (BCH) code. Based on the NGMI thresholds available in[6], the code rate, c, can be determined. Afterwards, the net bitrate is calculated as $R_s H c$, where R_s is the symbol rate and H is the entropy of the PAM signal, and plotted in Figure 3(b).

The highest net bitrate is achieved by a PAM-8 modulated signal at 140 GBd. With an NGMI of 0.89 this results in a net bitrate of 354 Gbit/s. For PAM-4 modulation, the highest achieved net bitrate is 278 Gbit/s at 148 GBd (NGMI of 0.995). Up to 200 GBd PAM-2 transmission is successfully demonstrated. The highest net bitrate for PAM-2 is obtained at 180 GBd (NGMI of 0.94 and net bit rate of 161 Gbit/s).

Conclusion

Waveguide-coupled UTC photodiodes can be integrated on a SiN-platform by means of micro-transfer-printing. This heterogeneous approach delivers a high-performing photodetector with excellent bandwidth performance at 1550 nm. Over a short-reach optical link, net data rates exceeding 350 Gbit/s are achievable (at a line rate of 420 Gbit/s, i.e. PAM-8 at 140 GBd) and symbol rates up to 200 GBd is demonstrated with net bit rates of 150 Gbit/s (PAM-2). To the best of our knowledge, these are the highest data rates achieved with a SiN photodetector.

Acknowledgements

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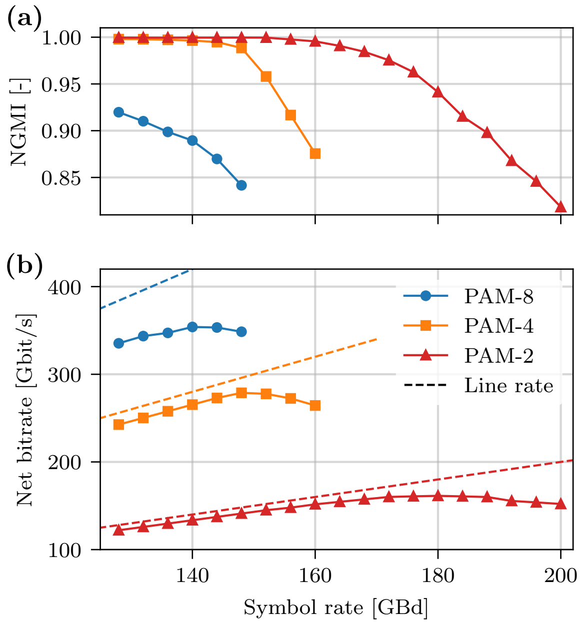

Fig. 3: (a) The normalized generalized mutual information (NGMI) for PAM-2, PAM-4 and PAM-8 results in **(b)** net bitrates in excess of of 350 Gbit/s (PAM-8 at 140 GBd). For PAM-2, symbol rates up to 200 GBd are achieved with a net bitrate beyond 150 Gbit/s.

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