PROCEEDINGS OF SCIENCE

Concept, design and verification of components for an integrated on-detector silicon photonic multi-channel transmitter

Yunlong Zhang*, Djorn Karnick, Marc Schneider, Lars Eisenblätter, Thomas Kühner, Marc Weber

Karlsruhe Institute of Technology, Institute for Data Processing and Electronics
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
E-mail: `zhang.yunlong@partner.kit.edu`, `djorn.karnick@kit.edu`, `marc.schneider@kit.edu`, `lars.eisenblaetter@kit.edu`, `thomas.kuehner@kit.edu`, `marc.weber@kit.edu`

The data throughput of future detector readout systems is ever increasing. To satisfy the requirements of ultra-broad bandwidth, we propose a high-performance optical link utilizing silicon photonics and wavelength division multiplexing. The key components are monolithically integrated transmitter units, each comprising Echelle grating (de-)multiplexers and Mach-Zehnder modulators. In this paper, we present the design and measurements of the building blocks as well as the first data transmission experiment.

Topical Workshop on Electronics for Particle Physics (TWEPP2018)
17-21 September 2018
Antwerp, Belgium

*Speaker

1. Introduction

Along with the continuous increase of detector readout channels in high energy physics and photon science, the number of readout channels will easily reach millions or billions [1]. As a result, a great amount of raw data will be generated every second [2]. Effective methods to cope with the data throughput are data compression and developing high bandwidth systems. But even with dramatic data compressing, current optical links cannot offer the required bandwidth.

Optical links in state-of-the-art detector systems are using vertical cavity surface emitting lasers (VCSEL) [3, 4] where a data rate of 10 Gbit/s per fiber is realized. While higher data rate systems are in development, radiation levels at the innermost part of future high energy physics experiments will be too high for the use of VCSELs [5].

We propose a novel solution based on wavelength division multiplexing (WDM) technology and radiation tolerant silicon photonics [6, 7]. In our design, laser sources are located off-detector to avoid irradiation. They generate optical carriers with different wavelengths which are combined and transmitted over one common single mode glass fiber (SMF) to a silicon-photonic transmitter chip inside the detector. An on-chip Echelle grating demultiplexes the different carriers to individual wavelength channels and forwards each to an individual electro-optic modulator. Processed electrical signals from the sensor elements are amplified and fed to the transmitter channels for optical transmission. The modulated optical carriers are combined again by an on-chip Echelle grating multiplexer and transmitted through an optical fiber to the counting room for further processing.

PoS(TWEPP2018)057

2. Integrated 4-channel WDM transmitter unit

Figure 1 shows our photonics chip with an on-chip size of 9.2×9.2 mm^2, including four WDM transmitter units (top-right corner), single modulators with different lengths and structures, Echelle grating (de-)multiplexers, thermal modulators, and other test structures. The chip is fabricated at IMS Chips (Institut für Mikroelektronik Stuttgart, Germany) on an SOI wafer with 220 nm top silicon. Each WDM transmitter unit is comprised of four Mach-Zehnder modulators (MZM), an Echelle grating demultiplexer, a multiplexer and several grating couplers. The dimension of one transmitter unit is 3.8×1.67 mm^2. Two of the units use 1×7 (de-)multiplexers and the other two units use 1×9 (de-)multiplexers. However, only four channels from these

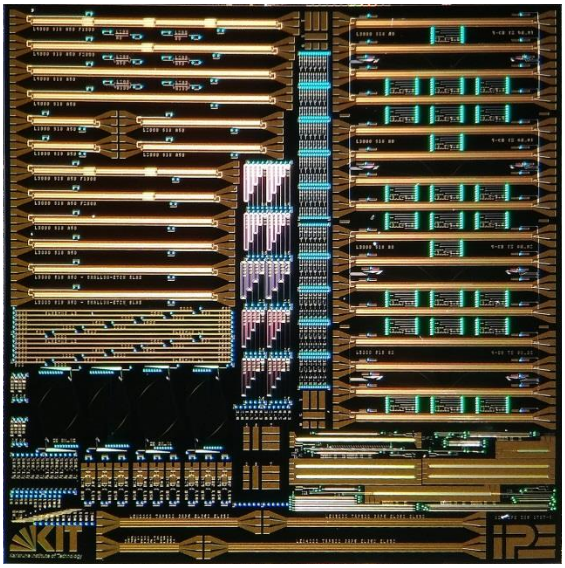

Figure 1: Photograph of a photonic system chip (9.2×9.2 mm²) with 4-channel WDM systems, single MZM, thermal modulators, Echelle gratings, and test structures.

(de-)multiplexers are in use for the WDM transmitters.

3. Transmitter unit components

3.1 Carrier-depletion MZM

We use carrier-depletion Mach-Zehnder modulators [8] in our design as they are mature, well-studied and broadband in terms of operating wavelengths. They consist of two phase shifters in the arms of a Mach-Zehnder interferometer. The phase shifters are vertical pn-junctions along the center of a rib waveguide utilizing the plasma dispersion effect for changing the refractive index with respect to the reverse voltage across the pn-junction. The width and height of the rib is 500 nm and 220 nm, respectively, the thickness of the slab for electrical contacting is 70 nm. The MZM arms are located in the gaps of a coplanar transmission line to achieve a push-pull configuration while driving the common center electrode. By combining the two optical paths, an amplitude modulation is achieved depending on the phase relation of the optical waves from the two MZM arms.

Although only 3 mm long modulators are used for the transmitter units, several individual MZMs with different shifter lengths are included on the chip to test the modulation efficiency. As can be observed from figure 2, longer shifters require less voltage for the same phase shift. A fabrication error led to too low doping concentrations and results in the presented low modulation efficiency. Nevertheless, it is feasible to approach a bias point around the quadrature point and usually a π phase shift is unnecessary.

Frequency response measurements of the modulators were made using a microwave signal generator Rohde & Schwarz SMB100A, a tunable laser Agilent 81689A, a photodetector New Focus 1014 and a spectrum analyzer Rohde & Schwarz FSW43. The bias voltages for the phase shifters were set to +1.0 V and -6.0 V respectively. Figure 3 shows the normalized frequency response after subtracting the losses. The curve shows a linear decrease with a slope of 0.58 dB/GHz and a 3 dB cut-off frequency of 5.15 GHz. The dominant reason for the low cut-off frequency is the aforementioned fabrication error. Besides, impedance mismatch between transmission line (25 Ω), generator, and load resistance (both 50 Ω) also contributes to this

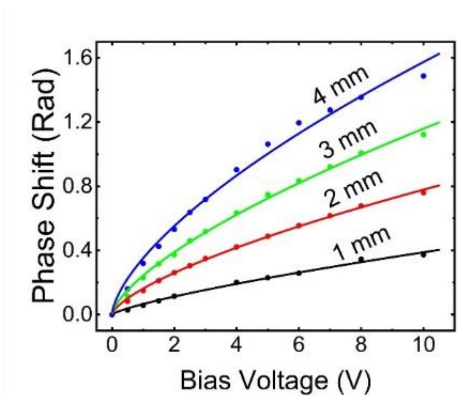

Figure 2: Phase shift versus bias voltage of an individual pn-junction phase shifter for different device lengths.

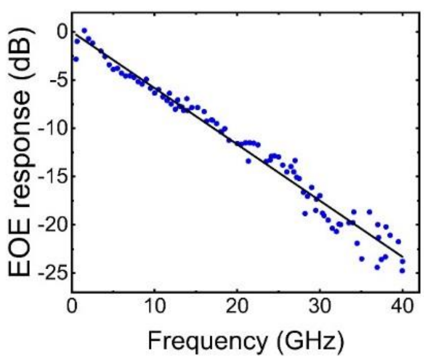

Figure 3: Frequency response of an MZM of an integrated WDM transmitter unit with 3 mm long phase shifters.

result.

A data transmission experiment at a wavelength of 1550 nm uses a single channel of the transmitter unit. The signal source was an Altera Stratix V GX FPGA board. Optimum bias voltages in this experiment were +2.1 V and -7.5 V respectively. The electrical signals from the FPGA were amplified to a voltage swing of 7 V_{PP} to drive the modulator. The electrical receiver output reached a voltage swing of 0.3 V_{PP}, as can be seen in figure 4. This signal was fed back to the FPGA for bit error rate (BER) measurements. We achieved an average BER of 1.7×10^{-9} for a 5.65 Gb/s PRBS-7 signal within 45 minutes, much less for shorter durations. With error-free doping, higher speeds and lower BER are highly expected.

3.2 Echelle grating (de-)multiplexer

The wavelength filter is a key component for a WDM system. We use Echelle gratings in our designs due to their advantages over arrayed waveguide gratings like their tolerance on edge roughness, their low loss and small chip size.

Two slightly different designs of Echelle grating (de-)multiplexers were implemented for the transmitter units on our chip. While the (de-)multiplexers exhibit seven and nine channels, only four of them are in use for the transmitter unit with an unused channel between each used one. The required parameters to construct the Echelle grating (de-)multiplexers using the Rowland circle method [9] are channel spacing, diffraction order, radius of the Rowland circle, length of the grating, input angle and output angle. We set them to be 3.19 nm, 9, 600 µm, 500 µm, 53° and 51°, respectively, to get the layout of the 1×9 Echelle grating (de-)multiplexers with an on-chip size of 1350 µm×670 µm. Omitting the outer two channels, we got the layout of 1×7 (de-)multiplexer.

The transmission spectrum of each wavelength channel was measured in the range of 1524 nm to 1576 nm and the result is shown in Figure 5. According to our measurement, the average optical loss is around 4 dB, the maximum crosstalk between adjacent channels -15 dB. It can also be observed that the left sides of the transmission peaks are not as smooth as expected and show notches. This result seems due to the individual combination of diffraction order and non-optimum gratings design. This will be optimized in future designs, but has no

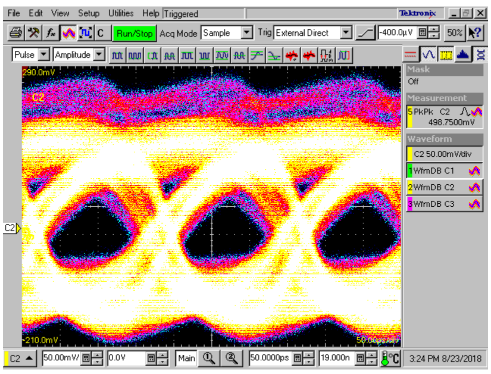

Figure 4: Eye diagram of one 4-channel integrated WDM transmitter at a bit rate of 5.65 Gbit/s.

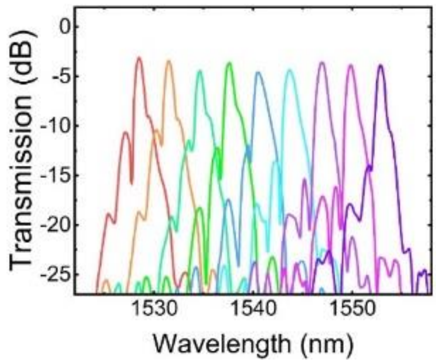

Figure 5: The transmission spectrum of a 1×9 demultiplexer of an on-chip integrated WDM transmitter unit.

negative impact for the transmitter unit.

4. Conclusion and Outlook

In this paper we present a novel silicon photonic, monolithically integrated WDM transmitter together with the experimental results on key components of the system. The measured cut-off frequency of the transmitter unit MZMs is 5.15 GHz due to a fabrication error. We demonstrated a transmission at the data rate of 5.65 Gb/s for one transmitter channel with a BER of 1.7×10^{-9}. The Echelle grating demultiplexers are efficient with an average optical loss of 4 dB, the crosstalk between adjacent channels is -15 dB, while between practically exploited adjacent channels is less than -20 dB. The presented results in this paper confirm that the proposed ultra-broadband data transmission scheme is feasible and is a promising solution for future detector instrumentation.

Acknowledgements

This research is supported by the program Matter and Technology of the Helmholtz Association, Germany and the China Scholarship Council (CSC), China.

References

[1] L. Rossi et al., *High Luminosity Large Hadron Collider A description for the European Strategy Preparatory Group*, CERN-ATS-2012-236 (2012).

[2] P. Baldwin and M. Gaillard. (2016). CERN's IT gears up to face the challenges of LHC Run 2. [Online]. Available: http://cerncourier.com/cws/article/cern/65031.

[3] F. Vasey, Optical links for LHC: experience from the CMS project and future prospects, in 10th Workshop on Electronics for LHC and Future Experiments, September 2004, p. 31.

[4] CMS collaboration, The versatile link, a common project for super-LHC, 2009 JINST 4 P12003.

[5] J. Troska et al., "Radiation damage studies of lasers and photodiodes for use in multi-Gb/s optical data links," IEEE Trans. Nucl. Sci., vol. 58, no. 6, pp. 3103–3110, Dec. 2011.

[6] P. Skwierawski et al., A silicon photonic wavelength division multiplex system for high-speed data transmission in detector instrumentation, 2016 JINST 11 C01045.

[7] D. Karnick, P. Skwierawski, M. Schneider, L. Eisenblätter and M. Weber, "Optical links for detector instrumentation: on-detector multiwavelength silicon photonic transmitters," J. Instrum., vol. 12, p. C03078, Mar. 2017.

[8] J. Ding, H. Chen, L. Yang, L. Zhang, R. Ji, Y. Tian, W. Zhu, Y. Lu, P. Zhou, R. Min, and M. Yu, "Ultra-low- power carrier-depletion Mach–Zehnder silicon optical modulator," Opt. Exp., vol. 20, no. 7, pp. 7081–7087, 2012.

[9] R. J. Lycett, D. F. G. Gallagher, and V. J. Brulis, "Perfect chirped echelle grating wavelength multiplexor: Design and optimization," IEEE Photon. J., vol. 5, no. 2, Apr. 2013, Art. ID 2400123.