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Ultra-Compact 0.8 Tbit/s Plasmonic Modulator Array

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Abstract *A new plasmonic interconnect solution offering 0.8 Tb/s on a 90×5.5 µm^2 footprint is introduced. The interconnect comprises of a 4 channel plasmonic modulator array that directly interconnects a fiber array.*

Introduction

Future optical interconnect technologies need transceivers with a high level of parallelism on an ultra-small footprint, offering highest bandwidths at lowest possible power consumption [1-5]. Such interconnect solutions are of interest for high-performance computing, inter- and intra-data center connections – and if quality permits even for larger communications networks [5].

Currently, the challenge is neither in fiber technology – as fiber arrays, multicore [6] and multimode fibers [7] already offer highest densities – nor on the detector side – as photodiodes do not require large footprints. Instead, the challenge is on the transmitter footprint where either sources or modulators occupy a large space. Miniaturization of the transmitters would therefore be a commendable goal. VCSEL are respected as a compact solution – 39 µm pitch multicore fiber and on-chip interconnect solutions have already been convincingly demonstrated [8, 9]. However, VCSELs are inherently bandwidth limited and the direct modulation limits the applicability for longer distances [5]. Higher modulation bandwidths can be achieved with external modulators. For instance, ring modulators have already shown remarkable compact footprints of 6×5 µm^2 in photonics [10] and more recently of 4×4 µm^2 in plasmonics [11]. However, ring modulators are resonant structures and thus limited in bandwidth. In addition, the footprint in these external modulator concepts is typically governed by couplers and waveguides. A novel solution offering a most compact footprint with the advantages of the large bandwidth of an external modulator would therefore be of highest interest. Recently, a high-speed all-metallic Mach-Zehnder modulator was introduced. This device features a short length of 36 µm [12].

In this paper, a novel plasmonic modulator array concept is introduced. The plasmonic modulators are as short as 12 µm and feature built-in couplers and modulation sections. In a modulator array arrangement, 0.8 Tbit/s data modulation on 90×5.5 µm^2 is demonstrated. The array is composed of four plasmonic phase modulators, each transmitting 200 Gbit/s, being optically connected through a 12 µm pitch fiber array.

Concept

The plasmonic array interconnect is composed of four densely arranged ultra-compact, high-speed modulator channels, see Fig. 1. The device pitch of only 24 µm allows the densest arrangement of high-speed data channels enabled by current fiber array technology. This leads to a record-low footprint of 90×5.5 µm^2 to transmit 0.8 Tbit/s.

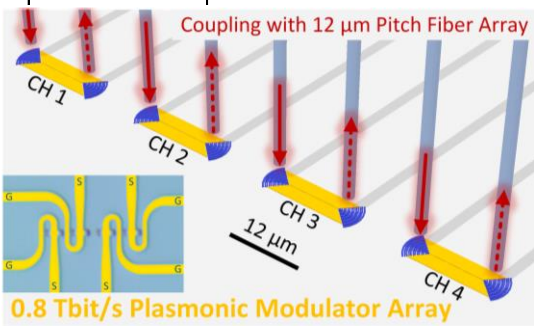
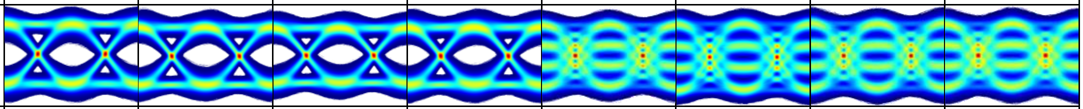


Fig. 1: Layout of four channel plasmonic modulator array. Each channel is composed of an input coupler, a 9 µm plasmonic modulator and an output coupler. The full array is ultra-compact, directly interfaces the 12 µm pitch fiber cores and transmits 0.8 Tbit/s. The inset shows a colorized microscope image of the transmitter.

A single, 9 µm short modulator occupies an area of only 17×5.5 µm^2, including the fiber-to-chip coupling using an optical fiber array with 12 µm pitch. The device comprises a high-index silicon grating coupler converting perpendicularly incident fiber mode directly into an on-chip plasmonic slot mode. This novel design advantageously combines photonics and plasmonics, making photonic waveguides and photonic-plasmonic converters obsolete and hence minimizing the insertion loss. The only 9 µm short plasmonic section provides strong high-speed modulation.

The arrays have been fabricated with in-house cleanroom technology as described in [6]. As

Tab. 1: 100 GBd single-channel data modulation experiment. The experiment was carried out at a wavelength of 1550 nm with optical input power of 0.5 dBm for BPSK or 4.5 dBm for 4-PSK. For BPSK, all four channels transmitted 100 Gbit/s with ~15 dB SNR and BERs below 10^{-5}. For 4-PSK, 200 Gbit/s per channel were demonstrated at SNR values around 14 dB and BERs below $1.50 \cdot 10^{-2}$. The SNR was determined from the received and synchronized data.

PSK	BPSK				4-PSK			
Bitrate	100 Gbit/s				200 Gbit/s			
Channel	1	2	3	4	1	2	3	4
Eye Diagram								
SNR	14.96	15.30	14.83	14.55	13.76	14.40	13.75	13.40
BER	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	$1.25 \cdot 10^{-2}$	$0.84 \cdot 10^{-2}$	$1.23 \cdot 10^{-2}$	$1.50 \cdot 10^{-2}$

nonlinear material, the organic electro-optic material HD-BB-OH/YLD124 was used [13].

Optical fiber-to-fiber transmission of -15 dB have been found for single devices. Transmission losses in the array were 21±0.5 dB for all devices at 1550 nm. The losses can be attributed to plasmonic propagation loss in the 55 nm narrow slot (7 dB), fiber array insertion loss (about 1 dB) and fiber-to-slot coupler (6.5 dB per coupler).

Single Channel Performance

The individual plasmonic interconnect channels were tested for high-speed data transmission with 100 GBd phase shift keying (PSK).

Data modulation experiments were carried out for each channel separately, see results in Tab. 1 and setup in Fig. 3. Electrically, 100 GBd BPSK and 4-PSK NRZ signals were generated with a Micram DAC4 to drive the plasmonic modulators contacted by RF probes. For 4-PSK, a pre-distortion of the electrical signal was applied. Low optical input power of 0.5 dBm for BPSK and 4.5 dBm for 4-PSK was sufficient to achieve data transmission of 100 Gbit/s below the KP4 FEC limit [14] and 200 Gbit/s below the SD-FEC limit [15], respectively. Tab. 1 compares the four array channels. Very consistent performance was demonstrated, which makes plasmonic modulator arrays a viable option for large scale parallelization. Subsequently, channel 3 (CH 3) is chosen as a representative worst-case channel as it sits between two neighboring devices.

Electrical and Optical Crosstalk

For parallel operation of all four channels, both electrical and optical crosstalk should be minimal.

Electrical crosstalk in CH 3 was measured and found to be below -50 dB from channel 2 (CH 2) and below -40 dB from channel 4 (CH 4), see Fig. 2A). The slightly higher crosstalk from CH 4 can be explained by an RF line passing between the channels. Similar experiments have been performed with other modulators confirming low electrical crosstalk. In any case, the crosstalk is below the amplified spontaneous emission (ASE) noise floor of low-noise erbium-doped fiber amplifiers (EDFA) and can be neglected.

Optical crosstalk in CH 3 was measured to be -26.0 dB from CH 2 and -18.4 dB from CH 4, see Fig. 2B). The increased crosstalk from CH 4 is due to the proximity of its input core to CH 3 output core. The optical crosstalk led to an SNR penalty below 1.1 dB with respect to single channel operation.

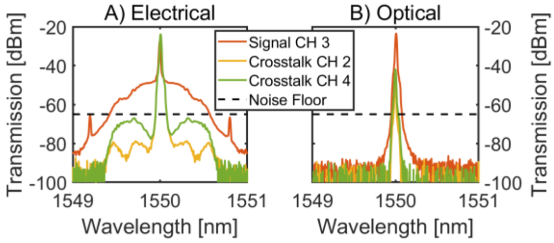


Fig. 2: A) Electrical crosstalk from the two neighboring channels compared to the signal in the central channel 3. The crosstalk is below the ASE noise of a low-noise EDFA (dashed line) and therefore negligible. B) Optical crosstalk of -26.0 and -18.4 dB from channel 2 and 4, respectively. This leads to about 1.1 dB electrical SNR penalty.

Plasmonic Array Interconnect Experiment

Parallel operation of the plasmonic array interconnect channels at 200 Gbit/s per channel was demonstrated with the same experimental setup as before (Fig. 3). A multi-channel RF probe and a fiber array were used to operate three channels simultaneously. Three signals built from randomly generated bits were driving the modulators, which were operated at telecom wavelength with 4.5 dBm optical input power. After modulation, all channels were coupled back to the fiber array and fed to the receiver, where the signal was amplified, filtered and detected in a coherent homodyne detection scheme. While direct detection is often preferred for simplicity and low-cost, we use coherent detection as a proof of concept. In an offline DSP step, signal recovery and equalization were performed to retrieve the sent signal.

100 GBd data modulation experiments were carried out and 100 Gbit/s BPSK and 200 Gbit/s 4-PSK were transmitted below the KP4- and the SD-FEC limit, respectively. The central channel (CH 3) was chosen as reference for the investigation. Fig. 3A) shows the single channel performance for comparison.

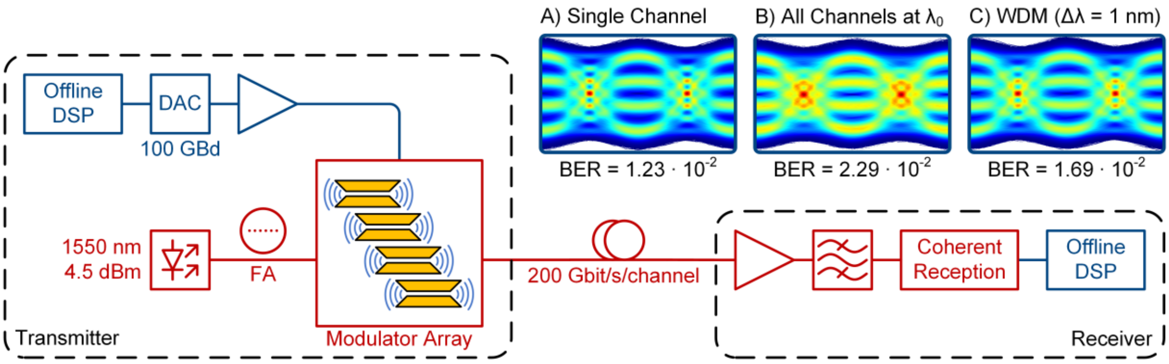


Fig. 3: Schematic of the experimental setup used for the array demonstration. At the transmitter, independent 100 GBd electrical signals are simultaneously driving the plasmonic modulators in the array. A 12 µm pitch fiber array (FA) is used to couple the optical carriers at λ_0 = 1550 nm into and out of the plasmonic modulator. At the receiver, the optical signal is amplified and filtered before being detected by a coherent detection scheme. Offline DSP is applied for signal recovery and equalization. A) Channel 3 with the other channels turned off. B) Channel 3 operation with all channels running at the same wavelength λ_0 for mimicking SDM. The BER remained below the SD-FEC limit for 200 Gbit/s 4-PSK (SNR penalty of 1.1 dB). C) WDM operation with a 1 nm wavelength spacing. Single channel performance is almost retained (SNR penalty of 0.5 dB).

Space division multiplexing (SDM) is the most straightforward application of the suggested high-density transmitter as it minimizes additional system complexity. An operation wavelength λ_0 of 1550 nm was used for all channels. For 100 GBd BPSK, a BER below 10^{-5} and an SNR of 14 dB were measured. For 100 GBd 4-PSK, the measured BER was $2.29 \cdot 10^{-2}$ with an SNR of 12.64 dB, see Fig. 3B). Since electrical crosstalk was found to be negligible, the SNR penalty of 1.1 dB can be attributed to optical crosstalk. Nevertheless, the data experiment shows that crosstalk is no limiting factor.

Wavelength division multiplexing (WDM) is a further application scenario for such densely integrated interconnects. All channels are combined for a single fiber link between transmitter and receiver. To emulate such a scenario, the array channels were operated with a wavelength spacing Δλ of 1 nm. 200 Gbit/s were transmitted with a BER of $1.69 \cdot 10^{-2}$ and an SNR of 13.2 dB. The reduced optical crosstalk allowed almost single channel performance.

In summary, we demonstrated a plasmonic array interconnect with 4×200 Gbit/s data transmission, operational with SDM or WDM.

Conclusions

This works demonstrates extremely dense integration of four plasmonic modulator channels for optical interconnects. 0.8 Tbit/s were transmitted on only 90×5.5 µm². For future 2-dimensional realizations on hexagonal grids, a data density of 800 Tbit/s/mm² can be envisioned. Furthermore, such a compact device concept enables new options for dense co-integration with electronics.

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