Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

D 6.4 – Report on plasmonic chip-to-chip interconnect prototype testing and evaluation

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Executive Summary

In this task, a simple but complete SiP for a chip-to-chip interconnect is demonstrated. Light from an external laser is fed to an array of four plasmonic modulators. All four modulators are driven with electrical signals after amplification on an electrical board. On the receiver side, IMEC's conventional Si-Ge photodiodes are used to make the optical to electrical signal conversion. The electrical signals after the photodiodes are amplified with the transimpedance amplifiers. The optical link between transmitter and receiver is realized through multicore fibers. Each component was tested independently before assembly. The final chip-to-chip interconnect operated successfully at 20 Gbit/s.

Change Records

Version	Date	Changes	Author
1 (submission)	2015-08-03		Claudia Hoessbacher

Introduction

The envisioned chip-to-chip plasmonic interconnect is shown in Fig. 1. Light from an external laser is fed to an array of four plasmonic modulators. All four modulators are driven with electrical signals after amplification on an electrical board. IMEC's Si-Ge photodiodes are used to make the optical to electrical signal conversion. The electrical signals after the photodiodes are amplified with the trans-impedance amplifiers. The optical link between transmitter and receiver is realized through multicore fibers.

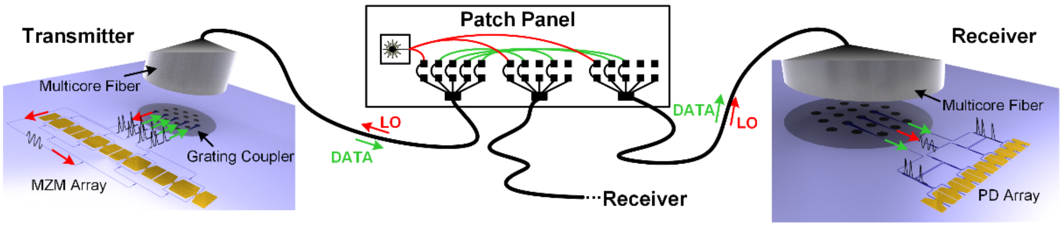

Fig. 1 Compact plasmonic interconnect scenario. A central laser is distributed by a multicore fiber (MCF) to integrated plasmonic transmitters (Tx) and receivers (Rx). The Tx encodes several data streams onto the central laser. Each signal from the modulator is transmitted in another core of the MCF and fed to the central patch panel from where it is distributed to the Rx.

Optical link between transmitter and receiver

The optical link between transmitter and receiver shall provide minimum light loss and the possibility to place an additional optical amplifier between the two chips. This link is a particular challenge, due to the fact that the distance between the optical channels is only 50 µm. In deliverable 6.2, the consortium decided to use a multicore fiber (Chiral Photonics, PROFA) as shown in Fig. 2. The multicore fiber consists of 19 channels with a pitch of 50 µm where we use four for our system demonstrator. Transmission measurements showed a power penalty compared to standard single mode fibers of less than 1 dB. To investigate the optical crosstalk, we fed 4 different wavelengths through 4 different channels of the MCF, while coupling to standard silicon waveguides. The optical output spectrum of each channel was recorded using an optical spectrum analyser. The optical interchannel crosstalk was found to be better than -31 dB in all instances, Fig. 2 (c).

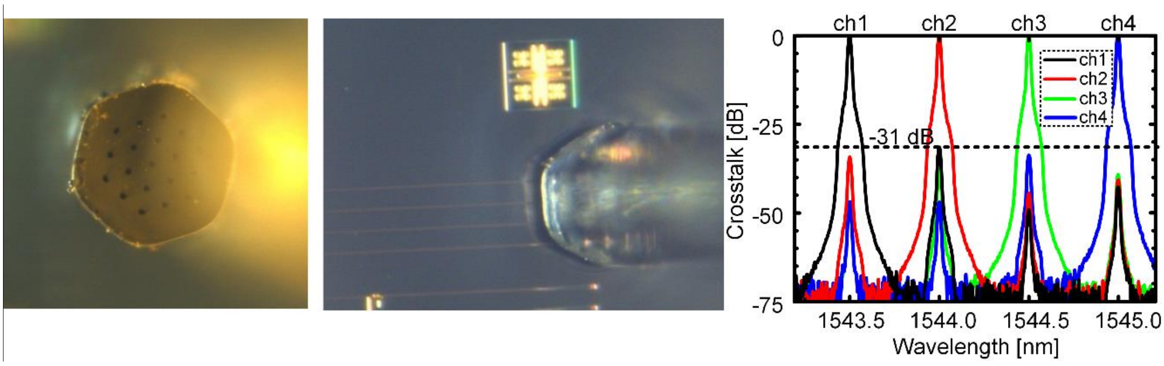

Fig. 2 Multicore fiber: (left) facet with 19 channels; (middle) top view when coupling to four channels on chip. (right) Optical interchannel crosstalk below -31 dB for four channels. The spectra were obtained by coupling four different wavelengths to the multicore fiber.

Transmitter

Navolchi's transmitter consists of a plasmonic modulator array integrated with its driving electronics in a single package. The plasmonic modulator array is described in detail in D6.3. Details to the driving electronics are described in the following.

Driver amplifiers

Main challenges concerning the driving electronics are: Firstly, the high frequencies require high precision alignment and K-connectors in order to minimize electrical crosstalk. Secondly, a high thermal density is expected due to the RF amplifiers that is addressed by a cooling unit below the transmitter. As shown in Fig. 3(a), a first prototype electrical board was fabricate where we used SMA-connectors (limited to 10 GHz) and a single RF amplifier to simplify fabrication. First tests on the electrical characteristics showed up to 24 dB gain at 1 GHz.

For the final transmitter, a customized copper housing was fabricated to assemble the plasmonic and electronic components, see Fig. 3(b). Electrical wire bonding interconnected the electronic board with the plasmonic modulator array. To minimize the length of the wirebonds, the plasmonic chip was placed in a cavity in the middle of the housing, while providing two RF signals from each side. On the board the signal was amplified by four RF amplifiers. The data signal was fed to the electronic board via high-speed K-connecters at the edge of the housing. As an external heat sink, a copper block was placed below the transmitter. It further adjusted the height to our characterization setup. To allow for easy testing, PCB and housing were not minimized in size.

Before integrating the driving electronics with the plasmonic modulators, the amplifiers were tested using RF probes at the output. S-Parameter measurements are shown in Fig. 4. The amplifiers provide >20 dB gain up to 20 GHz while the input reflection is below -6 dB in all instances. In addition, data experiments were carried out at 10 Gbit/s and 20 Gbit/s (PRBS 15, 500 mV_{pp} input signal) showing open eye diagrams for all amplifiers.

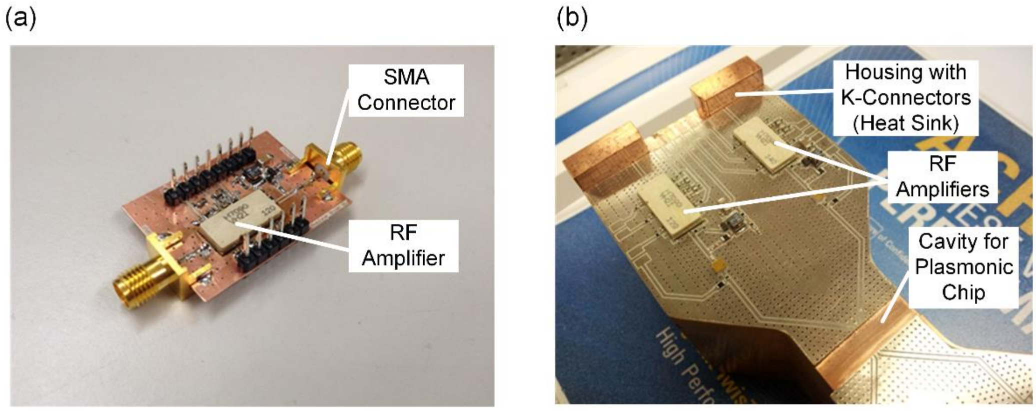

Fig. 3 (a) Prototype of the transmitter electronic board. (b) Final board for the transmitter with RF amplifiers and cavity for the plasmonic chip. The housing provides high-speed K-connectors and an external heat sink.

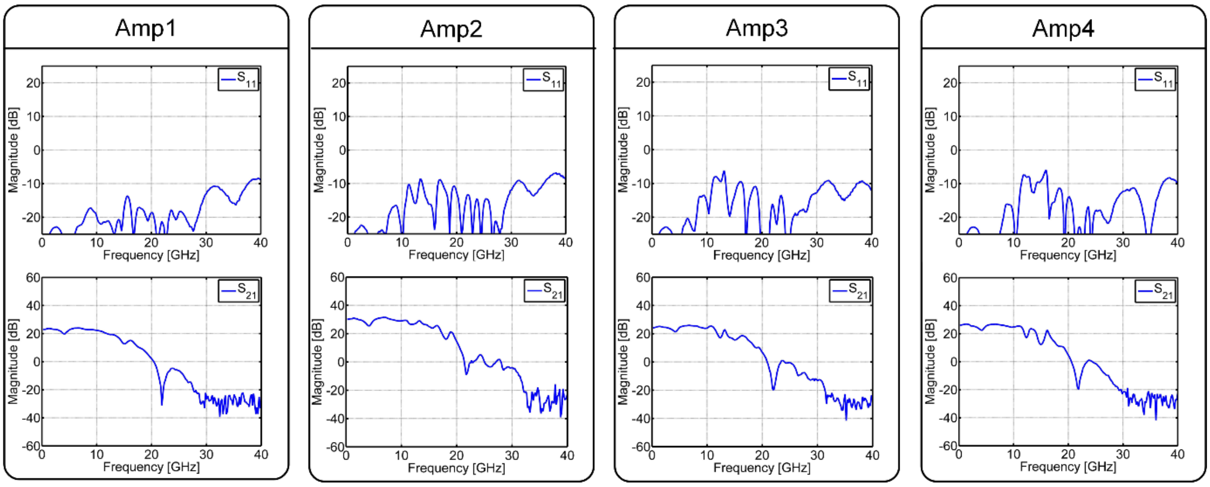

Fig. 4 S-Parameters (input reflection S11 and gain S21) for the four amplifiers on the PCB before bonding to the plasmonic modulators. The signals were measured with RF probes at the output of the amplifiers. The amplifiers provide >20 dB gain up to 20 GHz while the input reflection is below -6 dB in all instances.

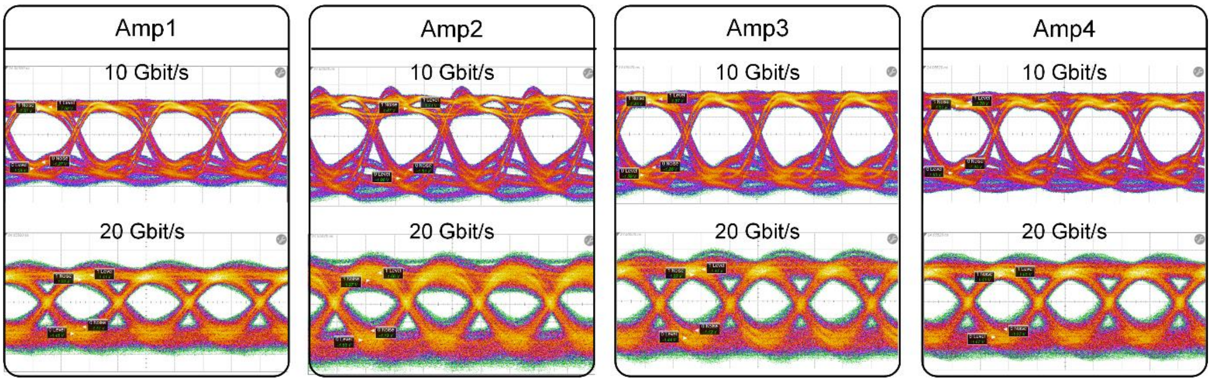

Fig. 5 Eye diagrams at 10 Gbit/s and 20 Gbit/s for the four amplifiers on the PCB before bonding to the plasmonic modulators**.**

Plasmonic modulator array integrated with driver amplifiers

In a next step, the plasmonic modulators were integrated with their driving electronics in a single package as shown in Fig. 6(a). A multicore fiber (MCF) and a standard single mode fiber (SMF) were used as an optical input and output, respectively.

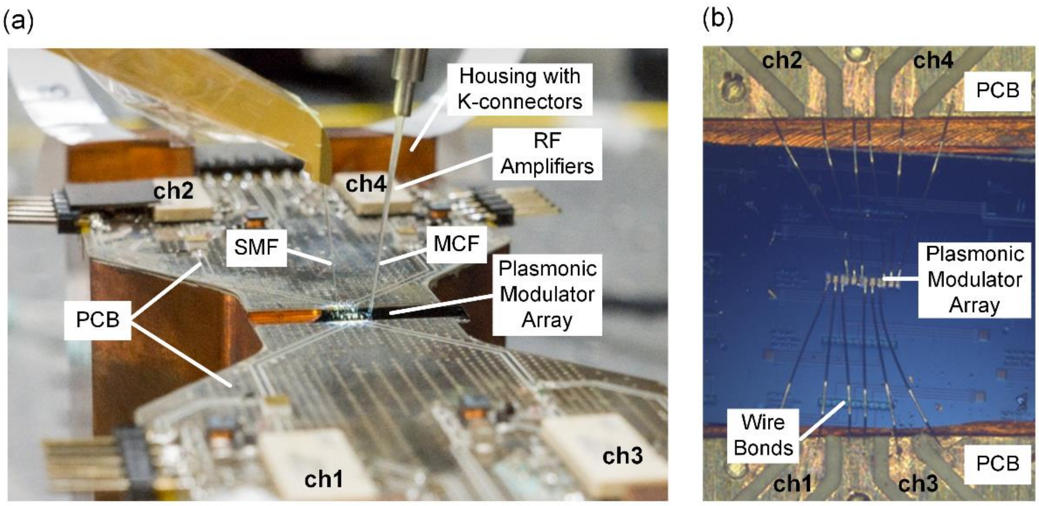

Fig. 6 Transmitter. (a) Customized package with plasmonic modulator array and PCB containing driving electronics. (b) Plasmonic modulators wirebonded to the PCB.

The applicability plasmonic transmitter in communication systems was verified by data modulation experiments. Data signals with binary phase shift keying (BPSK) at 10 Gbit/s were generated. Four CW laser sources (1549.3 nm to 1551.9 nm, $\Delta\lambda \approx 1$ nm) were coupled to the array via the MCF. Two digital-to-analog converters (72 GSa/s, 6 bit) generated uncorrelated, differential signals D1 and D2 (pulse shape: square-root-raised cosine, roll off $\alpha = 1$) with De Bruijn bit sequences (DBBS 11). $D_1, D_2, \overline{D}_1$, and $\overline{D}_2$ were fed to the single ended transmitter. The four channels were received sequentially with a standard single mode fiber in a coherent receiver. Pre-distortion and post-equalization of the electrical signal was used to mitigate the frequency dependence of the RF amplifiers and the DACs. Fig. 8 depicts the measured optical eye diagrams and constellation diagrams for all four channels at 10 Gbit/s. All channels have bit error ratios (BERs) below the FEC limit of 2×10^{-3} (7 % overhead); no error was detected within the 10 million recorded bits for channel 1 and 3.

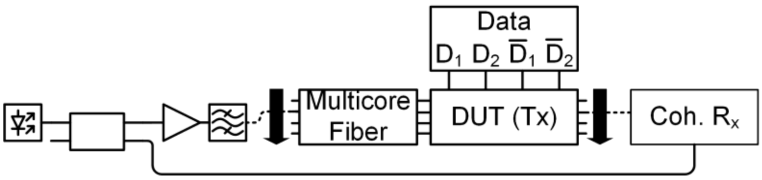

Fig. 7 Experimental setup for data modulation experiments. Laser light at different wavelengths ($\Delta\lambda \approx 1$ nm at $\lambda \approx 1550$ nm) was amplified and coupled via a multicore fiber to the transmitter (Tx). Four electrical data streams were fed to the Tx by two independent DACs. The modulated light of the channel under test was received by a coherent receiver. The laser source was also used as local oscillator in the receiver.

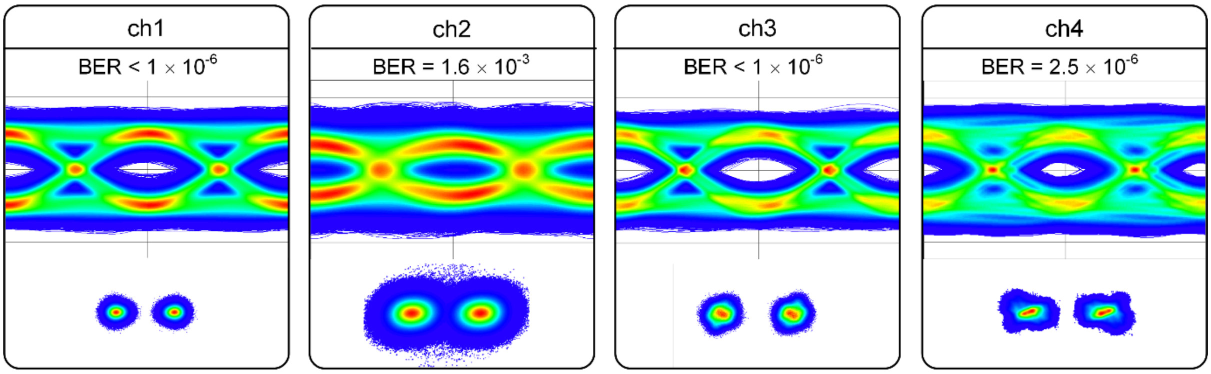

Fig. 8 Optical eye and constellation diagrams with bit error ratios (BER) of the data experiments (BPSK) at data rates of 10 Gbit/s. All four channels have a BER below the FEC limit of 2×10^{-3}.

Receiver

On the receiver side, IMEC's Si-Ge photodiodes (PD) were used and wire bonded to a 4 channel 28 Gb/s transimpedance limiting amplifier (TIA) array, see Fig. 9. The photonic and electronic components were assembled on an evaluation board. To minimize the length of the wirebonds, the photonic chip was diced close to the contact pads and placed in proximity to the electronic chip. Channel 2 could not be bonded, though, since the arrangement of the anode and cathode contact pads on the optical and the electronic chip did not perfectly match. The optical signal was coupled in via a standard single mode fiber.

The receiver was tested in data experiments as shown in Fig. 10. Data signals with Non-Return-to-Zero (NRZ, rectangular) at 28 Gbit/s were generated by an arbitrary waveform generator and a commercial modulator at 1550 nm wavelength. The three channels were tested sequentially with a standard single mode fiber. The signal was recorded with a digital communication analyzer. TIA settings were optimized for high quality factors and low jitter. Fig. 11 depicts the measured optical eye diagrams and quality factors for the three channels. The eye diagrams are convincingly open.

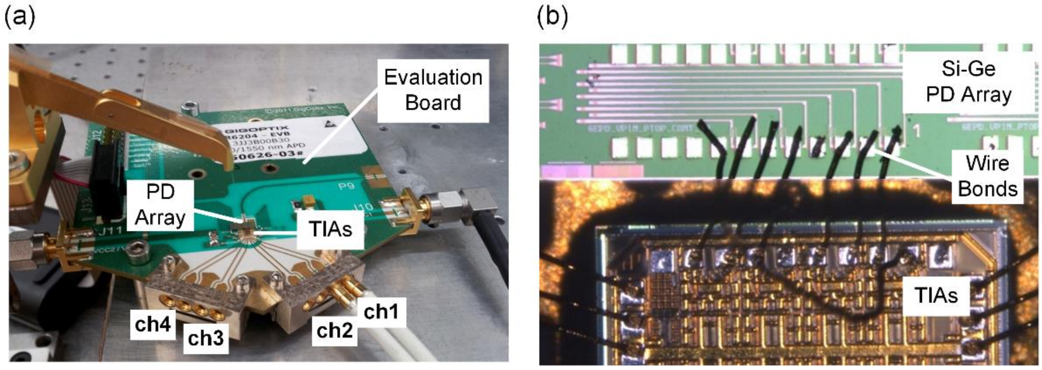

Fig. 9 Receiver **(a)** Evaluation board with Si-Ge photodiode array and PCB containing electronics. **(b)** Photodiodes wirebonded to the PCB. Channel 2 could not be bonded, since the arrangement of the anode and cathode contact pads on the optical and the electronic chip did not perfectly match.

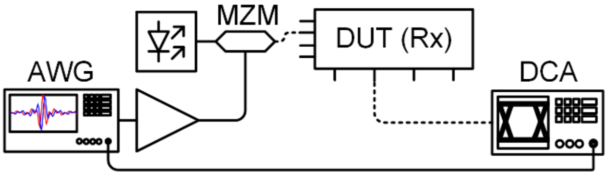

Fig. 10 Experimental setup for data modulation experiments. Laser light at 1550 nm was coupled to a commercial Mach-Zehnder modulator (MZM). Electrical data streams were generated by an arbitrary waveform generator (AWG) and amplified, before being sent to the MZM. The modulated light was sent to the channel under test of the receiver (Rx). The received signal was measured with a digital communication analyser (DCA).

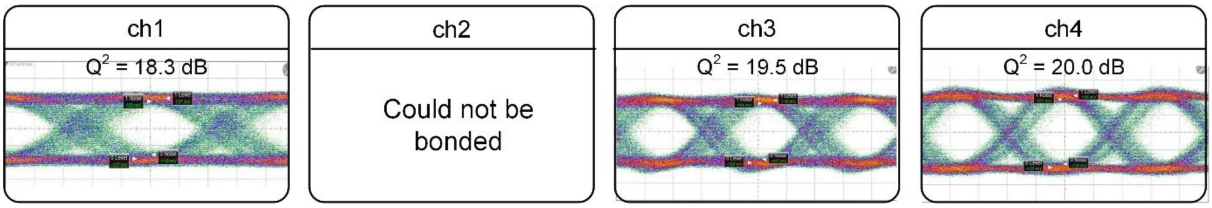

Fig. 11 Optical eye diagrams with quality factor (Q^2) of the data experiments (NRZ, rectangular) at data rates of 28 Gbit/s. Channel 2 could not be bonded (see **Fig. 9**), so no data experiment was carried out. Channel 2,3,4 show open eye diagrams.

Chip-to-chip interconnect

In a final step, transmitter and receiver were tested as a full chip-to-chip interconnect, see Fig. 12. Since time at the end of the project was very limited, only one channel is shown here as an example. The chip-to-chip interconnect successfully operated at 20 Gbit/s with a BER of 7.9×10^{-5}.

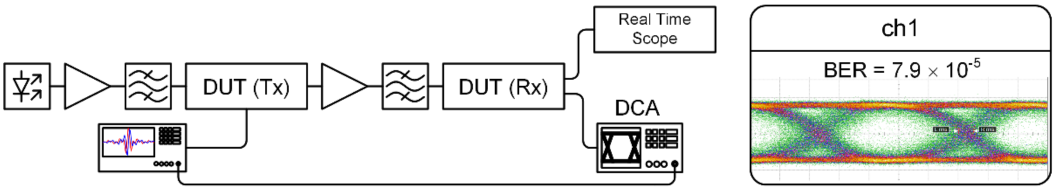

Fig. 12 (a) Experimental setup for data modulation experiments of the full chip-to-chip interconnect. Laser light at 1547.8 nm was coupled to the transmitter shown in **Fig. 6**. Electrical data streams were generated by an arbitrary waveform generator (AWG) and sent to the channel under test of the transmitter. The modulated signal was amplified and sent to the receiver (see **Fig. 9**). At the receiver output, eye diagrams were measured with a digital communication analyser (DCA), while the bit error ratios were obtained with a real time scope. (b) Optical eye diagram of the data experiment (NRZ, rectangular, DBBS 15) at data rates of 20 Gbit/s for Channel 1 as an example.