Active Plasmonics in True Data Traffic Applications: Thermo-Optic ON/OFF Gating Using a Silicon-Plasmonic Asymmetric Mach–Zehnder Interferometer

Dimitrios Kalavrouziotis, Sotirios Papaioannou, Konstantinos Vyrsokinos, Ashwani Kumar, Sergey I. Bozhevolnyi, Karim Hassan, Laurent Markey, Jean-Claude Weeber, Alain Dereux, Giannis Giannoulis, Dimitrios Apostolopoulos, Hercules Avramopoulos, and Nikos Pleros

***Abstract*—We present the first system-level demonstration of an active plasmonic device in 10-Gb/s data traffic conditions. An asymmetric silicon-plasmonic Mach–Zehnder interferometer with dielectric-loaded plasmonic waveguides serving as the electrically controlled arms, operates as thermo-optic ON/OFF gating element with 2.8-μs response time and 10.8-mW power consumption.**

***Index Terms*—Active plasmonics, dielectric-loaded surface plasmon polaritons, Mach–Zehnder interferometer, silicon-on-insulator photonics, thermo-optic switch.**

I. INTRODUCTION

THE need for low-energy and high-bandwidth connectivity in datacom and computercom environments has turned photonics into a promising candidate for short-range and even for chip-scale communications [1]. Profiting from the remarkable progress witnessed in the area of photonic integration, the roadmap of optical interconnects extends currently along the entire range of optically enabled functions: passive optical waveguides, active transceiver circuitry as well as optical routing structures for photonic Network-on-Chip implementations [2]. Hybrid on-chip opto-electronic routing fabrics with optical switching elements controlled by electronic signals have been already shown to provide significant power consumption and performance benefits [2], taking advantage of the high-capacity attributes of optics and of the enhanced processing capabilities of electronics for carrying out "intelligent" controlling operations.

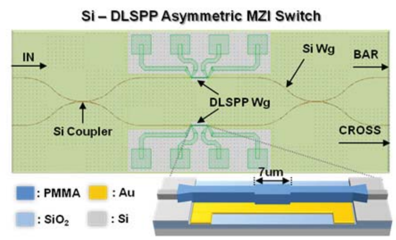

Fig. 1. Si-DLSPP asymmetric MZI switch and widened plasmonic waveguide.

In this perspective, the discipline of plasmonics has raised a great promise for additional energy consumption savings: Surface Plasmon Polariton (SPP) waveguides support light propagation along metallic stripes, offering in this way a natural and energy-effective interface for electronic and optical signal interaction [3]. A suitable mechanism for transforming the electronic control signal into switched light-paths is via the utilization of the thermo-optic (TO) effect, which has been already proposed for the deployment of high-capacity and energy-effective routing architectures for interconnect purposes [4]. In the area of silicon photonics, TO-based switching has been heavily researched during the last years [5-8] with most of the work having been devoted to the Mach-Zehnder Interferometric (MZI) type of thermo-optic switch arrangements due to their wavelength-insensitive and consequently broadband operational properties. In the area of plasmonics, however, only a limited number of TO control demonstrations [9-13] have been reported so far, all of them exploiting the Dielectric-Loaded SPP (DLSPP) waveguide platform but still not concluding to a solid proof of their low switching energy promises in true data traffic conditions. Dynamic ON/OFF switching operation has been presented only through the heterointegration of DLSPP structures on a MgF_2 substrate, with energy consumption and time response metrics being in the order of hundreds of mWs and a few ms, respectively [9].

Manuscript received December 23, 2011; revised March 5, 2012; accepted March 6, 2012. Date of publication March 19, 2012; date of current version May 10, 2012. This work was supported in part by the European FP7 ICT-PLATON ICT- STREP 249135 Project.

D. Kalavrouziotis, G. Giannoulis, D. Apostolopoulos, and H. Avramopoulos are with Photonics Research Communications Laboratory, School of Electrical and Electronic Engineering, National Technological University of Athens, Athens 15773, Greece (e-mail: dkalav@mail.ntua.gr; jgiannou@mail.ntua.gr; apostold@mail.ntua.gr; hav@mail.ntua.gr).

S. Papaioannou and N. Pleros are with the Department of Informatics, Aristotle University of Thessaloniki – Informatics and Telematics Institute, Center for Research and Technology Hellas, Thessaloniki 57001, Greece (e-mail: sopa@csd.auth.gr; npleros@csd.auth.gr).

K. Vyrsokinos is with the Informatics and Telematics Institute, Center for Research and Technology Hellas, Thessaloniki 57001, Greece (e-mail: kv@iti.gr).

A. Kumar and S. I. Bozhevolnyi are with the Faculty of Engineering/Institute of Sensors, Signals and Electrotechnics, University of Southern Denmark, Odense 5230, Denmark (e-mail: asku@iti.sdu.dk; seib@sense.sdu.dk).

K. Hassan, L. Markey, J.-C. Weeber, and A. Dereux are with the Institute Carnot de Bourgogne, University of Burgundy, Dijon 21078, France (e-mail: karim.hassan21@gmail.com; laurent.markey@u-bourgogne.fr; jcweeber@u-bourgogne.fr; adereux@u-bourgogne.fr).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2012.2191147

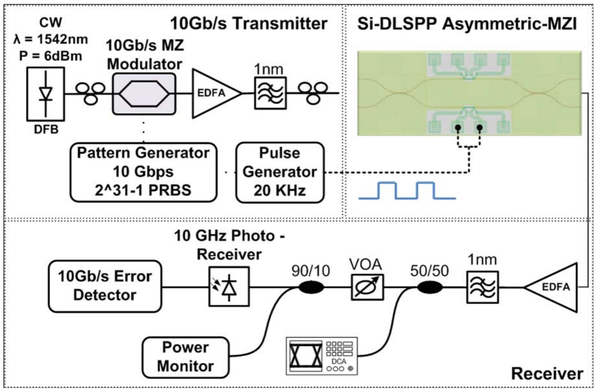

Fig. 2. Experimental setup.

In this article, we demonstrate for the first time, to the best of our knowledge, TO ON/OFF gating operation at 10 Gb/s using a plasmonic TO switching element integrated with Silicon-on-Insulator (SOI) access waveguides featuring only 2.8 μs response time and 10.8 mW power consumption. The switch configuration relies on an asymmetric MZI (A-MZI) layout with 90-μm-long active poly-methyl-methacrylate (PMMA)-loaded plasmonic waveguides as its branches heterointegrated on a SOI rib waveguide platform and located in-between two SOI-based coupler stages. The TO response of the device is experimentally characterized in dynamic operational conditions, showing a 62% modulation depth with 2.8 μs rise- and 4.6 μs fall-time. The bit error rate (BER) performance of the device has been also addressed, showing error-free performance in both ON and OFF states with up to 1.7 dB power penalty for a 10^{-9} BER value. Finally, its system-level credentials are presented at 10 Gb/s yielding successful ON/OFF gating with 6 dB extinction ratio (ER).

II. A-MZI Characterization-Experimental Setup

The investigated hybrid A-MZI-based switching structure comprised two 90-μm-long PMMA-loaded SPP waveguides serving as the active MZI branches and heterointegrated on a SOI rib waveguide platform (Fig. 1). The DLSPP waveguides consisted of 65-nm-thick and 3-μm-wide gold stripes, on top of which dielectric PMMA ridges with cross-sections of 500×600 nm^2 were placed. The interferometric layout was completed by two Si coupler stages at the MZI input and output, interfaced with the plasmonic waveguide arms through a butt-coupling approach. A detailed description of the heterointegration process and the 400×340 nm^2 SOI rib waveguide platform hosting the plasmonic elements is described in [11]. The lower plasmonic arm was modified in order to induce a default phase asymmetry between the two A-MZI optical paths and bias the A-MZI at its quadrature point. This phase asymmetry was achieved by widening a 7-μm-long DLSPP waveguide section from 500 nm to 700 nm, as shown in Fig. 1, exploiting the resulting effective index value enhancement for the plasmonic propagation mode in the wider DLSPP waveguide. Biasing at the quadrature point enables higher quality modulation depths within the limited phase tuning range of the 90-μm-long PMMA-loaded plasmonic sections, which is determined by PMMA's TO coefficient (TOC) in combination with its maximum service temperature and the requirement for reasonable total plasmonic propagation losses. The Si couplers placed at the A-MZI's input/output stages had a coupling ratio of 95:5 due to an unfortunate design error, restricting the device operation from high quality 2×2 switching, which should be in principle expected in case of perfect 3-dB couplers. This issue however can be easily tackled in future fabrication runs. The total fiber-to-fiber losses of the device were found to be 46 dB, 29 dB of them coming from the SOI grating couplers, 3 dB owing to Si propagation losses, 9 dB due to plasmonic propagation losses and 5 dB stemming from the Si-to-DLSPP coupling interfaces.

Fig. 2 illustrates the experimental setup. A continuous wave (CW) signal at 1542 nm was launched into a Ti:$LiNbO_3$ Mach-Zehnder modulator driven by a pseudo-random bit sequence (PRBS) pattern generator, yielding a 10 Gb/s $2^{31}-1$ (and 2^7-1) non-return-to-zero (NRZ) data sequence at its output. The modulated signal was then amplified, using a high-power erbium-doped fiber amplifier (EDFA) providing 26 dBm output power, filtered and launched into the hybrid A-MZI. The MZI's output signal was amplified in a low-noise EDFA, filtered, split and then fed simultaneously into a 30 GHz sampling oscilloscope and a 10 GHz photo-receiver that was connected to an error detector. The control signal was provided by a 20 KHz pulse generator that was directly connected to the electrical pads of the lower (wider) DLSPP waveguide.

III. Results and Discussion

The A-MZI described above was experimentally characterized in both static and dynamic operation (Fig. 3). For static characterization purposes, a CW at 1542 nm was used as input signal while a direct current (DC), connected to the metal pads of the structure, was used to change the switch's state. Fig. 3(a) depicts the variation of the output power at the BAR and CROSS ports plotted against the applied current. The graph reveals that for an applied current range starting from 0 to 30 mA, the static ER of the BAR and CROSS ports was found to be 1 and 6 dB, respectively. The poor performance of the BAR port is due to the unequal (95:5) coupling realized in the MZI directional couplers (instead of intended 3-dB coupling). The ER value between BAR and CROSS output powers at 0 mA indicates that the phase asymmetry introduced in the A-MZI was $\sim$100°, which is close to the originally intended $\pi/2$ value. The 6 dB ER obtained at the CROSS port when driving the A-MZI at 30 mA suggests that the optical wave travelling through the modified branch experiences a thermo-optically induced phase shift of –100° that corresponds to a temperature change of $\sim$45 K, bringing in this way the interferometer back in balance. This performance confirms the principle of asymmetric biasing of the A-MZI, so that π phase difference between the 149 A-MZI arms and higher ER values during switching should be, in principle, expected when using a dual-drive electrical control.

Fig. 3(b)-(c) show the dynamic response of the device when driven by 20 KHz rectangular pulses of 25 μs duration and a nominal electric current peak value of 30 mA. The oscilloscope traces in Fig. 3(b)-(c) indicate complementary

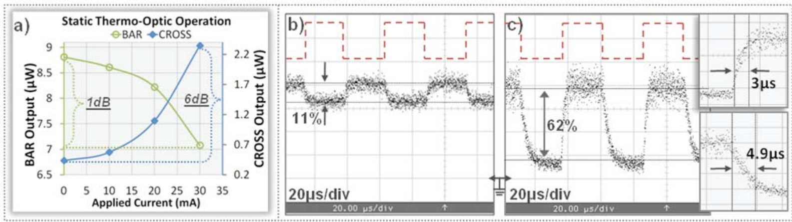

Fig. 3. (a) Static TO characterization of the A-MZI. (b) BAR output TO gating operation. (c) CROSS output TO gating operation and rise/fall times (insets).

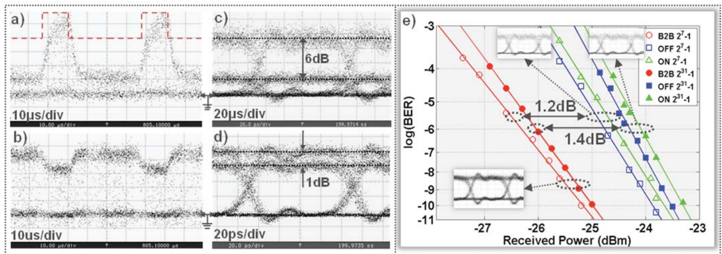

Fig. 4. (a) 10-Gb/s data trace-CROSS port. (b) 10-Gb/s data trace-BAR port. (c) 10-Gb/s eye diagram (CROSS). (d) 10-Gb/s eye diagram (BAR). (e) $(2^{31}-1)$ and $(2^{7}-1)$ BER measurements for B2B, ON, and OFF state.

operation as well as 11% and 62% modulation depth for the BAR and CROSS ports, respectively. The insets in Fig. 3 depict the rising and falling edge of the pulses at the CROSS port, revealing a 2.8 μs rise and 4.6 μs fall time. The resistance of the electrically connected A-MZI arm was estimated to be 10 Ω prior current injection (25 °C) and 12 Ω after the applied current (70 °C) due to the temperature-dependent resistivity of gold. To this end, the power consumption characteristics of the device calculated in switching operating conditions for 30 mA driving current are 10.8 mW.

The performance of the switch in a realistic data switching scenario with 10 Gb/s NRZ optical input signals and 15 μs electrical pulses at 20 KHz repetition rate controlling the device are shown in Fig. 4(a)-(d). Fig. 4(a) presents a snapshot of the signal's trace exiting the CROSS port compared to the applied control pulses (red dashed line), while Fig. 4(b) shows the corresponding trace for the BAR port. The eye diagrams of the CROSS and BAR output signals are shown in Fig. 4(c)-(d), respectively, clearly illustrating an ER value of 6 dB for the CROSS port and 1 dB for the BAR port, in agreement with the static characterization values.

The transmission quality properties of the A-MZI when being in both ON and OFF states have been evaluated through BER measurements performed both for 10 Gb/s 2^7-1 and $2^{31}-1$ PRBS data streams, as shown in Fig. 4(e). During ON-state characterization, the A-MZI was driven by a DC of 30 mA. Both the CROSS-port during ON- and the BAR-port during OFF-state operation exhibit similar BER performance with up to 1.7 dB power penalty (at 10^{-9} BER value) compared to the back-to-back (B2B) measurements.

IV. Conclusion

We have demonstrated a thermo-optic hybrid silicon-plasmonic A-MZI device performing as ON/OFF gating element with true 10 Gb/s optical signals. Device operation with 2.8 μs response time and 6 dB ER was achieved, requiring 10.8 mW of electrical power. Complete 2×2 switch operation with high-quality performance at both CROSS and BAR output ports should be feasible by improving the design through the use of 3-dB Si couplers at the MZI's input/output stages and by employing a dual-driving scheme with electric current applied to both A-MZI arms.

References

[1] M. A. Taubenblatt, J. A. Kash, and Y. Taira, "Optical interconnects for high performance computing," in *Proc. Commun. Photon. Conf. Exhibit.*, Shanghai, China, 2009, pp. 1–2.

[2] K. Bergman, "Photonic networks for intra-chip, inter-chip, and box-to-box interconnects in high performance computing," in *Proc. Opt. Commun. ECOC Eur. Conf.*, Cannes, France, 2006, pp. 1–64.

[3] H. A. Atwater, "The promise of plasmonics," *Sci. Amer.*, vol. 296, no. 4, pp. 38–45, Apr. 2007.

[4] S. Papaioannou, *et al.*, "A 320 Gb/s-throughput capable 2×2 silicon-plasmonic router architecture for optical interconnects," *J. Lightw. Technol.*, vol. 29, no. 21, pp. 3185–3195, Nov. 1, 2011.

[5] R. L. Espinola, M.-C. Tsai, J. T. Yardley, and R. M. Osgood, "Fast and low-power thermooptic switch on thin silicon-on-insulator," *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp. 1366–1368, Oct. 2003.

[6] Q. Fang, *et al.*, "Ultralow power silicon photonics thermo-optic switch with suspended phase arms," *IEEE Photon. Technol. Lett.*, vol. 23, no. 8, pp. 525–527, Apr. 15, 2011.

[7] Y. Shoji, K. Kintaka, S. Suda, H. Kawashima, T. Hasama, and H. Ishikawa, "Low-crosstalk 2×2 thermo-optic switch with silicon wire waveguides," *Opt. Express*, vol. 18, no. 9, pp. 9071–9075, 2010.

[8] M. W. Geis, S. J. Spector, R. C. Williamson, and T. M. Lyszczarz, "Submicrosecond submilliwatt silicon-on-insulator thermooptic switch," *IEEE Photon. Technol. Lett.*, vol. 16, no. 11, pp. 2514–2516, Nov. 2004.

[9] J. Gosciniak, *et al.*, "Thermo-optic control of dielectric-loaded plasmonic waveguide components," *Opt. Express*, vol. 18, no. 2, pp. 1207–1216, 2010.

[10] K. Hassan, J. C. Weeber, L. Markey, and A. Dereux, "Thermo-optical control of dielectric loaded plasmonic racetrack resonators," *J. Appl. Phys.*, vol. 110, no. 2, pp. 023106-1–023106-7, 2011.

[11] G. Giannoulis, *et al.*, "Data transmission and thermo-optic tuning performance of dielectric-loaded plasmonic structures hetero-integrated on a silicon chip," *IEEE Photon. Technol. Lett.*, vol. 24, no. 5, pp. 374–376, Mar. 1, 2011.

[12] K. Hassan, J.-C. Weeber, L. Markey, A. Dereux, A. Pitilakis, O. Tsilipakos, and E. E. Kriezis, "Thermo-optic plasmo-photonic mode interference switches based on dielectric loaded waveguides," *Appl. Phys. Lett.*, vol. 99, no. 24, pp. 241110-1–241110-3, 2011.

[13] D. Kalavrouziotis, *et al.*, "0.48Tb/s (12×40Gb/s) WDM transmission and high-quality thermo-optic switching in dielectric loaded plasmonics," *Opt. Express*, to be published.