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

Reports on the impact and outcome of the organized promotion events

Deliverable no.: D7.5
Due date: 31/7/2015
Actual Submission date: 11/9/2015
Authors: AIT, UVEG, KIT, IMEC, UGent, TU/e
Work package(s): WP7
Distribution level: PU[1]
Nature: document, available online

List of Partners concerned

Partner number	Partner name	Partner short name	Country	Date enter project	Date exit project
1	Karlsruher Institut für Technologie	KIT	Germany	M1	M45
2	INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM VZW	IMEC	Belgium	M1	M45
3	TECHNISCHE UNIVERSITEIT EINDHOVEN	TU/e	Netherlands	M1	M45
4	RESEARCH AND EDUCATION LABORATORY IN INFORMATION TECHNOLOGIES	AIT	Greece	M1	M45
5	UNIVERSITAT DE VALENCIA	UVEG	Spain	M1	M45
6	STMICROELECTRONICS SRL	ST	Italy	M1	M45
7	UNIVERSITEIT GENT	UGent	Belgium	M1	M45

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[1] **PU** = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
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Executive Summary

This document presents the main impact and outcome of the organized promotion events of the NAVOLCHI. Also it presents the main impact of the dissemination activities during the NAVOLCHI project. Overall, during the period of the project, there have been published over 37 journals and 74 conference proceedings. In addition, a cover article on plasmonic communications has been publish in the May 2013 issue of Optics & Photonics News. Furthermore, a NAVOLCHI workshop on plasmonics-based components has been organized at the ICTON 2012 conference at Warwick (UK), attracting more than 50 attendees. Another NAVOLCHI workshop has been organized in ICTON 2013 (June 2013, Cartagena, Spain) attracting more than 60 attendees.

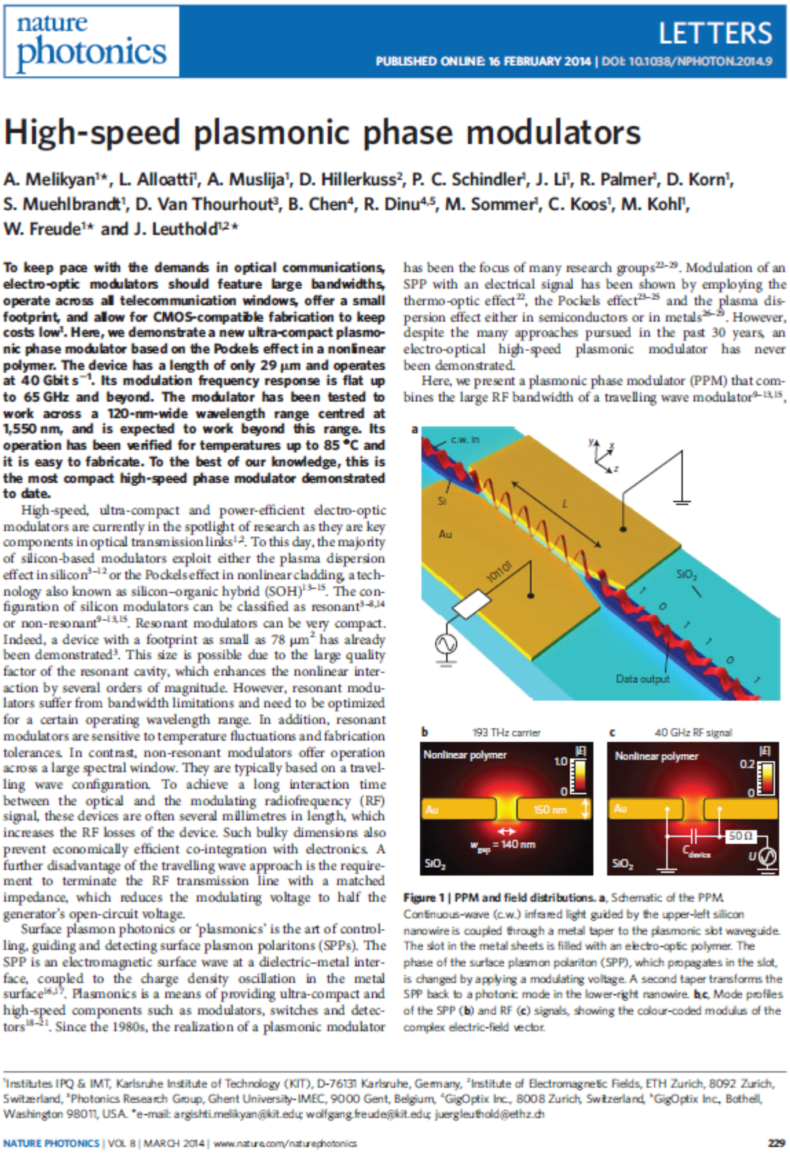
Contents

1. Impact of the dissemination activities

NAVOLCHI partners have been very active disseminating and promoting the activities and results of the project. The following list summarizes the related activities of the project.

- 37 journals (among others **2 Nature photonics** papers and one **cover article in Optics and Photonics News**)
- 74 conference publications disseminating the project have been published by NAVOLCHI partners,
- 4 Ph.D. thesis
- 7 Master thesis

One of the flagship paper of the NAVOLCHI was the paper entitled *High-speed plasmonic phase modulators* in Nature Photonics in 2014.



nature photonics
LETTERS
PUBLISHED ONLINE: 16 FEBRUARY 2014 | DOI: 10.1038/NPHOTON.2014.9

High-speed plasmonic phase modulators

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To keep pace with the demands in optical communications, electro-optic modulators should feature large bandwidths, operate across all telecommunication windows, offer a small footprint, and allow for CMOS-compatible fabrication to keep costs low[1]. Here, we demonstrate a new ultra-compact plasmonic phase modulator based on the Pockels effect in a nonlinear polymer. The device has a length of only 29 μm and operates at $40\ \mathrm{Gbit\,s^{-1}}$. Its modulation frequency response is flat up to 65 GHz and beyond. The modulator has been tested to work across a 120-nm-wide wavelength range centred at 1,550 nm, and is expected to work beyond this range. Its operation has been verified for temperatures up to 85 °C and it is easy to fabricate. To the best of our knowledge, this is the most compact high-speed phase modulator demonstrated to date.

High-speed, ultra-compact and power-efficient electro-optic modulators are currently in the spotlight of research as they are key components in optical transmission links[1,2]. To this day, the majority of silicon-based modulators exploit either the plasma dispersion effect in silicon[3–12] or the Pockels effect in nonlinear cladding, a technology also known as silicon–organic hybrid (SOH)[13–15]. The configuration of silicon modulators can be classified as resonant[3–8,14] or non-resonant[9–13,15]. Resonant modulators can be very compact. Indeed, a device with a footprint as small as $78\ \mu m^2$ has already been demonstrated[3]. This size is possible due to the large quality factor of the resonant cavity, which enhances the nonlinear interaction by several orders of magnitude. However, resonant modulators suffer from bandwidth limitations and need to be optimized for a certain operating wavelength range. In addition, resonant modulators are sensitive to temperature fluctuations and fabrication tolerances. In contrast, non-resonant modulators offer operation across a large spectral window. They are typically based on a travelling wave configuration. To achieve a long interaction time between the optical and the modulating radiofrequency (RF) signal, these devices are often several millimetres in length, which increases the RF losses of the device. Such bulky dimensions also prevent economically efficient co-integration with electronics. A further disadvantage of the travelling wave approach is the requirement to terminate the RF transmission line with a matched impedance, which reduces the modulating voltage to half the generator's open-circuit voltage.

Surface plasmon photonics or 'plasmonics' is the art of controlling, guiding and detecting surface plasmon polaritons (SPPs). The SPP is an electromagnetic surface wave at a dielectric–metal interface, coupled to the charge density oscillation in the metal surface[16,17]. Plasmonics is a means of providing ultra-compact and high-speed components such as modulators, switches and detectors[18–21]. Since the 1980s, the realization of a plasmonic modulator has been the focus of many research groups[22–29]. Modulation of an SPP with an electrical signal has been shown by employing the thermo-optic effect[22], the Pockels effect[23–25] and the plasma dispersion effect either in semiconductors or in metals[26–29]. However, despite the many approaches pursued in the past 30 years, an electro-optical high-speed plasmonic modulator has never been demonstrated.

Here, we present a plasmonic phase modulator (PPM) that combines the large RF bandwidth of a travelling wave modulator[9–13,15],

Figure 1 | PPM and field distributions. a, Schematic of the PPM. Continuous-wave (c.w.) infrared light guided by the upper-left silicon nanowire is coupled through a metal taper to the plasmonic slot waveguide. The slot in the metal sheets is filled with an electro-optic polymer. The phase of the surface plasmon polariton (SPP), which propagates in the slot, is changed by applying a modulating voltage. A second taper transforms the SPP back to a photonic mode in the lower-right nanowire. **b**,**c**, Mode profiles of the SPP (**b**) and RF (**c**) signals, showing the colour-coded modulus of the complex electric-field vector.

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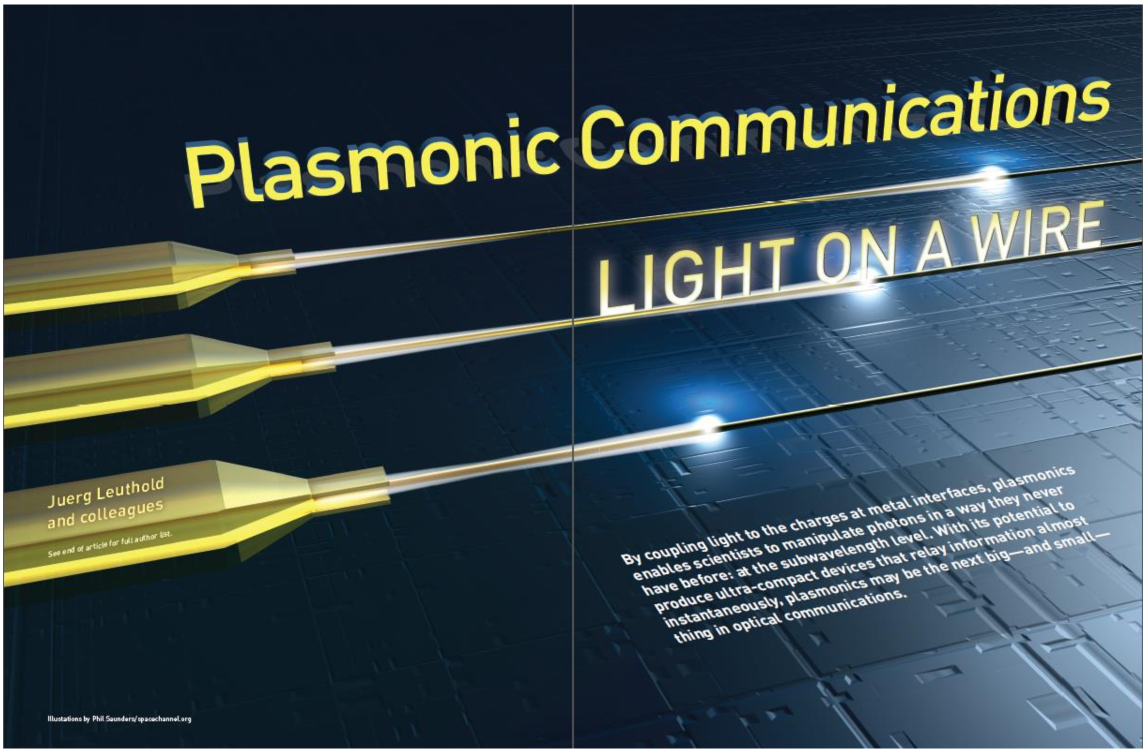
Figure 1. Nature Photonics paper on High speed optical phase modulators

Another major paper was the Plasmonic Communication: Light on a Wire that has been the cover article in the May Issue of Optics and Photonics News.



Plasmonic Communications

LIGHT ON A WIRE

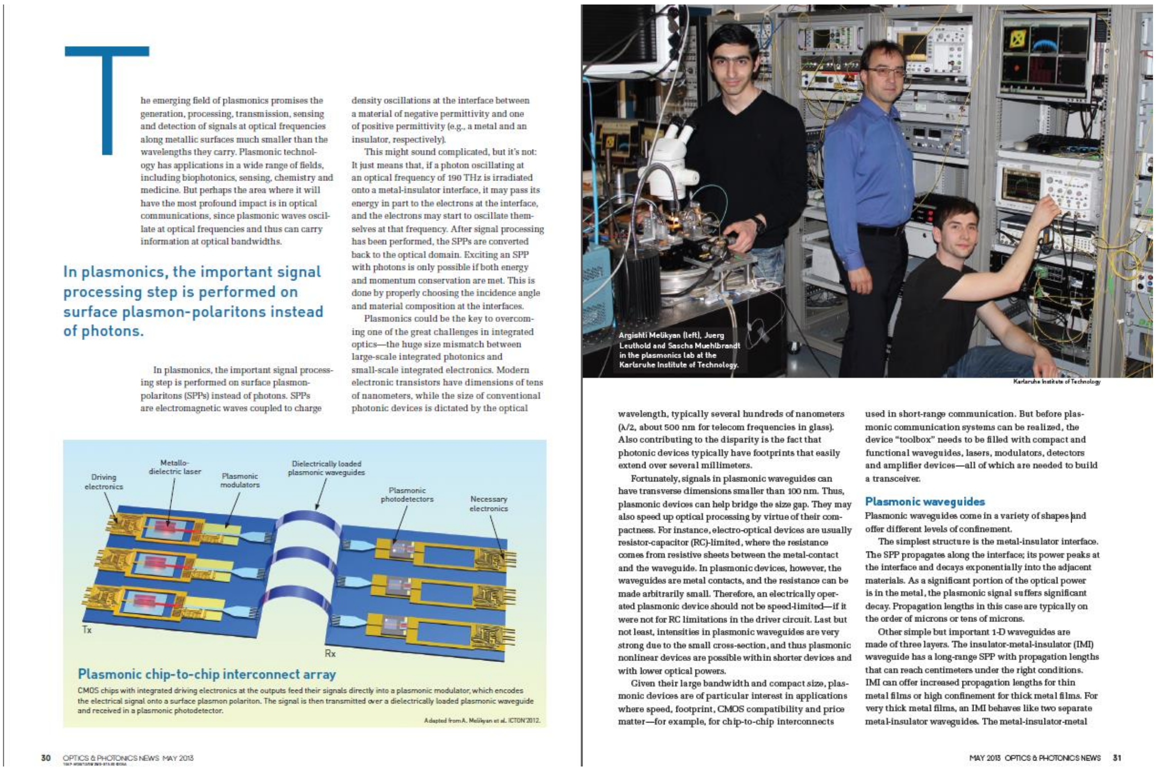
Juerg Leuthold
and colleagues

See end of article for full author list.

By coupling light to the charges at metal interfaces, plasmonics enables scientists to manipulate photons in a way they never have before: at the subwavelength level. With its potential to produce ultra-compact devices that relay information almost instantaneously, plasmonics may be the next big—and small—thing in optical communications.

Illustrations by Phil Saunders/spacechannel.org

Figure 2. Plasmonic Communications: Light on a Wire (p.1-2)



The emerging field of plasmonics promises the generation, processing, transmission, sensing and detection of signals at optical frequencies along metallic surfaces much smaller than the wavelengths they carry. Plasmonic technology has applications in a wide range of fields, including biophotonics, sensing, chemistry and medicine. But perhaps the area where it will have the most profound impact is in optical communications, since plasmonic waves oscillate at optical frequencies and thus can carry information at optical bandwidths.

In plasmonics, the important signal processing step is performed on surface plasmon-polaritons instead of photons.

In plasmonics, the important signal processing step is performed on surface plasmon-polaritons (SPPs) instead of photons. SPPs are electromagnetic waves coupled to charge density oscillations at the interface between a material of negative permittivity and one of positive permittivity (e.g., a metal and an insulator, respectively).

This might sound complicated, but it's not: It just means that, if a photon oscillating at an optical frequency of 190 THz is irradiated onto a metal-insulator interface, it may pass its energy in part to the electrons at the interface, and the electrons may start to oscillate themselves at that frequency. After signal processing has been performed, the SPPs are converted back to the optical domain. Exciting an SPP with photons is only possible if both energy and momentum conservation are met. This is done by properly choosing the incidence angle and material composition at the interfaces.

Plasmonics could be the key to overcoming one of the great challenges in integrated optics—the huge size mismatch between large-scale integrated photonics and small-scale integrated electronics. Modern electronic transistors have dimensions of tens of nanometers, while the size of conventional photonic devices is dictated by the optical wavelength, typically several hundreds of nanometers (λ/2, about 500 nm for telecom frequencies in glass). Also contributing to the disparity is the fact that photonic devices typically have footprints that easily extend over several millimeters.

Plasmonic chip-to-chip interconnect array

CMOS chips with integrated driving electronics at the outputs feed their signals directly into a plasmonic modulator, which encodes the electrical signal onto a surface plasmon polariton. The signal is then transmitted over a dielectrically loaded plasmonic waveguide and received in a plasmonic photodetector.

Adapted from A. Melikyan et al. ICTON'2012.

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Argishti Melikyan (left), Juerg Leuthold and Sascha Muehlbrandt in the plasmonics lab at the Karlsruhe Institute of Technology.

Karlsruhe Institute of Technology

Fortunately, signals in plasmonic waveguides can have transverse dimensions smaller than 100 nm. Thus, plasmonic devices can help bridge the size gap. They may also speed up optical processing by virtue of their compactness. For instance, electro-optical devices are usually resistor-capacitor (RC)-limited, where the resistance comes from resistive sheets between the metal-contact and the waveguide. In plasmonic devices, however, the waveguides are metal contacts, and the resistance can be made arbitrarily small. Therefore, an electrically operated plasmonic device should not be speed-limited—if it were not for RC limitations in the driver circuit. Last but not least, intensities in plasmonic waveguides are very strong due to the small cross-section, and thus plasmonic nonlinear devices are possible within shorter devices and with lower optical powers.

Given their large bandwidth and compact size, plasmonic devices are of particular interest in applications where speed, footprint, CMOS compatibility and price matter—for example, for chip-to-chip interconnects used in short-range communication. But before plasmonic communication systems can be realized, the device "toolbox" needs to be filled with compact and functional waveguides, lasers, modulators, detectors and amplifier devices—all of which are needed to build a transceiver.

Plasmonic waveguides

Plasmonic waveguides come in a variety of shapes and offer different levels of confinement.

The simplest structure is the metal-insulator interface. The SPP propagates along the interface; its power peaks at the interface and decays exponentially into the adjacent materials. As a significant portion of the optical power is in the metal, the plasmonic signal suffers significant decay. Propagation lengths in this case are typically on the order of microns or tens of microns.

Other simple but important 1-D waveguides are made of three layers. The insulator-metal-insulator (IMI) waveguide has a long-range SPP with propagation lengths that can reach centimeters under the right conditions. IMI can offer increased propagation lengths for thin metal films or high confinement for thick metal films. For very thick metal films, an IMI behaves like two separate metal-insulator waveguides. The metal-insulator-metal

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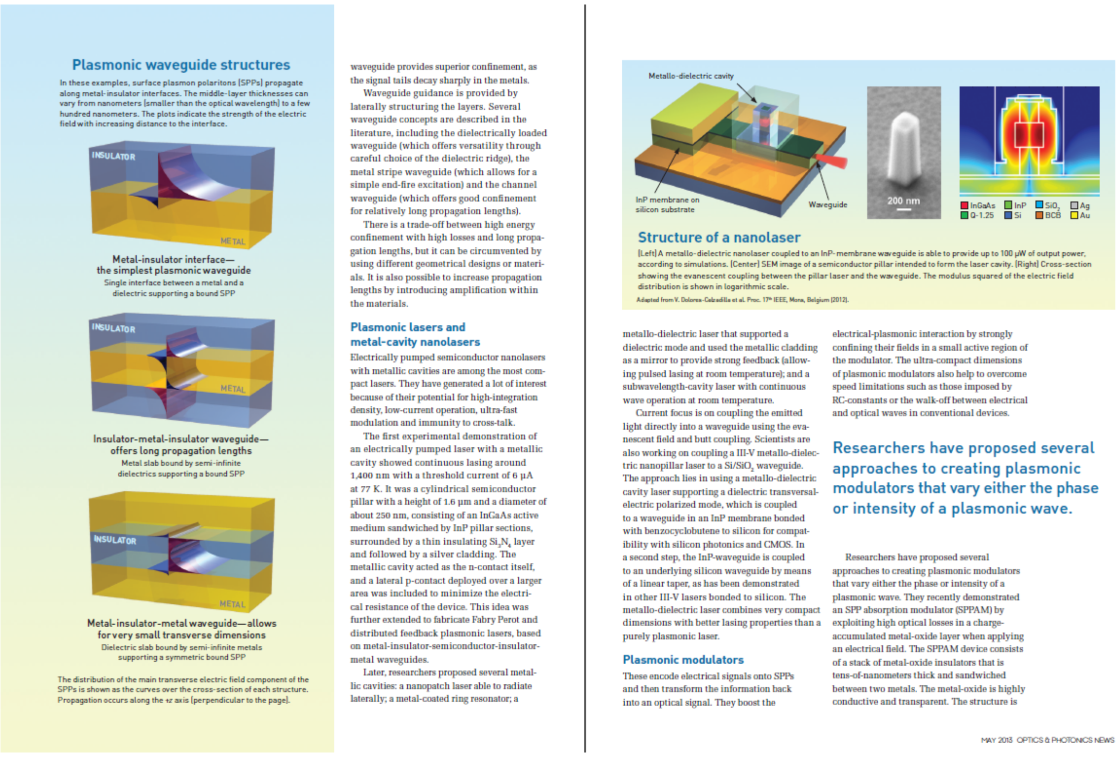
Figure 3. Plasmonic Communications: Light on a Wire (p.3-4)



Plasmonic waveguide structures

In these examples, surface plasmon polaritons (SPPs) propagate along metal-insulator interfaces. The middle-layer thicknesses can vary from nanometers (smaller than the optical wavelength) to a few hundred nanometers. The plots indicate the strength of the electric field with increasing distance to the interface.

Metal-insulator interface—the simplest plasmonic waveguide
Single interface between a metal and a dielectric supporting a bound SPP

Insulator-metal-insulator waveguide—offers long propagation lengths
Metal slab bound by semi-infinite dielectrics supporting a bound SPP

Metal-insulator-metal waveguide—allows for very small transverse dimensions
Dielectric slab bound by semi-infinite metals supporting a symmetric bound SPP

The distribution of the main transverse electric field component of the SPPs is shown as the curves over the cross-section of each structure. Propagation occurs along the +z axis (perpendicular to the page).

waveguide provides superior confinement, as the signal tails decay sharply in the metals.

Waveguide guidance is provided by laterally structuring the layers. Several waveguide concepts are described in the literature, including the dielectrically loaded waveguide (which offers versatility through careful choice of the dielectric ridge), the metal stripe waveguide (which allows for a simple end-fire excitation) and the channel waveguide (which offers good confinement for relatively long propagation lengths).

There is a trade-off between high energy confinement with high losses and long propagation lengths, but it can be circumvented by using different geometrical designs or materials. It is also possible to increase propagation lengths by introducing amplification within the materials.

Plasmonic lasers and metal-cavity nanolasers

Electrically pumped semiconductor nanolasers with metallic cavities are among the most compact lasers. They have generated a lot of interest because of their potential for high-integration density, low-current operation, ultra-fast modulation and immunity to cross-talk.

The first experimental demonstration of an electrically pumped laser with a metallic cavity showed continuous lasing around 1,400 nm with a threshold current of 6 µA at 77 K. It was a cylindrical semiconductor pillar with a height of 1.6 µm and a diameter of about 250 nm, consisting of an InGaAs active medium sandwiched by InP pillar sections, surrounded by a thin insulating Si_3N_4 layer and followed by a silver cladding. The metallic cavity acted as the n-contact itself, and a lateral p-contact deployed over a larger area was included to minimize the electrical resistance of the device. This idea was further extended to fabricate Fabry Perot and distributed feedback plasmonic lasers, based on metal-insulator-semiconductor-insulator-metal waveguides.

Later, researchers proposed several metallic cavities: a nanopatch laser able to radiate laterally; a metal-coated ring resonator; a metallo-dielectric laser that supported a dielectric mode and used the metallic cladding as a mirror to provide strong feedback (allowing pulsed lasing at room temperature); and a subwavelength-cavity laser with continuous wave operation at room temperature.

Structure of a nanolaser

[Left] A metallo-dielectric nanolaser coupled to an InP-membrane waveguide is able to provide up to 100 µW of output power, according to simulations. [Center] SEM image of a semiconductor pillar intended to form the laser cavity. [Right] Cross-section showing the evanescent coupling between the pillar laser and the waveguide. The modulus squared of the electric field distribution is shown in logarithmic scale.

Adapted from V. Dolores-Calzadilla et al. Proc. 17th IEEE, Mons, Belgium (2012).

Current focus is on coupling the emitted light directly into a waveguide using the evanescent field and butt coupling. Scientists are also working on coupling a III-V metallo-dielectric nanopillar laser to a Si/SiO_2 waveguide. The approach lies in using a metallo-dielectric cavity laser supporting a dielectric transversal-electric polarized mode, which is coupled to a waveguide in an InP membrane bonded with benzocyclobutene to silicon for compatibility with silicon photonics and CMOS. In a second step, the InP-waveguide is coupled to an underlying silicon waveguide by means of a linear taper, as has been demonstrated in other III-V lasers bonded to silicon. The metallo-dielectric laser combines very compact dimensions with better lasing properties than a purely plasmonic laser.

Plasmonic modulators

These encode electrical signals onto SPPs and then transform the information back into an optical signal. They boost the electrical-plasmonic interaction by strongly confining their fields in a small active region of the modulator. The ultra-compact dimensions of plasmonic modulators also help to overcome speed limitations such as those imposed by RC-constants or the walk-off between electrical and optical waves in conventional devices.

Researchers have proposed several approaches to creating plasmonic modulators that vary either the phase or intensity of a plasmonic wave.

Researchers have proposed several approaches to creating plasmonic modulators that vary either the phase or intensity of a plasmonic wave. They recently demonstrated an SPP absorption modulator (SPPAM) by exploiting high optical losses in a charge-accumulated metal-oxide layer when applying an electrical field. The SPPAM device consists of a stack of metal-oxide insulators that is tens-of-nanometers thick and sandwiched between two metals. The metal-oxide is highly conductive and transparent. The structure is

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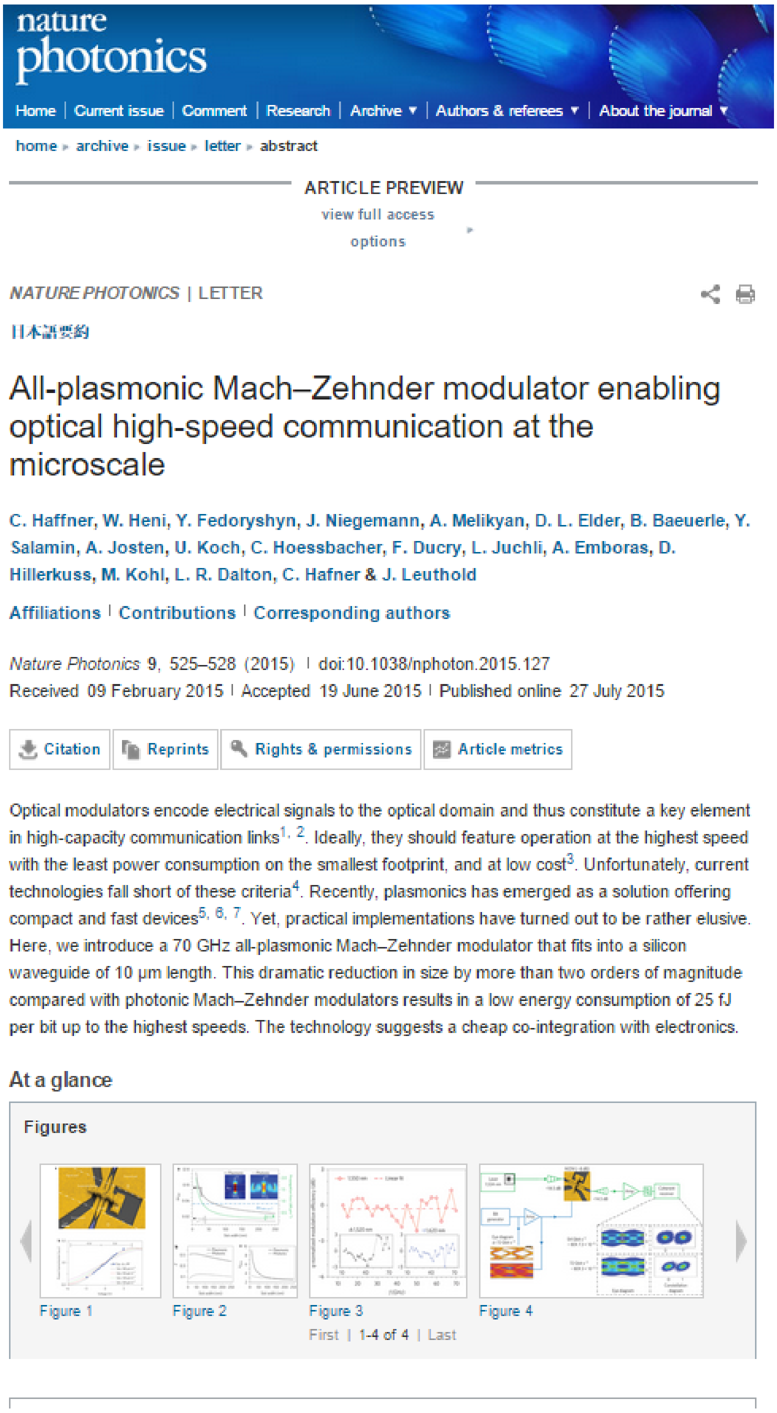
Figure 4. Plasmonic Communications: Light on a Wire (p.5-6)

Finally, one more flagship paper was one additional paper on Nature photonics entitled “All-plasmonic Mach–Zehnder modulator enabling optical high-speed communication at the microscale”.



NATURE PHOTONICS | LETTER

日本語要約

All-plasmonic Mach–Zehnder modulator enabling optical high-speed communication at the microscale

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Affiliations | Contributions | Corresponding authors

Nature Photonics 9, 525–528 (2015) | doi:10.1038/nphoton.2015.127
Received 09 February 2015 | Accepted 19 June 2015 | Published online 27 July 2015

Optical modulators encode electrical signals to the optical domain and thus constitute a key element in high-capacity communication links[1, 2]. Ideally, they should feature operation at the highest speed with the least power consumption on the smallest footprint, and at low cost[3]. Unfortunately, current technologies fall short of these criteria[4]. Recently, plasmonics has emerged as a solution offering compact and fast devices[5, 6, 7]. Yet, practical implementations have turned out to be rather elusive. Here, we introduce a 70 GHz all-plasmonic Mach–Zehnder modulator that fits into a silicon waveguide of 10 μm length. This dramatic reduction in size by more than two orders of magnitude compared with photonic Mach–Zehnder modulators results in a low energy consumption of 25 fJ per bit up to the highest speeds. The technology suggests a cheap co-integration with electronics.

At a glance

Figures

Figure 5. The latest paper on plasmonic modulator on Nature photonics.

The following table shows the most highly cited paper of the NAVOLCHI project. The high number of citations for several papers indicates the impact of the NAVOLCHI project in the domain of plasmonics.

Paper	**Number of citation (Google Scholar)**
High-speed plasmonic phase modulators, Nature Photonics, 2014	76
Plasmonic communications: light on a wire, Optics and Photonics News, 2013	14
Electrically Controlled Plasmonic Switches and Modulators, IEEE STQE, 2015	2
The plasmonic memristor: a latching optical switch, Optica 2014	4
Photonic-to-plasmonic mode converter, Optics Letter, 2014	4
High-speed plasmonic Mach-Zehnder modulator in a waveguide, ECOC 2014	11
Surface plasmon polariton high-speed modulator, CLEO: Science and Innovations	3
Highly efficient metal grating coupler for membrane-based integrated photonics, Optics Letters, 2014.	4
Low-optical-loss, low-resistance Ag/Ge based ohmic contacts to n-type InP for membrane based waveguide devices, Optical Materials Express, 2015	2
Polymer/QDs nanocomposites for waveguiding applications Journal of Nanomaterials, 2012	6
Patterning of Conducting Polymers Using UV Lithography: The in-Situ Polymerization Approach The Journal of Physical Chemistry C 116, 17547-17553, 2012.	3

2. Impact of the Promotion Activities

Two workshops have been organized for the promotion of the NAVOLHCI project. The first activity was the “NAVOLCHI Special Section on Plasmonics Based Components” on ICTON 2012, in Coventry, England. The event attracted more than 50 attendees from both the industry and the academia.

The second workshop was organized in ICTON 2013. The session was entitled "CMOS Fabrication-Based Photonic Technologies for Communications" and was co-organized by the NAVOLCHI and the SOFI (on hybrid silicon-organics technology) projects. It was chaired by Dr Emmanouil-P. Fitrakis (AIT, lead), Dr Panagiotis Zakynthinos (AIT), Prof. Juerg Leuthold (KIT) and Dr Ioannis Tomkos (AIT). The event attracted more than 60 attendees from both the industry and the academia and there were several fruitful discussions on the future of the plasmonics for communications and the research outcomes of the NAVOLCHI projects.

ETHZ also participated in the "Scienficia" event (http://www.scientifica.ch/scientifica-2015) in which they had a booth at this outreach event in Zurich and they had the chance to present their activities in NAVOLCHI to over 25 000 visitors (general public).

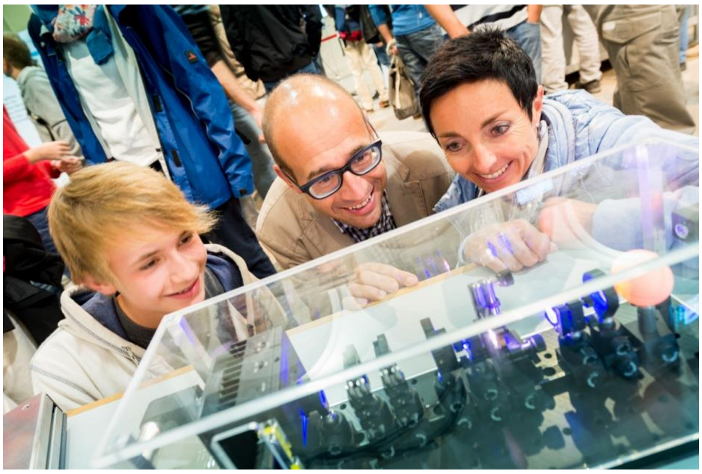

Figure 6. Scientifica event 2015

Finally, we also presented our research on nanolasers funded by NAVOLCHI to Dr. Jet Bussemaker, Minister of Education, Culture and Science of The Netherlands, during her visit to the Technical University of Eindhoven.

Figure 7. Visit of Minister Dr. Jet Bussemaker to NanoLab@TU/e cleanroom facilities.