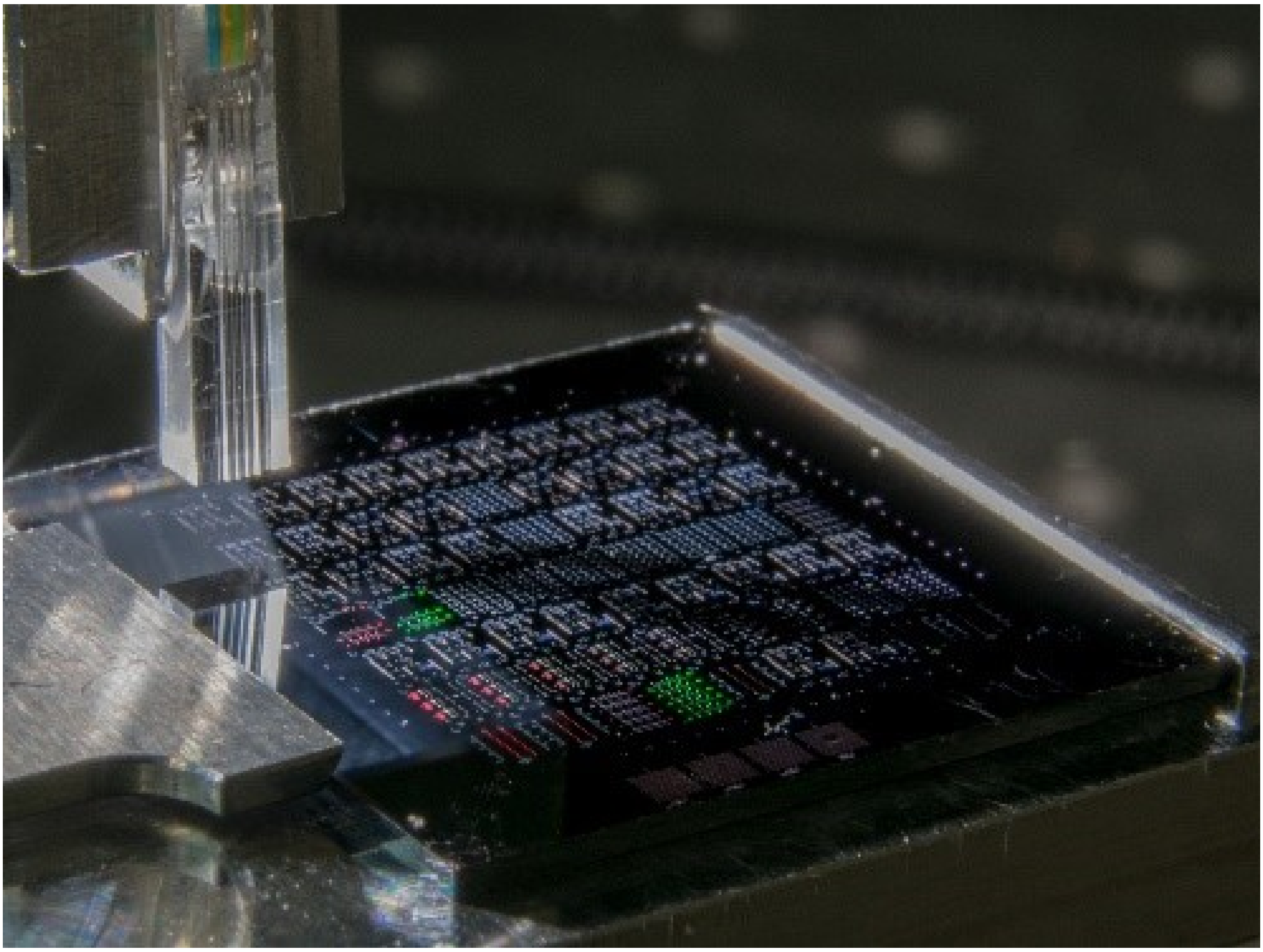


The Bridge between Electronics and Optics

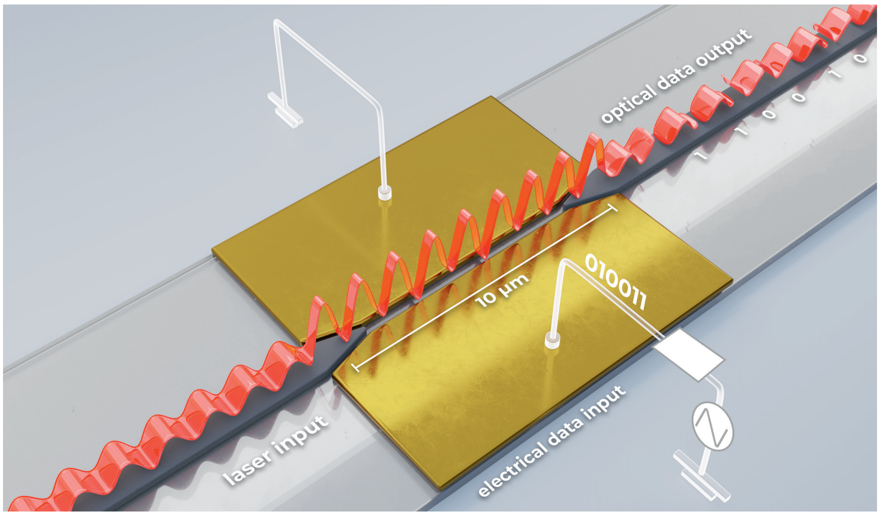
Plasmonics describes a technology, which compresses electromagnetic fields into nanoscopic structures, thus enabling a new generation of efficient and fast computer chips. In early 2019, three ETH researchers decided to found the spin-off public company Polariton Technologies with the vision of molding plasmonics into a market-ready technology.

BENEDIKT BÄUERLE

Plasmonics builds a nanoscopic bridge between the electronic and optic world thus opening a new chapter in the history of integrated circuits. The convergence of these two worlds is of great interest to the information society of the present day. Nowadays different forms of information (databases, images, videos etc.) are distributed through a global fiber optic network, which on the one hand connects entire continents with another, but on the other hand, bridges the shortest distances within data centers and brings the Internet to our homes. However, the processing and storing of information, for example on a mobile phone or within a data center, still takes place in electronic form. A technology, which would be able to unite these worlds efficiently, miniaturized and with a high bandwidth, is required.

The Principle

Plasmonics describes the creation, processing, transmission, detection and measurement of signals in optical frequencies, which are coupled to a charge carrier oscillation in a solid state material. When electromagnetic fields couple with a charge carrier vibration at a metal dielectric interface, they are referred to as surface plasmon polaritons. These charge carriers oscillate with an



Functional principle: In this manner, a plasmon moves along a slotted waveguide on a silicon chip.

optical frequency along the material interface, but with a much shorter wavelength. Therefore, an optical wave can be coupled with a charge carrier vibration smaller than the wavelength. As a result, the information of the light is concentrated in the smallest possible space. The surface plasmon polaritons are strongly confined to the material interface, along which they move, thus resulting in a strong light-matter-interaction.

The strong concentration of information allows for the formation of plasmonic structures, which enable an efficient generation, processing and detection of light on a nanoscopic level. In addition to optical information technology, further applications can be found primarily in the fields of sensor technology, microscopy and biophotonics.

Within the realm of optical information technology, the motivation lies in the convergence of the two worlds of integrated electronic circuits and of photonic integrated circuits. Photonic integrated circuits are an analog of the electrical integrated circuits, in order to generate, manipulate and detect laser light on a computer chip. The minimum size of the optical components, however, is limited by the diffraction limit and cannot be much smaller than the wavelength of the utilized laser light, which is usually found on the scale of 1500 nm. Today's silicon transistors in electronic circuits are, on the contrary, smaller than 100 nm. This dimensional mismatch can be overcome by plasmonics that confines light onto the dimensions below its diffraction limit. If the complexity of integrated photonic circuits should grow over the years, but the chip size should not increase to the same extent, and the shrinking of photonic components is not possible due to the diffraction limit, then plasmonics could be a solution to overcoming this issue.

Plasmonic Modulators

A research group led by Professor Jürg Leuthold at the ETH Zurich has taken advantage of this physical effect and established plasmonics as the future technology in the realm of electro-optical modulators in the field of communication technology. These constitute the interface between electronics and optics. An electro-optical modulator is a switch, operated by an electrical signal, which turns a laser light on and off. As a result, electrical information consisting of ones and zeros can be encoded onto an optical signal in the form of switching a laser on and off.

Phase Modulator

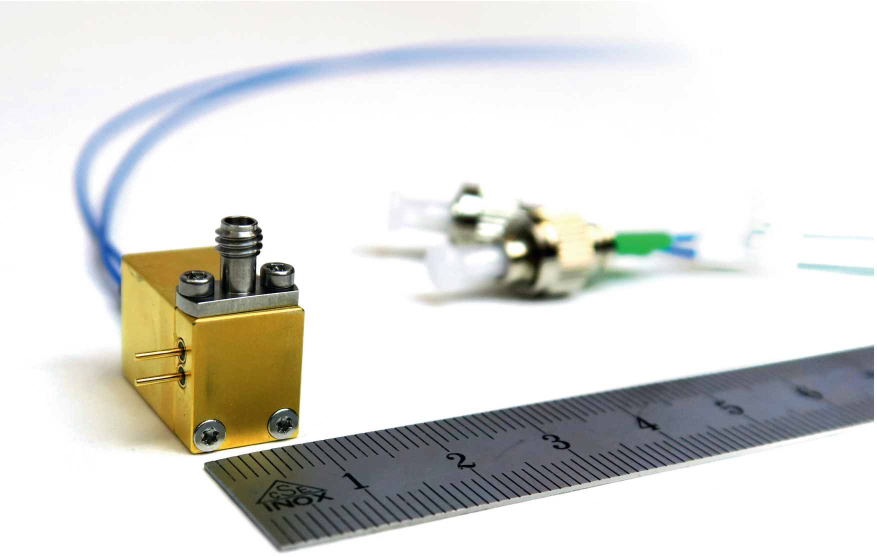
The elementary component is a phase modulator. In it, the refractive index of the material is altered through the creation of an electric field, which changes the phase of the light. This phase modulation can additionally be transformed into an amplitude or intensity modulation of the light through an interferometric structure (for example a Mach-Zehnder interferometer) with constructive and destructive interference. Therefore, the amplitude and the phase of the light can be encoded with information. Additionally, the polarization and the wavelength of the light can be utilized to convey information. The required refractive index change for the phase modulation can be produced through various effects, such as the change in the charge carrier density in a semiconductor or the Pockels-effect, which uses the birefringence in the material.

Drawing on proven techniques

Silicon photonics has increasingly come into the industry's focus within the last years, since it is a technology, which provides the platform for such electro-optical modulators. The phase modulation is reached by means of the plasma dispersion effect in a p–n junction, which is caused by a change in the charge carrier density in silicon. The greatest technical advantage of silicon photonics, however, is rooted in the possibility of drawing on established techniques from classic CMOS-semiconductor technology. Silicon photonics offers all the functionalities that are crucial for integrated photonic circuits. Among other things, this also includes light guiding through waveguides, junctions and convergences, light detection with integrated germanium, as well as light modulation with pn-junctions. Solely the light generation with a laser must usually be realized separately on an indium phosphide chip.

Simple Scaling

Because the established industrial processes of the semiconductor industry can be used for silicon photonics, cost-efficient scaling toward the mass market is feasible. This industrialization process includes the classic steps of the semiconductor industry, such as design and software layout with standardized component libraries, contract



The photonic-plasmonic chip is encased in a casing. A fiber optic connection, a RF-plug and DC-pins ensure the interface to the outside world. .

manufacturing of silicon chips in CMOS-fabs, standardized testing on wafer level through external service providers and packaging of the silicon chips through contract manufacturers.

The p–n junction, which helps realize the phase modulation, reaches its limits with regard to two characteristics. On the one hand, the plasma dispersion effect is caused by charge carrier movements, which limit the speed of the modulation. On the other hand, the effect is not as efficient, which is why the modulator dimension is in the millimeter range. Conventional electro-optical modulators are currently limited to the bandwidths of 40 to 50 GHz on the silicon platform.

In order to make use of the advantages of silicon photonics, while simultaneously being able to overcome their limitations in size and speed, the research group at ETH established the integration of plasmonics on silicon photonics ICs platform. This integration process further incorporates all passive components of silicon photonics, which can be supplied through, for example, established component libraries. One can therefore continue to rely on the advantages of silicon photonics. The issue regarding speed and size can be solved by replacing the p–n junction with a plasmonic-organic phase modulator. This results in two crucial advantages: an electro-optic bandwidth of multiple 100 GHz and a size reduction in the micrometer range.

The laser light is optically guided on the silicon chip in a waveguide and then converted into a surface plasmon by means of a specially configured structure for the phase modulation. This surface plasmon subsequently moves along a metal-insulator-metal slotted waveguide, to then be converted back into an optical mode, in order for it to be able to pass through conventional waveguides.

In the plasmonic slotted waveguide, the phase modulation takes place over a length of a few micrometers. A highly nonlinear organic material, which allows for the utilization of the Pockels-effect, resides between the two metals of the slotted waveguide. The Pockels-effect describes an almost instantaneous change of the refractive index generated by an applied electrical field. The two metals, with isolating organics in between, not only function as a plasmonic waveguide, but also act as electrodes. Consequently, when an electrical field is applied between the two metals, the refractive index in the organic material changes. As a result, the phase of the moving surface plasmon can be changed or modulated by means of an applied electrical field. Here plasmonics offers some determining advantages. On the one hand, the fields are strongly concentrated, which allows for the structures to be built very small, and on the other hand, the strong field concentration leads to a very efficient interaction between the electrical and optical fields.

This facilitates the possibility of constructing short and efficient phase modulators with a length of only a few micrometers on the silicon platform. The modulation bandwidth is therefore almost unlimited, which is why any frequencies of electrical signals can be modulated onto the light. Here, one uses the almost instantaneous Pockels-effect and the fact that the plasmonic waveguides simultaneously function as electrodes. In the case of the plasmonic modulator, the electrode design represents a simple microscopic capacity, which pushes the RC-limitation of the attached electrical circuit into the region of multiple 100 GHz. Thus, plasmonics enables electro-optical modulation with a bandwidth of multiple 100 GHz on a micrometer scale.

Successful Demonstrations

The elementary component of the plasmonic phase modulator could already be successfully demonstrated by the research group led by Jürg Leuthold at ETH Zurich in several configurations for a number of applications. This includes optical fiber communication for short ranges in data centers, long ranges between data centers or continents, wireless millimeter wave communication, as well as the detection of high frequency signals. In data centers, ranges of up to 2km can be bridged per fiber optic. Here the plasmonic modulator is employed in order to modulate the intensity for data rates of at least 100 Gbit/s to 200 Gbit/s per channel.

An additional area of application is telecommunication, in which information is transmitted over distances between data centers and even continents. Here, not just the intensity of the light is modulated, but also the amplitude and the phase of the light, which corresponds to a complex or coherent modulation. This is accomplished by a second parallel plasmonic modulator, which is displaced in its phase by 90° towards the first one. With this configuration, it was possible to achieve data rates of up to 400 Gbit/s per polarization. With a modulation of the second polarization, as much as 800 Gbit/s could be achieved.

The research group at ETH has also already made a step towards the ultimate goal of integrating electronics and photonics as intimately as possible with one another. For this purpose, a plasmonic modulator was monolithically integrated on an electronic BiCMOS chip in order to demonstrate an optical transmitter with data rates of 120 Gbit/s. Hence, with plasmonics, the electronic and photonic worlds were fused together on the same chip.

Further areas of Application

An additional application of the plasmonic modulator lies in the domain of wireless millimeter wave technology. For this purpose, the plasmonic phase modulator and an antenna were integrated together on a silicon photonics chip. This configuration acts as a millimeter-waves-to-optics-converter or a millimeter wave detector. The required space on the chip was less than 1 mm2. In a trial setup, the transmission of 20 Gbit/s on a 60 GHz carrier could be demonstrated. This type of setup can find its application in a number of scenarios in which a fiber optic line is bridged with a wireless transmission, for example, if the installation of optical fiber is too time-consuming, but a high data rate nevertheless still needs to be achieved. This could be the so-called "last mile" to the consumer's household or also the connection of mobile communications antennas to the fiber optic network in difficult-to-access areas. A plasmonic microwave detector can also be utilized in various sensing applications where high frequency signals should be detected. It has been demonstrated that the plasmonic modulator is capable of detecting frequencies from 0 to 500 GHz, as well as in the terahertz spectrum.

After successful demonstrations in ETH laboratories, the objective now is to develop the market maturity of plasmonic technology. The spin-off public company Polariton Technologies has made this subject its mission. The company wants to transform plasmonics into a fundamental pillar of the communication infrastructure of the future, to ensure that our information society, with its ever growing demand for data, can continue to rely on stable, broadband and secure Internet access. However, Polariton's vision goes beyond all this: plasmonics should not be limited to communications, but should be combined with photonic integrated circuits to become a modular solution for many applications, such as miniaturized sensors and computer chips.

In a preliminary demonstration in cooperation with Nokia, a record in data transmission for data centers could be demonstrated. Now Polariton Technologies is prioritizing qualification tests and the development of scalable manufacturing, in order to deliver a reliable product. This year already, potential customers will receive the first photonic chips with plasmonic modulators built into casings as prototypes.

Autor
Dr. **Benedikt Bäuerle** ist Mitgründer und Co-CTO von Polariton Technologies AG.
→ Polariton Technologies AG, 8803 Rüschlikon
→ benedikt@polariton.ch

RÉSUMÉ

Un pont entre l'électronique et la lumière

Une nouvelle technologie sur la voie de la commercialisation

La plasmonique est une technologie qui confine les champs électromagnétiques dans des structures nanoscopiques, permettant ainsi la réalisation d'une nouvelle génération de puces informatiques rapides et efficaces. Début 2019, trois chercheurs de l'ETHZ ont décidé de fonder le spin-off Polariton Technologies AG, dans l'objectif de faire de la plasmonique une technologie prête à être commercialisée. La plasmonique jette un pont nanoscopique entre les mondes de l'électronique et de l'optique, ouvrant ainsi un nouveau chapitre dans l'histoire des circuits intégrés. La convergence de ces deux mondes occupe un rôle central dans le secteur de l'information, car aujourd'hui l'informa-tion (bases de données, images, vidéos, etc.) est distribuée par le biais d'un réseau mondial de fibres optiques qui, d'une part, relie les continents, mais qui, d'autre part, comble aussi les distances les plus courtes dans les centres de données. Le traitement et le stockage des informations, que cela soit sur un téléphone mobile ou dans un centre de données, se font toutefois quant à eux toujours sous forme électronique. Une technologie qui relie ces mondes de manière efficace, miniaturisée et avec une large bande passante est nécessaire.

Les démonstrations réalisées avec succès dans les laboratoires de l'ETHZ indiquent que l'objectif de Polariton Technologies AG semble réaliste. La plasmonique est cependant non seulement appelée à devenir un pilier de la future infrastructure de communication, mais aussi, combinée à des circuits intégrés photoniques, une solution modulaire pour de nombreuses applications telles que des capteurs et puces informatiques miniaturisés. NO

The article was first published in German in the Bulletin SEV/VSE 10/2021.