

By turning on and off the control light, Kang *et al.*¹ also show that they can switch off the isolation effect. Once the control light goes off, the acoustic wave decays in the fibre and the photonic transition effect disappears. The switch-off time depends on how fast the acoustic wave decays. In the experiment, Kang *et al.* show a switch-off time as short as 45 ns. Such switching capability could be useful for advanced manipulation and routing of the optical signal in optical networks.

The demonstrated device¹ provides an in-fibre isolator that functions without the use of magnetic materials, in contrast with conventional Faraday rotators. According to Kang *et al.*, devices based on similar physical mechanism could also be realized on CMOS-compatible platforms. Being able to achieve a CMOS-compatible isolator has been a great challenge for silicon photonics,

and researchers have been searching for alternative approaches for decades. For example, isolators based on nonlinear optics have been proposed and demonstrated^{4–6}, but the nonlinear response of the devices has significantly limited their applications. Therefore, the findings of the team may represent a significant step towards non-magnetic isolators in integrated silicon photonics for next-generation high-speed, energy-efficient optical communications.

There are still substantial challenges that need to be overcome for the ultimate goal of non-magnetic integrated isolators on a chip to be achieved. For example, there is no cost-effective method of easily integrating photonic crystal fibres onto silicon chips. The size of the device also needs to be reduced significantly. In addition, both the bandwidth and the linearity of the present

device need to be improved before the isolator becomes practically useful. However, it is conceivable that all these issues are addressable with improved device design and experimental techniques. □

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VIEW FROM... ADVANCED PHOTONICS CONGRESS 2011

Harnessing plasmonics on a chip

Plasmonics has great potential for enabling energy-efficient, highly integrated optical interconnects. Reducing loss and realizing CMOS-compatible active plasmonic devices are two of the main topics on the current agenda.

Rachel Won

Photonic integrated circuits (PICs) have played an important role in information-processing devices and some other interesting devices such as biological and chemical sensors. The minimal dimensions of conventional PICs are ultimately restricted by the light-wave diffraction limit, which is approximately half of the light wavelength. For this reason, today's optoelectronic devices are much bigger than the smallest electronic devices. Moreover, to achieve control of light–material interactions for photonic device applications on the nanoscale, structures that guide electromagnetic energy with subwavelength-scale mode confinement are essential.

Combining the high localization of electronic waves and the propagation properties of optical waves, surface plasmon polaritons (SPPs) — coherent electron oscillations at conductor–dielectric (for example metal–air) interfaces — may overcome the size limitation of PICs. Plasmons can achieve extremely small mode wavelengths and large local electromagnetic field intensities, and hence not only reduce the size of photonic components to highly subwavelength scales, but also enhance the emission, detection and manipulation of optical signals on the nanoscale.

The potential of using SPPs in photonic integrated chips was brought up during Integrated Photonics Research, Silicon and Nano-Photonics (IPR), which took place on 12–15 June 2011 and is one of the six conferences constituting the Advanced Photonics Congress organized by the Optical Society of America in Toronto, Canada. Indeed, if we look at the several advantages of plasmonic circuitry over conventional photonic circuitry, it is obvious that they all come from the nature of plasmonic surface waves themselves, which exist only in conductors with free electrons.

“First, plasmonic waveguides effortlessly provide subwavelength confinement of the optical field without any special arrangements, potentially leading to nano-PICs. Secondly, owing to the high sensitivity of plasmonic modes to the environment, it is possible to build active components where signals can be controlled by electric field, another optical signal, or even magnetic field if needed, as they propagate along the plasmonic waveguide. Thirdly, simply a technological advantage but importantly, one can guide both electric and photonic signals along the same circuitry, allowing the delivery of electrically control signals along the PICs without the need of additional wiring,” said

Anatoly Zayats from King's College London, UK, who was one of the programme chairs of the IPR conference.

Having a metal in the optical path also has several implications for device architecture. “An important one is that, being electrically and thermally conductive, the metal can perform additional functions simultaneously to providing guidance. For example, the metal can be used to transmit an electrical signal, as an electrode to apply an electric field, as a Schottky or ohmic contact to a semiconductor, as a heating element by passing current along, or as a heat sink,” said Pierre Berini from the University of Ottawa, Canada, who gave an invited talk on active and passive SPPs.

There has been great progress in plasmonic photonic integrated chips over the past ten years, from a few ideas about plasmonic waveguides to the demonstration of full suites of components using several plasmonic waveguide technologies. The greatest progress has occurred with long-range metal stripe waveguides, dielectric-loaded metal film waveguides and metal gap (trenched or grooved) waveguides. “These different types of plasmonic waveguide technology have been used to fabricate passive PICs,” said Berini. “Essentially

all elements of interest have been demonstrated, including circular bends, S-bends, Y-junction splitters/combiners, multimode interferometers, couplers, Mach–Zehnder interferometers, ring resonators, Bragg gratings, filters, tapers and focusing waveguides.”

Although much work has been done on passive plasmonic devices, their present development seems to show that they have only niche applications in the context of photonic integrated chips, in spite of the fact that they offer smaller mode sizes and higher integration densities. “The predicament is their lower efficiency in comparison with silicon photonics due to the significant intrinsic loss associated with metal-based waveguides,” Zayats revealed.

Therefore, the general requirement for passive plasmonic devices is low insertion loss. Nevertheless, Berini said that in spite of attenuation issues, reasonable insertion losses can be achieved because plasmonic structures can be very compact. However, he pointed out that low polarization-dependent loss is often another requirement for passive plasmonic devices and that it is more difficult to reduce because SPPs have transverse magnetic polarization.

“Plasmonic passive elements are important building blocks to higher functions such as active devices and sensors, and thus approaches to overcome the loss issues are being investigated diligently,” Berini explained when asked about the impact of losses on active plasmonics devices, an area also being vigorously investigated.

“Plasmonic modes are very sensitive to the environment because of their field distribution. If one can control refractive index of the environment with some control signals, electrical or optical signals, the response of the plasmonic device will be stronger than the conventional photonic device of the same geometry, for example, Mach–Zehnder interferometer and ring resonator,” said Zayats, who is also the chair of Active Plasmonics, a UK research programme with the goal of showing that fully functional plasmonic PICs are possible with integrated plasmonic sources, modulators, switches and detectors.

Thermo-optical, electro-optical and all-optical components have been demonstrated using various plasmonic platforms. While presenting at the conference, Zayats showcased one of the smallest plasmonic electro-optical modulators, with dimensions of 20 nm × 20 nm × 200 nm, made by his group. The modulator gives modulation of >60% at a control voltage of 1 V.

Additionally, by integrating plasmons with various material systems, a wide variety of functions is being explored,



RACHEL WONG

Left: Comprising attendees from 22 countries, this year’s IPR conference had three joint plenary talks, 24 invited talks and 92 regular presentations. Right: Sanghoon Chin from École Polytechnique Fédérale de Lausanne in Switzerland sharing his thoughts with the attentive audience.

Berini pointed out. For example, tunable modulation or nonlinear functions can be achieved by integrating plasmons with crystals, electro-optic materials such as LiNbO₃, and electro-optical or thermo-optical polymers. Detection can be achieved by integrating plasmons with semiconductors. Emission, amplification and lasing is possible by integrating plasmons with optical gain media such as quantum dots, dyes, doped glasses and semiconductor quantum wells. This is particularly exciting, as recent efforts have culminated in several convincing amplification and lasing demonstrations involving SPPs, which could ultimately lead to nanoscale lasers, Berini emphasized. Several promising sensor applications are also being pursued using plasmonic PICs, including biological, biochemical and chemical sensors, and gas sensors.

Another merit of plasmonic PICs is that the operational wavelengths of plasmonic devices can be very broad as plasmonics is intrinsically broadband. Essentially, the choice of wavelength influences the choice of plasmonic metal. For instance, gold is for the red-to-infrared range, silver for the visible-to-infrared range and aluminium for the ultraviolet-to-infrared range. “The operating frequency must remain below the plasma frequency of the metal and should remain below interband absorption frequencies (energies), yet above terahertz frequencies where metals resemble perfect electric conductors, although structuring the metal surface can extend plasmonics down to the microwave regime,” explained Berini.

Given the great promise of using plasmons for highly integrated photonics interconnects, one may wonder whether plasmonic devices are compatible with the mature, cost-effective

technology behind the fabrication of complementary metal–oxide–semiconductors (CMOSs). The truth is that, until recently, most plasmonic devices were based on materials that are not CMOS compatible. “We are now beginning to see a big push towards CMOS-compatible structures and materials, and indeed aluminium and copper metals have been shown to provide parameters not much worse than the traditional gold or silver,” said Zayats.

Because plasmonics uses metals and dielectrics, as in the interconnect stacks of CMOS electronics, the potential for CMOS compatibility exists. Additionally, silicon can be used to help implement several functions, such as detection above and below bandgap, and tuning or modulation by means of the carrier refraction effect, said Berini. “There is a strong interest in developing plasmonic devices that are CMOS compatible but these are still early days.”

When asked about the limitations of plasmonics devices in PICs, both Zayats and Berini pointed out that the main pitfall of such devices is their ohmic loss due to metal resistivity and related limitations on the propagation length of plasmonic modes: it is difficult to send signals over large distances using plasmonic waveguides. One must mitigate or otherwise work around this attenuation in any foreseeable applications. “Having said that, probably you would not need a nanoscale waveguide to guide light over centimetres, would you?” said Zayats in jest. According to him, there is a big effort now to mitigate losses by amplifying plasmonic signals as they propagate in the waveguide. Complete loss compensation in the confined geometry has yet to be demonstrated, but significant increases in propagation length have been shown.

Like other schemes being researched, device commercialization is often a natural consideration, and there is no exception here given the great predicted technical impact of plasmonic PICs. As a new technology, the possibility of wide-ranging commercialization of plasmonics devices in the context of PICs depends on many factors. “Not only device performance, but also the cost and how long the industry can survive before adopting them,” said Zayats. He predicted that one of the very near-future commercial applications, probably available within the next three to five years, could be a hybrid plasmonic PIC in which the plasmonic part makes it possible to produce high-power nanoscale light sources for use in high-density magnetic data storage. Such storage, where there is no way forward without plasmonics, is an excellent example.

“In other areas, there is interest from both small-to-medium enterprises and big internationals, but it is still a long way to go from the final device design to mass production, and from the laboratory to prototype. It could take a decade,” suggested Zayats.

Some passive devices, such as thermo-optical modulators based on long-range plasmons, have already been commercialized, but this is niche market. Although plasmonic biosensors based on prism-coupling in the Kretschmann configuration have dominated the optical biosensing market for many years, they are mostly used in drug discovery applications. “I suspect that plasmonic

PICs for biosensing might then be the first place where they are commercialized. Approaches are being pursued which should lead to cheaper and more compact solutions compared with the Kretschmann configuration,” said Berini.

What are the challenges ahead? According to Zayats, integration of plasmonic components within standard photonic circuitry, and with silicon photonics, will boost the practical introduction of plasmonics in real-life devices. However, energy requirements and losses are the concerns. The good news is that, as mentioned before, there is at present a big drive to develop plasmonic amplifiers to compensate for these losses. All-optical control of signals in PICs is the ultimate goal, but this requires additional work to decrease the energy required per bit. For every potential application, it is necessary to select carefully the appropriate type of waveguide and use this as a basis for the active device required, Zayats added.

Berini raised the point that sustained interest in the field depends strongly on commercialization and that one important challenge is thus to develop good, competitive applications and get them to market. “Getting there, of course, will require overcoming several technical problems depending on the specific target. Although important strides have been made in recent times, much remains to be explored,” said Berini. There are plenty of fundamental and technical problems to be solved and

several applications to be explored. The most promising include SPP biosensors, lasers and detectors, he concluded.

“Ultimately, I can see plasmonic PICs of various sizes being main components of biosensing devices, active photonic interconnects of different scales between electronic components, ultrafast modulators and switches of optical signals, most definitely in nanoscale optical sources integrated in plasmonic or photonic circuitry,” said Zayats. Although he holds the opinion that the potential of plasmonic PICs is very great, he would not argue for complete replacement of conventional PICs with plasmonic versions. “Both will be synergetic and in many applications. Probably plasmonic components will be a part of silicon PICs providing active functionalities.”

All in all, the potential of integrated surface-plasmon devices that combine the high integration and functionality of electronic circuits with the bandwidth of photonic circuits on the nanoscale is apparent, and the community is active and progressive. It will be interesting to see how the field evolves and whether it will take less than a decade to bring plasmonic PICs to the market.

The next IPR conference will be held in Colorado Springs, Colorado, USA. □

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SEMICONDUCTOR LASERS

Expanding into blue and green

Are blue and green vertical-cavity surface-emitting lasers operating at room temperature just around the corner? New gallium-nitride-based vertical-cavity surface-emitting lasers are helping to overcome the intrinsic problem of low conductivities of p layers.

Hongxing Jiang and Jingyu Lin

In the research field of semiconductor lasers, there are at least two immediate challenges: the full extension of the lasing wavelength from blue to green, and the development of commercial devices. The latter effort means achieving high performance and desirable characteristics such as surface-normal output, circular beam shape, low beam divergence, low threshold currents, high-speed modulation, reliability and the capability to form two-dimensional arrays. The energy bandgap of GaN and our present technological

level are such that nitride vertical-cavity surface-emitting lasers (VCSELs) currently operate at room temperature in the near-UV region^{1–3} (wavelengths around 400 nm). However, operation around the blue and green wavelength regions remains challenging. This is possibly due to the difficulty of obtaining high-crystalline-quality multiple quantum wells (MQWs) with high indium content on a bottom-side dielectric distributed Bragg reflector (DBR) and the heat generation induced by current crowding in the side-by-side configuration⁴.

Writing in *Applied Physics Express*, Daiji Kasahara and co-workers⁵ from the Nichia Corporation now report that they have overcome these problems and have demonstrated operational room-temperature nitride blue (451 nm) and blue–green (503 nm) VCSELs. The work builds on a series of recent advances in nitride near-UV VCSELs^{1–3,6,7} that moved the technology from pulsed, low-temperature operation to continuous-wave, room-temperature operation at blue wavelengths. Kasahara’s team