PLASMONICS

Small and fast plasmonic modulator

Researchers have demonstrated a compact, high-speed, surface-plasmon phase modulator that operates at telecommunication wavelengths over a wide range of operational conditions. It has the potential to boost the speed of future miniaturized integrated circuits.

Min-Hsiung Shih

With the number of transistors per chip continuing to increase with time according to Moore's law, optoelectronic integrated circuits are becoming increasingly smaller and denser. As a consequence, their speed is expected to exceed 100 Gb s^{-1} in the near future. To construct functional chip-scale optoelectronic integrated circuits[1], it is vital to develop key circuit elements with ultrasmall footprints. Such elements include compact lasers for generating coherent light to carry functional signals and waveguides for routing high-speed signals. In addition, modulators convert electrical signals into optical signals, whereas detectors do the opposite. One of the most promising directions for miniaturizing photonic devices is the harnessing of surface plasmons — electromagnetic waves coupled to the surface plasma oscillations of a metal surface. Surface-plasmons waves are confined to the metal/dielectric interface along which they propagate; they decay evanescently in the direction normal to the interface. Because surface plasmon waves can overcome the fundamental diffraction limit of light in the dimensions for which they are evanescent, the sizes of future optoelectronic integrated circuits based on surface plasmon waves could be reduced to the order of a few micrometres. Key elements of chip-scale optoelectronic integrated circuits, including nanolasers[2,3], waveguides[4,5], modulators[6] and detectors[7,8], have been demonstrated using surface plasmons.

In 2011, Melikyan *et al.* reported an electrically controlled, ultracompact surface plasmon polariton absorption modulator that operates at the telecommunication wavelength of 1.55 μm (ref. 9). The size of this device depends on the required extinction ratio and the acceptable loss, and can be as small as a few micrometres. The small modulation device can operate at over 100 Gbit s^{-1} — its speed is limited only by the time constant of the associated RC circuit.

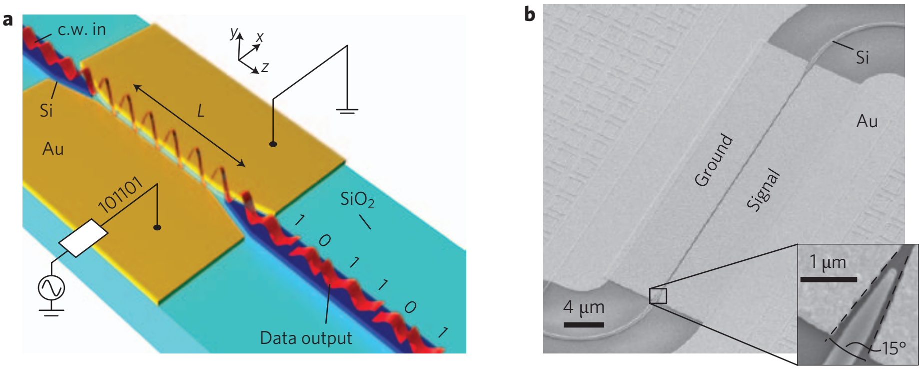

Figure 1 | An ultracompact plasmonic modulator. **a**, Schematic showing the structure of the reported plasmonic phase modulator operating at a wavelength of 1,550 nm. It employs tapered silicon nanowire waveguides. **b**, Scanning electron microscopy image of the plasmonic phase modulator before coating with an electro-optic polymer layer. The inset shows the coupling region between the silicon nanowire taper and the waveguide slot.

Ultracompact, high-speed, semiconductor electro-optic modulators are important for attaining chip-scale, high-density optoelectronic integrated circuits. The operational speed and bandwidth depend critically on whether a resonant or nonresonant modulator is employed. Modulators often have high-*Q* resonator cavities based on, for example, microdisks, microrings or photonic-crystal cavities. Such modulators can be quite compact and have a high modulation strength and a high operation speed. However, resonant modulators inevitably involve a trade-off — the stronger or sharper the resonance, the narrower is the device's operation bandwidth.

Previous studies have investigated compact, high-speed surface-plasmon modulators. Dionne *et al.* proposed using field-effect modulation of a plasmon waveguide structure, which functioned similarly to commercially available electronic complementary metal–oxide–semiconductor components[6]. By using the gate oxide as an optical channel, they realized electro-optic modulation in a volume of half a cubic wavelength using a femtojoule switching energy and with a modulation frequency that is potentially of the order of gigahertz.

Writing in *Nature Photonics*[10], Melikyan *et al.* now demonstrate an ultracompact plasmonic phase modulator that is based on the Pockels effect in a nonlinear polymer. Figure 1a schematically depicts the structure of this near-infrared plasmonic phase modulator. Continuous-wave input light from the silicon nanowire waveguide (upper left in Fig. 1a) is coupled to the plasmonic slot waveguide through a tapered metal region. A metal slot waveguide is filled with a nonlinear electro-optic polymer, which induces a strong Pockels effect to perform electro-optic modulation. The phase of the propagating surface-plasmon signal in the waveguide slot can be manipulated by applying a modulating voltage. The modulated signal is then coupled back to the silicon nanowire waveguide to facilitate further signal-processing procedures.

The non-resonant plasmonic modulator is approximately 29 μm long. Although it is not the smallest electro-optic modulator developed to date, its size is comparable with that of the ultracompact resonant silicon microring modulator, which has a 78 μm^2 footprint on a silicon-on-insulator substrate[11]. The plasmonic phase modulator was demonstrated at an operation speed of 40 Gbit s^{-1}; its modulation frequency response was flat beyond 65 GHz. The modulator functioned over a 120-nm-wide wavelength range centred at 1,550 nm. This indicates that the modulator can be used at most telecommunication wavelength regions in the optical S (1,460–1,530 nm), C (1,530–1,565 nm) and L (1,565–1,625 nm) bands. The proposed surface-plasmon modulator exhibited superior performance in terms of speed and wavelength range compared with other reported plasmonic modulators. The plasmonic modulator was found to be thermally stable for operation temperatures up to 85 °C.

In summary, Melikyan and colleagues have demonstrated a compact, high-speed, electro-optic modulator that employs surface-plasmon waves. It functions at telecommunication wavelengths and has a wide operating wavelength range. By integrating this modulation device with other key elements (such as nanolasers, plasmonic waveguides and detectors), chip-scale optoelectronic integrated circuits that employ surface-plasmon waves should become available in the near future. ❐

Min-Hsiung Shih is at the Research Center for Applied Sciences (RCAS), Academia Sinica, 128 Academia Road, Section 2, Nankang, Taipei 115, Taiwan and the Department of Photonics, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan.
e-mail: mhshih@gate.sinica.edu.tw

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OPTICAL MATERIALS

Nanostructured paper

Finding a substrate material for solar cells that simultaneously provides a high optical transparency and a high transmission haze (so that any transmitted light will scatter diffusively) is challenging. It now appears that an engineered paper could be an ideal substrate. Zhiqiang Fang and co-workers from the USA and China have developed a wood-fibre-based nanostructured paper that provides a transparency of ~96% and a haze of ~60% (*Nano Lett.* **14,** 765–773; 2014). This material is potentially useful for photovoltaics, where it could reduce the angular dependence of light harvesting for solar cells, and it could also benefit outdoor displays by reducing glare and specular reflections of sunlight.

The team produced the transparent paper by using an oxidation process called TEMPO to introduce carboxyl groups into the cellulose fibres of wood. This process weakens the hydrogen bonds between the cellulose fibrils, causing the wood fibres to swell. The result is a paper with a much higher packing density than usual and greatly improved optical transparency and haze.

Analysis by scanning electron microscopy revealed that the transparent paper has a homogenous surface as a result of voids being filled by small fibre fragments. In the spectral range of 400–1,100 nm, the transparent paper had a transmittance of ~96% and a transmission haze of ~60%.

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The benefits of the enhanced haze of the transparent paper for photovoltaic devices were demonstrated by laminating the paper to the top of an organic solar cell and measuring the cell's photocurrent as a function of the incident angle of white light. The measured photocurrents exceeded those of a control device that did not have the transparent paper for angles larger than 7° and for incident angles between 60° and 87°; improvements in the photocurrent of up to 15% were observed. The paper layer increased the power conversion efficiency of the solar cells by 10% (from 5.34% to 5.88%).

Fang explained that the improvements "can be explained by two factors: the reduced reflection of the light due to the low index contrast between the top layer of the photovoltaic device and the transparent paper, and the directional change of the incident light in the transparent paper."

NORIAKI HORIUCHI