A High-Performance Silicon-Based Plasmonic Modulator

Ren-Min Ma
Xiang Zhang
University of Califomia (UC), Berkeley, CA, USA

Photonic integrated circuits could be scaled down for future optical communication applications with the help of a new wavelength-scale modulator.

To meet the ever-increasing global demand for bandwidth, optical interconnects are now being used to cover shorter distances. They will eventually account for all the interconnects inside a chip, setting a roadmap for reducing the photonic component size to the nanoscale.[1] Another trend is toward CMOS-compatible optical communication and signal processing, for which a silicon modulator has been identified as the key driver.[2] Because silicon does not exhibit an efficient electro-optic effect, an optical silicon modulator requires a large device footprint, on the order of millimeters.[3, 4] The modulation strength per unit area can be increased by deploying a high-Q resonator, but with the trade-off of a significant sacrifice in bandwidth.[5]

By converting optical signals to deep subwavelength surface plasmons propagating along metal–dielectric interfaces, plasmonic devices can strongly increase the electromagnetic field. Therefore, they can be used to enhance the weak electro-optic effect.[6, 7] Furthermore, with the growing importance of the integration space and footprint, the small physical size of plasmonic devices will become a critical feature. The synergies between electronics and photonics are already becoming key design factors. For instance, the metal employed in plasmonic devices not only confines the optical field, but also can be used as electrodes and heat sinks simultaneously. Exploiting these unique properties, we have developed a wavelength-scale silicon-based plasmonic modulator that exhibits higher performance.[8]

Our device is based on a metal–insulator–semiconductor (MIS, Au–SiO_2–Si) waveguide, see Figure 1(a). An absorption-coefficient-tuneable indium tin oxide (ITO) layer (10nm thick) is inserted between the SiO_2 layer (20nm thick) and the Si layer (340nm thick). The continuity of the displacement field D at the material interfaces produces a strong optical field in the thin oxide layer normal to the metal and semiconductor.[9] The carrier concentration of the ITO can be greatly increased by applying an electrical bias to the MIS structure because an accumulation layer forms.[10, 11] The key design criterion is that the nanometer-scale carrier-accumulating ITO layer spatially overlaps the electric field maximum of the confined propagating optical mode, see Figure 1(b). This overlap strongly enhances the modulation effect owing to the increased electro-optic absorption of the mode.
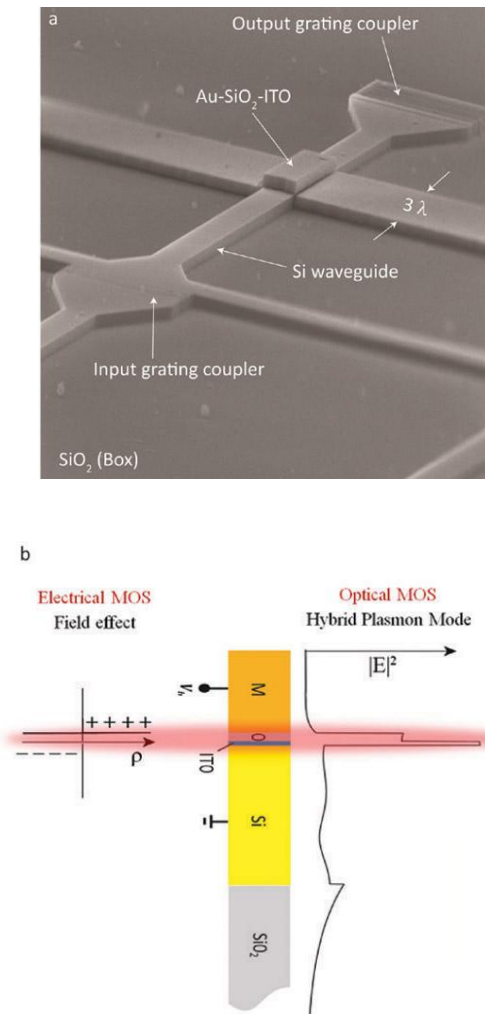

Figure 1. (a) Scanning electron microscopy image of our device. The three uppermost indium tin oxide (ITO)-SiO_2-Au layers are deposited via electron-beam lithography, electron-beam evaporation, and lift-off processing. In the modulation experiment, a continuous wave laser beam at a telecoms wavelength is free-space coupled into and out of the silicon-on-insulator waveguide via grating couplers, while a voltage bias across the MOS capacitor leads to a MOS-mode index change that alters the laser beam's intensity. **(b)** Schematic illustrating device operation. The ITO layer spatially overlaps the electric field maximum of the confined propagating optical mode (red area), which is a key design characteristic. λ: Wavelength. E: Electric field amplitude. ρ: Carrier concentration.
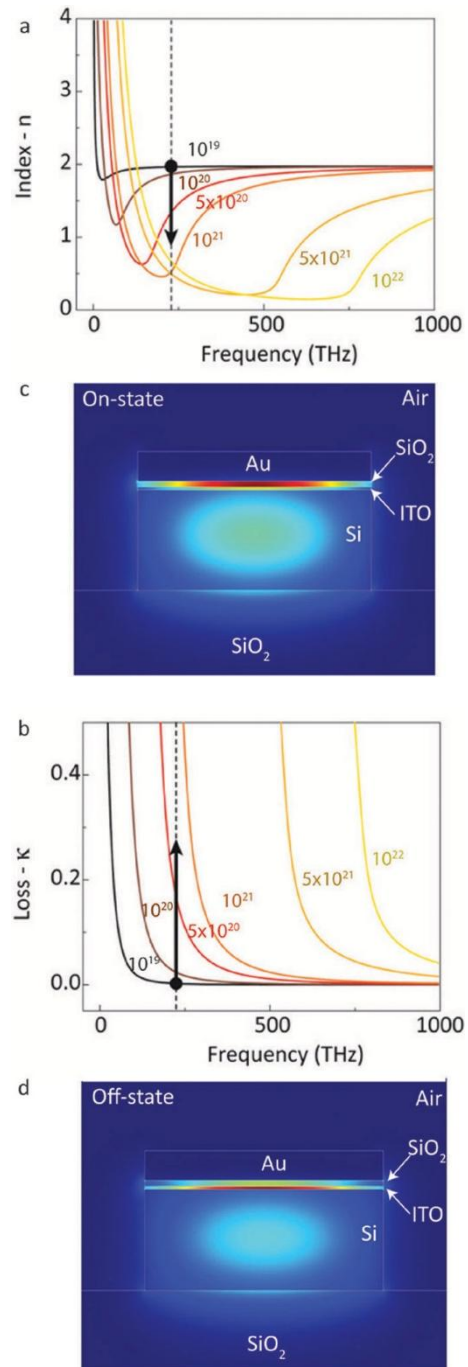
Figure 2a and b show the real and imaginary parts, respectively, of the refractive index of the ITO film versus the frequency for various carrier densities. The carrier concentration of the fabricated ITO is on the order of 10^{19}/cm^3 and is measured via a four-probe method. The carrier concentration of the

ITO increases when a bias voltage is applied between the silicon (ground) and metal (positive) contacts. The black arrows show the change in the carrier density of the ITO film corresponding to the experimental data. The bottom of each arrow corresponds to the modulator ON state (no voltage), and the tip of each arrow corresponds to the OFF state (voltage applied). The real part of the index n drops from about 2 to close to unity, whereas the imaginary part κ increases dramatically from virtually zero to 0.273. The change in the properties of the ITO film from being dielectric ($n_{ITO}>1$) to being quasi-metallic ($n_{ITO}\sim1$) effectively increases the optical field intensity in the ITO section. This is because a stronger discontinuity of the displacement current occurs across the MOS stack, see Figure 2(c) and (d). The increased carrier density simultaneously yields an increased loss that facilitates absorption of the laser light in the OFF state.
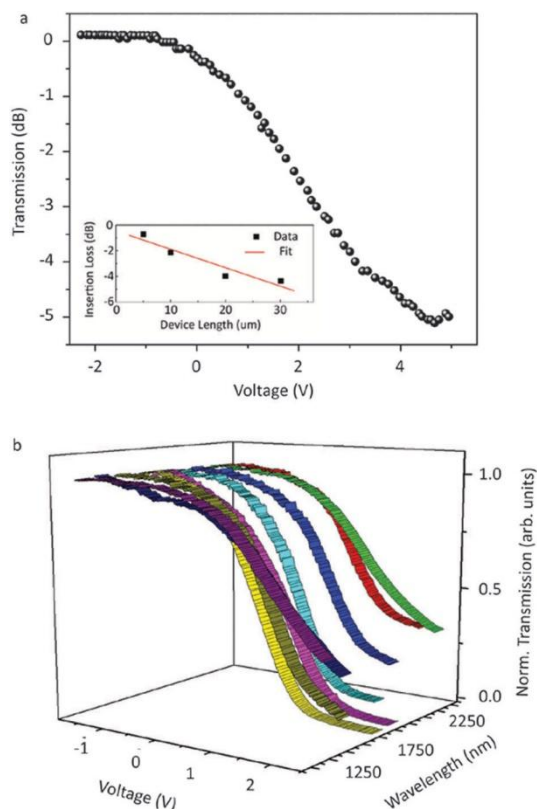
This plasmonic modulator exhibits an extinction ratio of 5dB for a device length of 5μm, see Figure 2(a). These results correspond to an extinction ratio of 1dB/μm, which is, to the best of our knowledge, the highest value among all the reported Si-based electro-optic modulators.[3,12] A noteworthy feature of our device is that it requires low voltage to switch the signal off. Whereas dielectric modulators show index changes per applied voltage of only one millionth, the voltage modulation potential of the modulator studied here is 10,000 times stronger for similar electrostatic geometries, see Figure 2(a).[3]

Another important device characteristic is the insertion loss in the ON state (no voltage applied) of the electro-optic modulator, where the goal is to minimize the optical loss. Our 5μm-long device suffers a total insertion loss of only about 1dB. This overall low loss is a significant improvement over photonic modulators. Even if the mode loss of a photonic modulator is much lower than that of the plasmonic one, the total insertion loss is even higher, because the photonic device requires millimeter-long interaction lengths where the loss is accumulated.[3]

In telecommunication, wavelength-division-multiplexing (WDM) has become established as the means of delivering high data bandwidths. It demands broadband operation of on-chip electro-optic modulation. We experimentally tested the broadband performance of our device by scanning the operating wavelength from 1.2 to 2.2μm and measuring the relative transmission as a function of the voltage, see Figure 3(b). The modulator exhibited good performance over this 1μm bandwidth. This broadband performance is a direct result of the non-resonance-based device modulation mechanism and holds promise for future deployment into WDM on-chip architectures.

Figure 2. The real (a) and imaginary (b) parts of the refractive index of the ITO film versus the frequency for various carrier densities. When the bias is applied, the carrier concentration of the ITO will increase, causing the real part of the index n to decrease and the imaginary part κ to decrease. In (c) and (d) we see the electric field densities for the ON and OFF state, respectively, of the modulator obtained by a finite element method simulation.

Figure 3. (a) The transmission versus the voltage for our device. Inset: The insertion loss versus the device length. The 5µm-long device suffers a total insertion loss of only about 1dB. (b) Broadband operating characteristics of the plasmonic modulator.

In conclusion, we have demonstrated a high-performance silicon-based plasmonic modulator. We have experimentally demonstrated a 1dB/µm extinction ratio with very low insertion losses of about −1dB for a device with a length three times the wavelength and showed broadband operation over a bandwidth of 1000nm. Such a silicon-on-insulator integrated device with high modulation strength, low insertion loss, and broadband capabilities enables ultracompact, power-efficient, and potentially fast on-chip data communication links for future photonic integrated circuits. We are working on demonstrating a high modulation bandwidth and integrating the silicon plasmonic modulator with other components.

References:
1. R. Kirchain, L. Kimerling, A roadmap for nanophotonics, Nat. Photonics 1, p. 303-305, 2007.
2. G. T. Reed, Silicon optical modulators, Nat. Photonics 4, p. 518-526, 2010.
3. A. Liu, A high-speed silicon optical modulator based on a metal–oxide–semiconductor capacitor, Nature 427, p. 615-619, 2004.
4. W. M. J. Green, M. J. Rooks, L. Sekaric, Y. A. Vlasov, Ultra-compact, low RF power, 10Gb/s silicon Mach-Zehnder modulator, Opt. Express 15, p. 17106-17113, 2007.
5. Q. Xu, B. Schmidt, S. Pradhan, M. Lipson, Micrometre-scale silicon electro-optic modulator, Nature 435, p. 325-327, 2005.
6. W. Cai, J. S. White, M. L. Brongersma, Compact, high-speed and power-efficient electrooptic plasmonic modulators, Nano Lett. 9, p. 4403-4411, 2009.
7. J. A. Dionne, PlasMOStor: A metal-oxide-Si field effect plasmonic modulator, Nano Lett.9, p. 897-902, 2009.
8. V. J. Sorger, N. D. Lanzillotti-Kimura, R. Ma, X. Zhang, Ultra-compact silicon nanophotonic modulator with broadband response, Nanophotonics 1, p. 17-22, 2012.
9. R. F. Oulton, V. J. Sorger, D. F. B. Pile, D. Genov, X. Zhang, A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation, Nat. Photonics 2, p. 496-500, 2008.
10. E. Feigenbaum, K. Diest, H. A. Atwater, Unity-order index change in transparent conducting oxides at visible frequencies, Nano Lett. 10, p. 2111-2116, 2010.
11. A. Melikyan, Surface plasmon polariton absorption modulator, Opt. Express 9, p. 8855-8869, 2011.
12. M. Liu, X. Yin, X. Zhang, Double-layer graphene optical modulator, Nano Lett. 12, p. 1482-1485, 2012.

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