Low-loss plasmon-assisted electro-optic modulator

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For nearly two decades, the field of plasmonics¹ - which studies the coupling of electromagnetic waves to the motion of free electrons in a metal² - has sought to realize subwavelength optical devices for information technology³⁻⁷, sensing⁸⁻⁹, nonlinear optics¹⁰,¹¹, optical nanotweezers¹² and biomedical applications¹³. Although the heat generated by ohmic losses is desired for some applications (e.g. photo-thermal therapy), plasmonic devices for sensing and information technology have largely suffered from these losses¹⁴. This has led to a widespread stereotype that plasmonics is simply too lossy to be practical. Here, we demonstrate that these losses can be bypassed by employing “resonant switching”. In the proposed approach, light is only coupled to the lossy surface plasmon polaritons in the device’s off-state (in resonance) where attenuation is desired to ensure large extinction ratios and facilitate sub-ps switching. In the on-state (out of resonance), light is prevented from coupling to the lossy plasmonic section by destructive interference. To validate the approach, we fabricated a plasmonic electro-optic ring modulator. The experiments confirm that low on-chip optical losses (2.5 dB), high-speed operation (>>100 GHz), good energy efficiency (12 fJ/bit), low thermal drift (4‰ K⁻¹), and a compact footprint (sub-λ radius of 1 μm) can be realized within a single device.
Our result illustrates the potential of plasmonics to render fast and compact on-chip sensing and communications technologies.

Telecommunication devices, such as electro-optic (EO) modulators must feature low insertion loss (IL) while providing a large phase ($\Delta n$) or amplitude ($\Delta \alpha$) change accumulated over a short device length. Beyond that, modulators should offer low driving voltages and high-speed operation.

In recent years, silicon photonic active devices have emerged which benefit from low propagation losses (3 dB/mm) but have struggled to achieve large modulation depth for sub-mm devices ($\Delta n$ and $\Delta \alpha$). State-of-the-art devices maximize their modulation through the use of resonant structures, enabling compact ($\mu$m-sized) and energy efficient components. However, the large Q-factor (on the order of a several 1000) limits the speed and increases the sensitivity of devices to temperature and fabrication fluctuations. More recently, surface plasmonic polariton (SPP) devices have exploited the extreme confinement of light to achieve exceptional modulation within a few $\mu$m ($\Delta n$ and $\Delta \alpha$). However, the metals that bring such promise to plasmonics are also the largest hindrance, as such devices suffer from large on-state loss (~dB/µm). To combat plasmonic losses, some devices employ hybrid-plasmonic-photonic modes while others minimize the length of the active section. Still, typical IL of 10 dB due to the plasmonic propagation loss and photonic-to-plasmonic mode conversion loss remain a concern for high-speed state-of-the-art devices. Thus, plasmonic on-chip technologies have been unable to replace the existing photonic or electronic solutions, placing the field of plasmonics at a crossroad to either abandon development or explore additional solutions.

We propose a novel approach, in which losses in plasmonic waveguides can be selectively used or bypassed to achieve low IL, strong modulation and high speed, simultaneously. This approach relaxes the prior goal to reduce the ohmic loss as much as possible to minimize the
device’s on-state loss. Instead, we show that plasmonic losses can be harnessed by designing the device geometry such that light passes through the lossy section when required (in the off-state). To achieve this, we utilize a plasmonic ring resonator coupled to a buried low-loss silicon photonic waveguide, see Fig. 1. Unlike prior approaches, which aim to reduce the resonator loss to realize high Q cavities or lasing\textsuperscript{8,24-27}, our resonator exhibits typical propagation losses within the plasmonic cavity and mostly bypasses this lossy section in the on-state through destructive interference. Using this design, we demonstrate for the first time, a plasmonic modulator that is able to meet the key performance metrics of modern optical communications links.

**Fig. 1:** False-colored SEM image of a plasmonic ring resonator and the corresponding transmittance over wavelength. (a) Top view and (b) cross section of the resonator. Photonic modes propagating in the buried silicon waveguide resonator couple partially to the SPPs in the metal-insulator-metal-ring when the resonance condition is fulfilled. While out of resonance operation results in a low loss light transmission. (c) Passive measurements of two identical ring resonators that only differ in radii (blue - 1030 nm; red - 1080 nm). Due to the resonant approach, insertion losses of 2.5 dB are measured with extinction ratios (ER) above 10 dB.

Fig. 1 shows the proposed device geometry, which comprises a gold metal-insulator-metal (MIM) slot waveguide ring coupled to a buried silicon bus waveguide, forming a notch filter with a resonant wavelength of (λ_{res}) (supplementary information: chapter II). The slot waveguide is filled with an organic electro-optic (OEO) material which alters the device’s
resonance condition through the Pockel’s effect ($\Delta n_{\text{SPP}}$)$^{28,29}$. This enables a fast and selective use of the plasmonic loss to attenuate the signal ($\Delta \alpha$) in the bus waveguide by applying a voltage.

Fig. 1(c) shows the measured transmittance over the wavelength of two representative devices that differ in radius. For these structures, we have observed a distinct off-resonance ($\lambda_0 \neq \lambda_{\text{res}}$) and on-resonance ($\lambda_0 = \lambda_{\text{res}}$) condition at the telecommunication wavelength of 1.54 $\mu$m with an IL of 2.5 dB, an extinction ratio (ER) of 10 dB, and a Q-factor of ~30. Alternatively, we note that non-resonant devices based on MIM waveguides with a similar length feature an IL ranging from 8-10 dB$^6,7,23$.

The reduced IL can be understood by comparing the exemplary operating principles of a non-resonant Mach-Zehnder (MZ)$^6$, Fig. 2(I) and a resonant ring, Fig. 2(II). The IL of the device is a function of its coupling efficiency, geometry and accumulated ohmic loss. In both concepts, light couples to and from the plasmonic structure with a coupling efficiency ($C$). A transmission modulation is then induced by the Pockels effect over an active plasmonic section of length or circumference ($l$). The modulation depth ($\Delta T$) – and also the loss ($L_{\text{SPP}}$) – scale with the length of the active plasmonic section$^6$. Fig. 2 shows the overall IL over the $L_{\text{SPP}}$ in the active plasmonic area for a MZ and a critically coupled resonator. The arrows indicate the performance of devices with an equal $\Delta T$. 
The following points arise from Fig. 2. First, the resonator’s loss is always smaller (blue curve < red curve) due to the bypassing mechanism\(^{30}\). Second, the resonator has a 1 dB lower IL at \(L_{SPP} \approx 0\) dB. This is because the non-resonant device requires two photonic-SPP converters as both the on- and the off-state propagate through the plasmonic section. Ohmic losses in the converters limit the conversion efficiency (\(C\)) to \(\sim 1\) dB\(^{23,31}\). Contrarily, the selection mechanism of the resonator (on-state⇒bus waveguide; off-state⇒ring) requires a converter which couples only a fraction of the light to the ring. Third, in the ring we take advantage of the resonantly enhanced \(\Delta T\) to reduce the device length (supplementary information: chapter VII). For our resonant structures, we have calculated an enhancement of \(\sim 1.5\). Consequently, our ring with a circumference of \(l = 6\) μm (\(L_{SPP} \approx 4\) dB) offers the same transmittance change as a MZ of \(l = 9\) μm (\(L_{SPP} \approx 6\) dB). In total, the ring device offers a 6 dB IL advantage over the MZ modulator. Additionally, losses can be further reduced by under-coupling the resonator as limited ERs of 10 dB are sufficient for many practical applications\(^{32}\).
To illustrate the modulation performance ($\Delta \mathcal{I}$) of the plasmonic resonator, the SPPs’ effective refractive index ($\Delta n_{SPP}$) is altered by applying a bias between the inner and outer rings.\(^{28}\) Fig. 3(a) shows the transmitted power versus applied voltage for a wavelength of $\sim 1.52$ $\mu$m. We observed an IL $< 3$ dB, an ER of $\sim 10$ dB, and a linear response (dashed green line) for a peak voltage of 3.5 V with an ER of $\sim 6$ dB. This performance in terms of IL and ER is similar to well-developed CMOS photonic resonators.\(^{20}\) We estimate that operation under a digital driving voltage ($1$ $V_{pp}$)\(^{20}\) is achievable in the near future by utilizing other plasmonic materials like silver or copper, using the newest OEO-materials and improving fabrication (supplementary information: chapter VIII). To highlight the mechanism of the modulation the transmission of the device has been measured under a positive and negative bias of $\pm 3.75$ V as a function of wavelength, see Fig. 3(b). This results in a normalized sensitivity ($S_{\lambda}/\Delta \text{FWHM} = \Delta \lambda_{\text{res}}/(\Delta \text{FWHM} \cdot \Delta n)$) of $\sim 17$ RIU$^{-1}$, assuming a relative change in OEO’s refractive index of $\sim 0.03$. This can be compared to commercial SPR sensors that achieve values of 50 RIU$^{-1}$ using a free-space Kretschmann configuration.\(^{33}\) So, currently our approach is already close to the non-integrated free space approaches.

**Fig. 3** Sensitivity and stability of the plasmonic resonator. (a) Voltage sensitivity of the resonator’s transmittance. (b) Sensitivity of the ring as a function of the wavelength. A small change ($\Delta n_{\text{slot}}=0.03$) in the refractive index of the slot-filling material causes a large change of the resonance wavelength (blue/red). (c) The resonator shows stable operation across a large thermal variation. These characteristics make the plasmonic MIM-ring resonator a promising candidate in the field of optical modulators and sensors.
The moderate Q-factor guarantees a high operational speed and provides good thermal stability. For example, the measured resonance frequency is plotted in Fig. 3(c) over a temperature range from 20°C up to 90°C. In this case, the resonant frequency is found to follow a linear trend line with a slope of ~0.4% K⁻¹. The insensitivity of the plasmonic resonator to temperature fluctuations is in strong contrast to photonic resonators, which are two orders of magnitude more sensitive to temperature fluctuations (~100% K⁻¹)¹⁹. This is extremely beneficial for applications where strong temperature fluctuations occur. For example, a plasmonic resonant sensor or modulator would be immune to thermal fluctuations of ±5 °C which normally occur in CPUs while photonic resonators require power-consuming temperature controls to maintain operation²⁰. Furthermore, the moderate Q factors are also beneficial for high-speed operation as desired in electro-optic modulators. As a result, we are able to push the bandwidth of a resonant electro-optic modulator well beyond 100 GHz (supplementary information: chapter XIII). In comparison, photonic resonators are more likely limited to bandwidths of ~20 GHz and below¹⁹,²⁰.

Fig. 4: High-speed data experiments with a plasmonic ring resonator used as an EO-modulator. (a) Depicts the experimental setup. (b) Bit-error-ratio (BER) vs. wavelength for a resonator with λ_resonance = 1549 nm. BERs below the hard-decision forward error correction (HD-FEC) limit show successful data modulation and detection without the use of a temperature control. The BER increases at the resonance wavelength as expected from the notch-filter response of the resonator. (c) Shows the bandwidth of the plasmonic resonator in the bottom, which is beyond 110 GHz.
Subsequently, we performed high-speed data experiments to demonstrate the robustness, high speed and low power switching capability. Although, the “resonant switching” principle can also be used to optimize sensors, we focus on high speed applications because their sensitivity and stability requirements are stricter.

In the experiment of Fig. 4(a) the peak driving voltage was ~3.3 V\textsubscript{peak} and the laser wavelength was varied to capture the response of the modulator. Low device losses of 2.5 dB and fiber-to-silicon waveguide losses of ~7 dB resulted in fiber-to-fiber coupling losses of 16.5 dB enabling successful operation with low laser powers of 4 dBm and below. The resulting bit-error-ratio (BER) versus wavelength for a 72 Gbit/s signal is shown in Fig. 4(b) where a peak in the BER is observed at \(\lambda\text{res}\). A high BER is observed at \(\lambda\text{res}\) since applying the same voltage with an opposing sign results in the same optical amplitude but a different phase. Consequently, we confirmed that the operating mechanism relies on amplitude modulation. Off-resonance, the BER quickly dropped to ~1×10\(^{-3}\) which is below the hard-decision forward error correction (HD-FEC) limit and allows for successful data modulation and detection\(^{34}\). No thermal heater was required for stabilization. Additionally, we reduced the data-rate to 36 Gbit/s and 18 Gbit/s and found BERs of ~2×10\(^{-6}\) and <1×10\(^{-6}\), respectively, indicating that the BER at 72 Gbit/s is mainly limited by the electrical equipment (supplementary information: chapter XIV). We estimate the energy consumption of the modulator to be ~12 fJ/bit at 72 Gbit/s\(^{15}\) for a device capacitance of 1.1fF.

We demonstrate that low-Q resonant designs can enable low-loss active plasmonic devices with a good modulation depth by utilizing highly confined SPPs. We believe that our approach – unlike conventional resonant photonics – breaks the trade-off between sensitivity (high-Q) on the one hand and speed and temperature stability (low-Q) on the other. Our work can be seen as a step towards practical plasmonics that ultimately serves as a compact and fast gateway.
between electronics (local signal processing) and photonics (broad bandwidth and low-loss data stream). The proposed slot waveguide approach could also open many applications in sensing because the resonant response can be exploited for many other material systems ranging from low index materials like aqueous solutions to high index materials such as silicon.

Supplementary information and methods are given in the supplementary information manuscript. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References:


**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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Author contributions:

C.H., N.K., V.S., A.B. and J.L. conceived the concept and supervised the project. C.H., D.C., S.S., and T.C. designed the modulator and developed the analytic framework for fast optimization. T.W. designed the photonic grating coupler. C.H., D.C. and Y.F. fabricated the modulator and developed the required process technology. B.C. developed a focused ion beam process to image the cross section with minimal destructive influence on the suspended bridge. D.L.E., W.H., C.H., and L.R.D. developed, synthesized and implemented the poling procedure of the OEO-material for plasmonic ring resonators. C.H., and J.L., designed the experiments. C.H., D.C. and T.C. performed the passive characterization. C.H. performed the temperature sensitivity, DC switching and electro-optic bandwidth experiments. B.B., A.J. and C.H. performed the high-speed data experiment. B.B. and A.J. designed, calibrated, and automated the high-speed data experiment. B.B. and A.J. developed the digital-signal processing for data generation and analysis of the high-speed data experiment. All authors discussed and analysed the data. C.H., N.K., D.C., and J.L. wrote the manuscript.

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