Compact nanomechanical plasmonic phase modulators

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Highly confined optical energy in plasmonic devices is advancing miniaturization in photonics. However, for mode sizes approaching ∼10 nm, the energy increasingly shifts into the metal, raising losses and hindering active phase modulation. Here, we propose a nanoelectromechanical phase-modulation principle exploiting the extraordinarily strong dependence of the phase velocity of metal-insulator-metal gap plasmons on dynamically variable gap size. We experimentally demonstrate a 23-μm-long non-resonant modulator having a 1.5π rad range, with 1.7 dB excess loss at 780 nm. Analysis shows that by simultaneously decreasing the gap, length and width, an ultracompact-footprint π rad phase modulator can be realized. This is achieved without incurring the extra loss expected for plasmons confined in a decreasing gap, because the increasing phase-modulation strength from a narrowing gap offsets rising propagation losses. Such small, high-density electrically controllable components may find applications in optical switch fabrics and reconfigurable plasmonic optics.

Surface plasmons (SPs) are collective electronic oscillations localized to metal–dielectric interfaces, with numerous plasmonic-based devices having been demonstrated previously. Gap plasmons (GPs) arise when two such metal–insulator interfaces are separated by a narrow gap across the insulator layer, transversely confining the electromagnetic energy in metal–insulator–metal (MIM) waveguides. The characteristics of GPs coupled to various MIM waveguide structures have been studied for about a decade. Investigations have been reported on the effects of the metal film thickness, how the effective index of MIM waveguides depends on the gap dimension, and how deep-subwavelength confinement can be achieved, with gaps as narrow as 3 nm. With deeper confinement, an increasingly larger fraction of the propagating mode energy is transferred from the waveguide insulator into the surrounding waveguide metals. Nanomechanically varying the gap provides a way to tune the effective refractive index of an MIM plasmonic device to electrically control the GP. Such a control mechanism could be used in switching fabrics for photonic applications and reconfigurable plasmonic optics.

Phase modulators, often used as active elements in photonic switches, enable the flexible provision of communication channels and the reconfiguration of networks at the physical layer. The application requirements for switches are distinct from those of data modulators: switching can often be slower than data modulation rates, with a premium put on compactness, low power consumption, wide optical bandwidth and low optical losses. As nanophotonic optical communication architectures and technologies are being developed in response to inter-chip and on-chip electronic bottlenecks, more compact, low-power optical switch fabrics, enabling the flexible signal routing and dynamic reconﬁguration of the optical layer, architecturally analogous to electronic field-programmable gate arrays.

Several different modulation principles have been proposed and used to realize a variety of compact phase modulators. Most are aimed at data modulation, and only recently have the ultimate limits of size scaling been approached experimentally. Non-resonant devices have limited phase modulation strength per area and include thermo-optical devices with large power dissipation, very fast slot plasmon electro-optical devices, where device size is limited by the Pockels effect, and electromechanical devices. Optically resonant electro-optical and electromechanical devices achieve higher phase-modulation strength at the expense of reduced optical bandwidth. Semiconductor and plasmonic devices based on a change in carrier concentration tend to have large absorption modulation, which results in high excess loss for phase modulation. These, as well as optomechanical plasmonic–resonance devices, work well as intensity modulators, which are not suitable for realizing passive 1 × 2, 1 × N or N × N switch fabrics.

Modulation principle

In this Article we propose and demonstrate a gap plasmon phase modulator (GPPM), where the effective refractive index for in-plane GP modes is varied strongly via electromechanical geometric reconfiguration. The index increases approximately proportional to the applied voltage squared, a dependence similar to the electro-optic effect in Kerr-nonlinear materials (Supplementary Section 3). GPs are broadband optical propagating modes that can be vertically and laterally conﬁned to sub-100 nm gaps between two metal layers, forming some of the smallest known optical waveguides and resulting in significant field enhancements. Low-loss coupling into such small GP waveguides has been demonstrated, making possible efficient connections to conventional dielectric waveguides for long-distance interconnects. The GPPM exploits the high sensitivity of the GP phase velocity to changes in the gap size by making one of the metal layers mechanically moveable via electrostatic actuation. No optical resonator is used to enhance the phase modulation and there is no low-frequency guided mode cutoff, making the modulation principle optically broadband, capable of operating from the visible to the far-infrared. The phase modulation strength per area of our experimentally demonstrated GPPM is comparable...
to that of resonant devices and an order of magnitude better than that achieved in mechanically tuned dielectric slot waveguides\(^ \text{22} \). Although in dielectric slots the effective index tends to a fixed value as the gap is reduced, in GPs it continues to increase steeply, underling the unique GPPM scalability.

The nature of confined energy modes at optical frequencies in plasmonic devices can itself be understood as electro-mechanical\(^ \text{38} \) as opposed to electromagnetic, with the kinetic energy of electrons, together with the Coulomb energy, playing a critical role and enabling localization at much smaller scales. This confinement comes at the expense of increased losses through inelastic electron scattering, which may impose fundamental limitations on the scaling of any plasmonic device and thus should be thoroughly understood. We present an analytical investigation showing, remarkably, that our GPPMs can be scaled down by at least a factor of 100 in area, while maintaining the greater than \( \pi \) rad modulation depth and \( \approx 5 \text{ dB} \) optical loss. The optomechanical modulation strength increases with decreasing gap, and the propagation losses can be kept constant by shortening the device length.

**Experimental**

The details of the GPPM are shown in Fig. 1. Figure 1a shows the GPPM located in a Mach–Zehnder interferometer (see Methods). A close-up shows the GPPM to be an electrostatically tunable gold–air–gold waveguide fabricated from a gold–SiO\(_2\)–gold MIM stack (see Methods) with a device-dependent initial air gap, \( g_0 \equiv g(V = 0) \), of \( \approx 270 \text{ nm} \) to \( 280 \text{ nm} \). The top gold film is patterned into 11 suspended deformable metal bridges, each 23.0 \( \pm 0.5 \mu \text{m} \) in length and 1.50 \( \pm 0.07 \mu \text{m} \) wide, supported at both ends by SiO\(_2\) pillars. A GP, launched via grating coupling with a focused free-space excitation laser, propagates underneath and along the

bridges. A focused reference beam, split from the excitation laser and incident at the \( y \)-\( z \)-plane at 13.2\(^ \circ \), interferes with the plasmon at the out-coupler slit. Light is collected from below and imaged onto a camera. As shown in Fig. 1c–e, when a voltage is applied, the electrostatic force deforms the bridges downwards into an approximately parabolic shape, narrowing the MIM gap at the bridge centre, \( g(V) \), by \( \approx 80 \text{ nm} \) (device-dependent) as the voltage increases up to a maximum of 7 V and phase-retards the GP. To avoid electrostatic ‘pull-in’\(^ \text{39} \), where the top gold bridges snap down to the bottom gold surface, the bridges are not actuated beyond one-third of \( g_0 \). To measure the GPPM optical performance, a 780 nm wavelength Gaussian laser beam is focused from above onto one in-coupler grating cut into the top film at the GPPM input, launching a collimated Gaussian GP mode into the device propagating in the \( x \)-direction (Fig. 1a–c). An out-coupler slit, parallel to the \( y \)-direction at the output of the GPPM, is used to sample the modulated plasmon using a microscope from below. A window in the top gold film, above the out-coupler slit, allows the introduction of a tilted-reference optical beam for phase-sensitive imaging of the modulated plasmon. Using a Mach–Zehnder type interferometer with the reference split off from the excitation laser, both the GP phase retardation and optical loss are measured as a function of \( g(V) \) by electrostatically controlling the GPPM bridge displacements (Fig. 1). Optical micrographs of the out-coupled GP light are collected with and without the reference optical beam at different applied d.c. voltages. The interference and GP–only intensity profiles are extracted by integrating the micrograph data in the \( x \)-direction, normal to the slit (see Fig. 2a, top, for a representative interference micrograph).

Figure 2 shows these profiles at different applied voltages for one of the devices. The interference patterns shift to the right as the GP...
The GPPM has an average optomechanical modulation strength of 52 ± 4 mrad nm⁻¹, producing a maximum 3π/2 rad phase shift, which can be compared to the π/2 rad shift demonstrated in a 170-μm-long optomechanical dielectric device⁴⁵. A modulation range in excess of π rad is required by many practical switching and modulation applications. To understand the GPPM performance we developed semi-analytical models of one dimensional GP propagation as well as a comparison to electro-optic modulation (Supplementary Section 2b). The analytic results for GP phase shift and intensity calculations agree well with the measured data (Fig. 3a,b solid line). The calculated intrinsic insertion loss through an unactuated device is 5.3 dB.

Scaling analysis
Unlike dielectric waveguides, MIM waveguides support a guided mode for any frequency below the SP resonance and for gaps down to the single nanometre range (below that, local classical theory begins to break down)⁴⁴. The effective index increases and the GP wavelength decreases dramatically in small gaps, making it particularly appealing for nanoscale motion
sensing and on-chip optical actuation in applications where strong yet broadband optomechanical coupling is required. Decreasing \( g_0 \) increases optical propagation losses, as a larger fraction of the optical power travels inside the metal. If the bridge length (optical travel distance) is also decreased, for each length there is a corresponding \( g_0 \) (Fig. 4a, inset) such that the insertion loss (loss through an unactuated device) remains constant, for example, at 1/e power (4.3 dB), with length scaling \( \sim g_0^{3/2} \). The striking result shown in Fig. 4a,b is that if we scale down the GPPM dimensions in this way, we will maintain the phase modulation range without incurring a loss penalty while simultaneously reducing both the length and \( g_0 \), by an order of magnitude or more, as the calculated phase and excess loss versus \( g(V) \) plots illustrate. In fact, the phase modulation range stays constant with miniaturization for a given optical loss. For \( g_0 \), much smaller than the SP evanescent decay distance, universal scaling emerges between the phase shift and the excess loss such that they are linearly related regardless of \( g_0 \); for example, as \( g(V) \) is decreased to 72% of \( g_0 \), the phase modulation stays constant at \( \pi \) rad and there is a small excess loss of 0.8 dB (Fig. 4b, inset), independent of the device scale.

For static MIM devices it has already been shown that the lateral dimensions can be scaled down together with \( g_0 \) and that low-loss coupling from larger mode waveguides suitable for long-distance signal transmission can be achieved\(^{14,15}\). A coupling efficiency of >70% has been demonstrated, coupling from a waveguide 500 nm wide \( \times \) 200 nm high to an 80 nm \( \times \) 17 nm waveguide using a 29° linear coupling taper\(^{15}\). As long as the device width is larger than \( g_0 \), the optical mode remains well-confined in the gap under the bridge\(^{15}\). Our GPPM model is quantitatively valid for device widths larger than approximately half the GP wavelength (estimated as 710 nm in the experiment, \( n_{eff} \approx 1.1 \)). As the effective index increases and GP wavelength decreases with \( g_0 \) (\( \approx 370 \) nm and \( n_{eff} \approx 2.1 \) for \( g_0 = 17 \) nm), the width of the device can also be reduced further. By way of example, an approximate linear downsizing by 10x keeps losses near 5 dB in a broadband, non-resonant modulator with a footprint of \( \leq 1 \mu m^2 \) (\( g_0 = 17 \) nm, 400 nm bridge width and 2 \( \mu m \) bridge length). In such a scaled GPPM the optomechanical modulation strength is increased approximately inversely with \( g_0 \) to \( \approx 560 \) mrad \( nm^{-1} \), despite the length decrease. Importantly, the electrostatic actuation amplitude also scales favourably with miniaturization. Within the applicability of linear beam-bending theory without in-plane stress, the shape of the deformation remains self-similar and the same percentage gap modulation can be achieved stably, without electrostatic pull-in, with voltage that scales as \( V^2 \sim g_0^2/L^{4/3} \), where \( L \) is the bridge length and \( f \) is the bridge thickness (see Methods). The displacement available before pull-in is always sufficient for \( \pi \) phase modulation, as both scale inversely with \( g_0 \). Given the bridge-length/\( g_0 \) combinations chosen according to the chosen scaling constraint of the inset to Fig. 4a, \( V \sim f^{2/3} \) is constant at fixed bridge thickness and approximately independent of the bridge length and \( g_0 \). If necessary, the bridge thickness can easily be scaled down by a factor of 4 or more (while staying well above the optical

**Figure 4 | GPPM scaling.** a. Calculated phase shifts versus gap \( g(V) \) for initial gaps \( g_0 \equiv g(0) \) varying from 280 nm to 20 nm. The bridge length of each line is chosen to give a 1/e (−4.3 dB) insertion loss for a given \( g_0 \) (inset). Lines show how the phase changes as \( g(V) \) is actuated from 100% to 40% of \( g_0 \). Identically coloured points indicate the same percent bridge actuation. An actuation depth of \( \approx 72\% \) results in a phase shift of \( \pi \) rad (dashed line) and avoids pull-in. Regardless of \( g_0 \), for the same percent actuation depth, the phase shift is almost constant as indicated by the horizontal rows of identically coloured points. b. Calculated excess loss versus \( g(V) \) using the same bridge lengths described. Excess loss is defined relative to the unactuated state. The same universality is seen here. For example, \( \approx 72\% \) actuation of \( g_0 \) gives \( \approx 0.8 \) dB loss (dashed line). Inset: phase shift versus excess loss is linear and independent of device scale.

\[ \text{Excess loss (dB)} \]

\[ \text{Phase shift (rad)} \]

\[ \text{Gap (nm)} \]

\[ \text{Zero (rad dB}^{-1}) \]

\[ \text{Slope} \]
skin depth of ~25 nm), reducing the actuation voltage below 1 V, to a level compatible with low-voltage CMOS circuitry. Electrical breakdown in dry air at these voltages should be avoidable, because such breakdown between platinum nanotip cathodes and plane gold film anodes has been measured to be linear down to 20 V for a 40 nm gap, extrapolating to 8.5 V for a 17 nm gap.

In vacuum, scanning tunnelling microscopy measurements between tungsten tips and silicon22 show tunnelling currents of only 1 nA at 8 V over a much smaller, ~2.3 nm gap.

The inset to Fig. 1e shows that the realized GPPM has a resonance frequency of 812 ± 6 kHz, an air-damping-dominated quality factor of 2.74 ± 0.14 and was actuated at a drive frequency up to 1 MHz. While we emphasize that a very high modulation frequency is not required for the envisioned on-chip optical switching and configuration applications, the mechanical resonance frequency scales as ~1/\(L^2\) and is able to increase up to ~100 MHz with fixed bridge thickness and drive voltage. The expected lifetime of the devices should far exceed gold-bodied micromechanical switches that have achieved over 10 billion cycles because the GPPM avoids contacting surfaces that are the main failure mechanism of the switches.44,45 Furthermore, non-plasmonic nanomechanical cantilever devices of similar dimensions have been made operating up to 1 GHz with careful material choice46,47 and such a fast, yet ultrasmall modulator can potentially operate at low voltage with the use of piezoelectric actuation.48–50

Discussion

Considering the negligible power dissipation of its electrostatic drive, actuation voltages at the level of the smallest high-speed transistors, length scale and feature size at the level of CMOS metallization layers, broadband optical operation and reasonable speed, we argue that a GPPM can play a unique and important role as a building block for optoelectronic integration. A device with these features is particularly well suited as an element for on-chip reconfigurable switch fabrics for future dynamic inter- and intra-chip optical communication architectures.

Passive 3 dB couplers and single-mode waveguides can be implemented in a narrow-gap MIM together with phase modulators to form, for example, Mach–Zehnder 2 × 2 switches (such as an ultrasmall 2 × 2 nanomechanical plasmonic switch). It is possible to array modulators side by side to form spatial plasmonic modulators and implement, for example, single-stage 1 × N switching and arbitrary multiport beamsplitting—functionalities demonstrated using spatial light modulators in free space. This may enable reconfigurable routing of photonic signals or reconfigurable flat plasmonic optics, where local phase modulation across an extended GP wavefront could be used to shape, focus or guide GP propagation via optics, where local phase modulation across an extended GP wavefront could be used to shape, focus or guide GP propagation via.

The authors chose a multiple-bridge GPPM as a step in that direction when a single bridge device would have sufficed.

We do not envision our devices competing with Pockels-effect devices22,24 for fast modulation, but instead we are exploring the limits of scalability. To that end, a scaled-down 2-μm-long GPPM, analytically described and depicted in Fig. 4 and with an applied voltage of 1 V, would yield a n voltage-length product of 2 V μm, more than an order of magnitude smaller than the state of the art.22 Additional analysis comparing Pockels-effect modulation scalability in MIM structures with a GPPM (Supplementary Section 2b and Fig. 3) suggests that the plasmonic losses make it difficult for the Pockels devices to maintain the modulation range and low insertion loss while continuing to scale down, as the GPPM does.

Conclusion

In summary, we have experimentally demonstrated exceptionally strong optomechanical transduction with low optical losses in electrostatically actuated nanoscale-gap MIM plasmon modulators. The 23-μm-long GPPMs, with an average optomechanical modulation strength of 52 mrad nm⁻¹ at 780 nm, achieved a maximum of 5 rad of phase modulation with low insertion and excess losses. An analytical model in good agreement with the measurements argues for direct miniaturization of these devices to a sub-1 μm² footprint, without any degradation in optical performance and with an increase in speed and decrease in actuation voltage. This new concept enables a new class of on-chip optical switching and optical circuit reconfiguration functionality.

Methods

Nanostructure and operation. A gold–SiO₂–gold stack, composed of sputtered gold and PECVD (plasma-enhanced chemical vapour deposition) SiO₂ layers (all three 220 ± 5 nm thick), was deposited onto nominal 500-μm-thick borosilicate glass with an ~10 nm chromium adhesion layer located between the substrate and bottom gold layer and an ~2.5 nm-thick titanium adhesion layer on either side of the SiO₂. All device features, except the out-coupler slit, were lithographically written with electron-beam lithography using ~500 nm poly methyl methacrylate (PMMA) electron-beam resist. After resist development, device components were argon ion-milled into the top gold layer. The bridges were released by wet etching of the underlying SiO₂ to ~1.5 μm and incident on a 50/50 beamsplitting CO₂ critical-point-dryed. The SiO₂ was completely removed everywhere below the lithographic patterns, leaving a lateral undercut of ~2.5 μm. After release, the SiO₂ pillars supporting the bridges at their ends were ~3 μm wide in the direction of GP propagation. The out-coupler slits were ~130 nm wide by ~20 μm long, and were cut with a focused ion beam (FIB). The suspended in-coupler gratings, composed of strips ~18 μm long and ~400 nm wide with periods of ~720 nm and ~760 nm, were electrically grounded to avoid unintended actuation.

An electrically isolating 2-μm-wide trench in the top gold layer surrounded the GPPM components (for partial view see Fig. 1b). A narrow wire nanofuse (Supplementary Fig. 1e) connected the area inside the trench to that outside to allow charging to dissipate during scanning electron microscopy and FIB. The nanofuses were electrically severed before electrostatic bridge actuation. The actuation voltage between the bridges and the bottom gold film was applied via probes electrically connected to the top and bottom films.

The GP-only intensity profile in Fig. 2a exhibit some non-Gaussian features that we attribute to small fluctuations in the heights (gaps) of individual bridges on the relief of stress in the top gold and PMMA during release. This effect varied from device to device and can be seen in Fig. 3b as intensity variations as the gap narrows.

Interferometer. A Mach–Zehnder type interferometer was used to measure the phase shift between a GP and a reference laser beam. This consisted of an inverted microscope custom-fitted with a top excitation objective and beam-steering optics. Laser light (λ = 780 nm, linewidth < 200 kHz, power = 0.2 mW) was fibre-coupled to the top, collimated to ~1.5 mm and incident on a 50/50 beamsplitting cube. Half of the light was directed to the objective and the other half formed a reference beam, circling back on itself using adjustable mirrors over an ~20 cm path length before also travelling into the ×10 excitation objective. The excitation beam, an ~8-μm-diameter focused spot, was placed onto the in-coupler grating, directly launching a GP through the waveguide. The reference beam was focused onto the out-coupler slit at a 13.2 ± 0.05° angle with respect to the normal. Near the out-coupler slit, the top gold film was removed and the GP from the device continued to propagate as an SP on the gold-air interface. The propagation distance between the in-coupler and out-coupler was ~60 μm, which is much smaller than the estimated Rayleigh range of ~165 μm, the estimated Rayleigh range of the plasmon. At the slit, the reference beam interference with the propagating SP developed into fringes. Gap narrowing by electrostatic beam actuation caused GP phase velocity retardation, and thus shifted the interference fringes from their initial positions. The angled reference beam was chosen to show multiple interference fringes across the in-coupler slit. For each device the beam intensity was adjusted to maximize the interference visibility before voltages were applied.

The reference incidence angle was measured with no device in place by analysing a series of images of the reference laser spot as it moved across the microscope objective focal plane as the objective was translated vertically by a known amount.

Static and dynamic displacement measurement. A commercial white-light optical profiler with defraction-limited in-plane resolution and out-of-plane resolution below 1 nm was used to measure the vertical bridge displacements. The dynamic mechanical response of the GPPM was measured with a strobed white light using harmonic sweep excitation voltages (1.5 V peak-to-peak sine wave with a 0.75 V d.c. bias) up to 1 MHz. The strobed pulses were phase-delayed for a phase-sensitive motion measurement. The response amplitude can be seen in Fig. 1e where it is fit by a damped harmonic oscillator model.

Gaussian interference fits. The phase difference between the GP and reference laser was extracted from Gaussian interference fits of the measured interference profiles in Fig. 2a and is the only variable used. The fits use (1) GP-only intensity profile data like that in Fig. 2b; (2) Gaussian reference beam parameters (width, peak...
position and integrated area) extracted from measured interference profiles and with the reference beam intensity maximized; and (3) the independently measured reference incidence angle (Fig. 1b). Fits from the data of one device are plotted in Fig. 2a. The results in Fig. 3 from several devices are the same within experimental error when adjusted for the initial phase differences caused by slightly different unaccounted gaps.

Uncertainty. The uncertainties reported throughout the manuscript represent one standard deviation (1 s.d.) statistical uncertainties, unless otherwise indicated. The uncertainty in device sizes is given by a conservative estimate of the scale calibration accuracy of the electron microscope used. The uncertainties in the \( g(V) \) values are standard deviations of \( g(V) \) under different bridges in a single device with a given applied voltage, and are probably due to mechanical variations from bridge to bridge. The measurement imprecision and errors in actuation repeatability are much smaller. The uncertainty in the phase measurement is dominated by the slow drift of the optical wavelength, which results in a phase drift between the excitation and reference beams passing through unequal paths. We therefore make separate reference unaccounted phase measurements before and after each non-zero voltage phase measurement. We used the variation in the unaccounted measurements to establish the statistical phase measurement uncertainty reported (the statistical uncertainty of the fitting procedure for each individual interferogram is much smaller).

Theory. To theoretically understand the GPPM performance we developed a semi-analytical model of one-dimensional GP propagation, assuming an infinitely wide plasmonic GP, quadratic bridge profiles, semi-infinite MIM gold layers and vacuum in the gap. The device was broken into 1 nm intervals in the direction of GP propagation, with each interval assigned a gap-dependent effective refractive index and the corresponding wavenumber. Using continuity boundary conditions from Maxwell’s equations, the phase shift and intensity were cumulatively calculated. The analytic results of GP phase shift and intensity calculations agree well with measured data (Fig. 3a,b solid line; Supplementary Section 1). Although the modelling procedure includes both forward- and backward-propagating waves, under the experimental conditions the gap changes adiabatically and the back-propagating power was found to be negligible throughout the model.

Mechanics. The electrostatic pressure \( P \) at the cantilever bottom is proportional to \( (V/g)^2 \). Within the applicability of linear elastic beam bending theory without in-plane stress, the shape of the deformation remains self-similar with size scaling, and the magnitude is \( P \) proportional to \( PL^3/t^4 \), so if we require \( z \) ~ \( g \), then \( g \sim (V/g)L^3/t^2 \) or \( V \sim g^3/L^3 \).
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Author contributions
B.S.D. developed the fabrication process, designed and fabricated the modulators, performed the experiments, analysed the data and wrote the manuscript. M.I.H. developed an analytical model and wrote the manuscript. G.B. developed the concept, designed the experiment and wrote the manuscript. D.A.C and D.L. developed the fabrication process. V.A.A. developed the concept, designed the experiment, performed simulations, developed the fabrication process, analysed the data and wrote the manuscript.

Additional information
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Competing financial interests
The authors declare no competing financial interests.