Subdiffraction optical motion transduction using a scalable plasmomechanical platform

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Abstract: We present a scalable platform for producing reconfigurable plasmonic devices. Using localized-gap plasmon resonators exhibiting large quality factors, we demonstrate sensitive, plasmon-based measurement of motion from a deep subdiffraction region. **OCIS codes:** (250.5403) Plasmonics; (230.4685) Optical microelectromechanical devices; (220.4241) Nanostructure fabrication

Plasmonic devices and metasurfaces have had a broad impact across optical nanoscience, with applications including optical tweezers, holograms, and ultrathin optical elements [1, 2]. Recently, there has been considerable interest in creating dynamic, mechanically reconfigurable plasmonic systems [3–5]. Such devices herald exciting opportunities for controlling light on the nanoscale, for instance, through the production of ultrafast and compact optical modulators [6]. Here, we present a new platform for creating these "plasmomechanical" devices, whereby gold plasmonic elements (rectangular blocks) are embedded directly into movable mechanical components (cantilever beams) and suspended above an underlying gold pad by a narrow gap (Fig. 1a). The gap, which is the critical feature defining plasmonic performance, is constructed "vertically" using a thin, planar Cr sacrificial layer that is selectively removed using wet-chemical etching; etching simultaneously releases the cantilevers from the substrate, allowing them to move. This method avoids complications associated with top-down milling processes, enabling repeatable production of large arrays of devices having precise, individual plasmonic gaps ≤ 15 nm in size. Using our platform, we demonstrate a new type of dynamic localized-gap plasmon (LGP) resonator, which is characterized by a high plasmonic quality factor and exceptionally large optomechanical coupling strength. We use these unique qualities of the LGP modes to achieve high-sensitivity transduction of mechanical motion from a deep subdiffraction region.

The basic concept features a mechanically coupled plasmonic resonator formed from a 350 nm long, 165 nm wide, 35 nm thick Au rectangular block embedded into a silicon nitride (SiN_x) mechanical resonator and suspended above an underlying Au pad by a narrow gap. As the mechanical resonator – in this case, a 4 µm long, 185 nm thick, singly clamped cantilever (Fig. 1b) – vibrates, the gap separating the block and pad is modulated. This, in turn, modulates the resonant optical frequency of the LGP mode. Consequently, the plasmomechanical device strongly couples the plasmonic resonance frequency and the local motion of the cantilever in a footprint determined by the block size.



Fig. 1. a, Fabrication process flow for the plasmomechanical devices using electron beam lithography (EBL), metal evaporation and liftoff (LO), plasma-enhanced chemical vapor deposition (PECVD), reactive ion etching (RIE), and critical point drying (CPD). Black lines surrounding the Au block are included for clarity. b, Optical image of the 4 μm long cantilever device with overlaid red circle showing the LGP resonator used for measurement.

The fabrication process (Fig. 1), which uses repeated aligned electron beam lithography (EBL) exposures and reactive ion etching (RIE) to pattern devices, has several unique features. First, devices are made with a very thin, 12 nm Cr sacrificial layer placed atop the Au pad using metal evaporation and lift off (LO). This layer temporarily supports the Au blocks, formed by a second EBL+LO step, and therefore defines the gap in the plasmonic

resonators. Second, we use low temperature (180 $^{\circ}$ C) plasma-enhanced chemical vapor deposition (PECVD) to deposit a conformal SiN_x layer onto the pad-sacrificial layer-block stack, thereby embedding the block directly into the mechanical resonator and ensuring, after release using a Cr wet-etch and critical point drying, that the block travels with the cantilever. In addition to yielding thousands of functioning devices per chip, our process provides facile tunability of the plasmonic and mechanical geometries via simple modification of the EBL write pattern.



Fig. 2. a, Experimentally measured reflectivity for the LGP resonance; inset shows the normalized total electric field of the LGP mode on resonance, calculated using the finite-element method. b, Setup for motion measurement; collimator (C), 50:50 beamsplitter (BS), electronic spectrum analyzer (ESA), polarization maintaining (PM) optical fiber. c, Measured mechanical response of the device with Lorentzian fit (blue curve), showing a full-width at half-maximum (FWHM) of 160 kHz. Signal reference power is 1 mW.

The LGP mode is a standing wave formed from counter-propagating gap plasmons that reflect from the ends of the upper block (Fig. 2a inset). We experimentally measure the LGP response of our device using a confocal optical spectroscopy setup. As shown in Fig. 2a, the LGP mode manifests as a distinct dip in the spectral reflectivity near a wavelength (λ) of 790 nm. The resonance has a quality factor $Q_{LGP} = 22$, which, owing to reduced radiation losses, is more than twice the value expected from dipolar antennas. From finite-element calculations, we find that for initial gaps < 15 nm, the optomechanical coupling constant (g_{om}), defined as the optical frequency shift of the LGP for a given change in gap size, ranges from 2 THz·nm⁻¹ to 4 THz·nm⁻¹. Such values are among the largest reported to date and more than 40× achieved in dielectric systems [7].

The combination of large Q_{LGP} and g_{om} makes the LGP resonators well-suited for transducing the motion of the overall plasmomechanical device. We measure the thermal motion of the cantilever by placing it in a vacuum chamber to reduce damping and probing the reflectivity of the LGP mode at wavelength $\lambda_p = 780$ nm on the resonance shoulder (Fig. 2b). Motion of the device gap introduces a minute shift in the LGP resonance, which alters the reflectivity for the probe laser. We measure this amplitude-modulated reflectivity by imaging reflected light, collected with a 0.3 numerical aperture objective, onto a photodiode connected to a spectrum analyzer. The displacement power-spectral density of the cantilever motion is given in Fig. 2c, which shows a calibrated noise floor of $\approx 32 \text{ fm} \cdot \text{Hz}^{-1/2} \pm 3.2 \text{ fm} \cdot \text{Hz}^{-1/2}$, where the uncertainty corresponds to an estimated 10 % error in determining the thermal displacement calibration factor. Transduction occurs from a region, corresponding to the (350×165) nm² plasmonic footprint, that is 150× smaller than the diffraction-limited focal spot of our microscope. This measurement represents a motion sensitivity $\approx 7 \times$ larger than previously demonstrated with comparable plasmomechanical devices.

References

- 1. N. Yu and F. Capasso, "Flat optics with designer metasurfaces," Nat. Mater. 13, 139–150 (2014).
- B. J. Roxworthy, K. D. Ko, A. Kumar, K. H. Fung, E. K. C. Chow, G. L. Liu, N. X. Fang, and K. C. Toussaint, "Application of Plasmonic Bowtie Nanoantenna Arrays for Optical Trapping, Stacking, and Sorting," Nano Lett. 12, 796–801 (2012).
- 3. N. I. Zheludev and E. Plum, "Reconfigurable nanomechanical photonic metamaterials," Nat. Nanotechnol. 11, 16–22 (2016).
- R. Thijssen, T. J. Kippenberg, A. Polman, and E. Verhagen, "Plasmomechanical Resonators Based on Dimer Nanoantennas.," Nano Lett. 15, 3971–3976 (2015).
- B. J. Roxworthy, A. M. Bhuiya, X. Yu, E. K. C. Chow, and K. C. Toussaint, "Reconfigurable nanoantennas using electron-beam manipulation," Nat. Commun. 5, 4427 (2014).
- B. S. Dennis, M. I. Haftel, D. a. Czaplewski, D. Lopez, G. Blumberg, and V. A. Aksyuk, "Compact nanomechanical plasmonic phase modulators," Nat. Photonics 9, 267–273 (2015).
- M. Eichenfield, R. Camacho, J. Chan, K. J. Vahala, and O. Painter, "A picogram- and nanometre-scale photonic-crystal optomechanical cavity.," Nature 459, 550–555 (2009).