An electromechanically reconfigurable plasmonic metamaterial operating in the near-infrared

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Current efforts in metamaterials research focus on attaining dynamic functionalities such as tunability, switching and modulation of electromagnetic waves. To this end, various approaches have emerged, including embedded varactors, phase-change media, the use of liquid crystals, electrical modulation with graphene, and superconductors, and carrier injection or depletion in semiconductor substrates. However, tuning, switching and modulating metamaterial properties in the visible and near-infrared range remain major technological challenges: indeed, the existing microelectromechanical solutions used for the sub-terahertz and terahertz regimes cannot be shrunk by two to three orders of magnitude to enter the optical spectral range. Here, we develop a new type of metamaterial operating in the optical part of the spectrum that is three orders of magnitude faster than previously reported electrically reconfigurable metamaterials. The metamaterial is actuated by electrostatic forces arising from the application of only a few volts to its nanoscale building blocks—the plasmonic metamolecules—that are supported by pairs of parallel strings cut into a flexible silicon nitride membrane of nanoscale thickness. These strings, of picogram mass, can be driven synchronously to megahertz frequencies to electromechanically reconfigure the metamolecules and dramatically change the transmission and reflection spectra of the metamaterial. The metamaterial’s colossal electro-optical response (in the order of $10^{-5}$ to $10^{-6}\,\text{m V}^{-1}$) allows for either fast continuous tuning of its optical properties (up to 8% optical signal modulation at up to megahertz rates) or high-contrast irreversible switching in a device only 100 nm thick, without the need for external polarizers and analysers.

Engineering fast, dynamically reconfigurable metamaterials for the optical spectral range, with metamolecular features on the scale of tens of nanometres, is a formidable technological challenge. However, working on the nanoscale also has some important advantages, because the electrostatic force, which is inversely proportional to distance, becomes dominant, allowing potential differences of only a few volts to overcome the elastic response of suitable nanostructures. Moreover, inertial and elastic forces scale differently with size, driving mechanical frequencies of microscale reconfigurable elements to megahertz values. However, existing electrically reconfigurable terahertz metamaterials, in which external comb-drive actuators drive the mass of the entire metamaterial, would not allow high-frequency operation, even if they could be scaled to the optical spectral range. Similarly, approaches based on the deformation of elastomeric substrates lead to low resonance frequencies as they require macroscopic displacement of a comparably high mass of low-stiffness material.

The electro-optical photonic metamaterial (Fig. 1) described here comprises a continuous plasmonic, metallic ‘meander near the wire’ pattern manufactured on a grid of flexible dielectric strings with picogram mass and megahertz mechanical resonances. Following

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![Figure 1](image_url)
application of a few volts to neighbouring strings (‘wire’ and ‘meander’ conducting patterns), an attractive electrostatic force of a few nanonewtons moves the strings in the metamaterial plane, closing the gap between them. This strongly affects the resonant optical response of the meander pattern, which is linked to excitation of a plasmonic mode\cite{7-19}, allowing reversible transmission and reflection modulation with megahertz bandwidth as well as non-volatile switching of the metamaterial.

The nanostructure was manufactured by focused ion beam milling on a 50-nm-thick silicon nitride membrane (which provides a stable and flexible base for the plasmonic pattern) to form alternating 50-nm-thick gold straight and meander wires. The wires are supported by 500-nm- and 250-nm-wide strings cut from the membrane and separated by 125-nm gaps to provide room for mutual motion. Pairs of strings were connected alternately to two electrical terminals on opposite sides of the device. To increase flexibility, the string ends were narrowed to \(~\sim\)200 nm, as shown in the scanning electron microscopy (SEM) image in Fig. 1a. The entire nanostructure has dimensions of 12 \(\mu\)m \(\times\) 35 \(\mu\)m. (For more fabrication details see Methods.)

When a voltage is applied across the device terminals, the strings are exposed to electrostatic forces resulting from strong fields in the gaps between them \((\sim 8\,\text{MV}\,\text{m}^{-1})\) at an applied control signal of 1 V; Fig. 1e). In response, pairs of strings bend towards one another. While the restoring force grows linearly with string displacement, the electrostatic attraction tends to infinity as the gap approaches zero. At a critical voltage the electrostatic attraction irreversibly overcomes the restoring force. For driving voltages below this threshold, reversible modulation of the metamaterial pattern and optical properties is possible. Exceeding the critical voltage results in step-like non-volatile switching and an abrupt change in the optical properties of the structure. The critical voltage can be estimated from the balance of electrostatic attraction between two strings and their elastic restoring force as \(U_c \approx \sqrt{32Etw/\varepsilon_0}}/(\pi\varepsilon_0L^3) \approx 3\,\text{V}\). Here, the average Young’s modulus of silicon nitride and gold is \(E = 169\,\text{GPa}\) and the initial gap size is \(g_0 = 125\,\text{nm}\). The string dimensions are thickness \(t = 100\,\text{nm}\), length \(L = 35\,\text{\mu m}\) and average width \(w = 375\,\text{nm}\). In the following, we will present both regimes of operation separately.

In the device reported here the critical voltage was measured to be \(~\sim 3\,\text{V}\), and continuous electro-optic modulation was possible at lower driving signals. Figure 2 shows the spectral dependence of the induced reversible changes in the transmission and reflection of the metamaterial relative to a reference case where no voltage is applied. The transmittance may be modulated by \(~\sim 5\%\) around wavelengths of 1.1 \(\mu\)m and 1.3 \(\mu\)m, and the reflectance can be modulated by up to 8% around 1.5 \(\mu\)m. (See Methods for characterization details.)

![Figure 2](image-url) | Reversible electro-optical tuning and modulation. a,b, Spectral dependence of changes in transmission \(T\) (a) and reflection \(R\) (b) induced by applying a static voltage to the reconfigurable photonic metamaterial.

![Figure 3](image-url) | Megahertz bandwidth electro-optical modulator. a, Modulator schematic. b, Frequency response function. c, Equivalent electric circuit diagram, where \(R\) stands for resistance and \(C\) for capacitance.
By increasing the applied voltage beyond the structure’s threshold voltage we enter the regime of step-like switching (see Supplementary Movie). Here, switching occurs at \( U_c = 3 \text{ V} \) (the optical characteristics of the ON and OFF states of the device are presented in Fig. 4). In the telecommunications band, the transmission, reflection and absorption spectra of the metamaterial redshift by \( \sim 20\% \) when the device switches, leading to dramatic 250\% transmission changes around 1.2 \( \mu \text{m} \) and 110\% reflectivity changes around 1.6 \( \mu \text{m} \). Such switching is irreversible, as the metamaterial remains in its ON configuration supported by the van der Waals force, even after the driving field is withdrawn. (This ‘sticking’ effect could be eliminated by resorting to modified designs, materials and chemical surface treatments.) The origin of the drastic switching-induced change in the metamaterial’s optical properties can be understood from Fig. 1d, which shows the optical electric field distribution before and after switching. For light polarized parallel to the wires, the resonances are mainly caused by excitation of plasmonic standing waves along the meander pattern. In the OFF state, interaction with the straight wires is relatively weak, and the electromagnetic field is mainly localized around the meander pattern. However, as straight and meander wires move closer together, their interaction becomes much stronger, the field redistributes into the narrow gap, and the resonances shift to longer wavelengths. In such a highly nonlinear system the switching dynamics are complex and strongly depend on the initial conditions and the shape of the control signal. However, by numerically solving the nonlinear equations of motion of a pair of strings, the characteristic switching time can be evaluated as \( \sim 500 \text{ ns} \) for the metamaterial going from the initial OFF state to the fully switched ON state, if a control signal equal to the static switching voltage \( U_c \) is applied abruptly.

To evaluate the power consumption of the device we approximated it with the equivalent circuit presented in Fig. 3. The leakage resistance of \( R^* = 400 \text{ k} \Omega \) dominates the power consumption in the low-frequency limit, and \( P = U^2 / R^* \) gives the power needed to drive the modulator (only \( \sim 2.5 \mu \text{W} \) at \( U = 1 \text{ V} \)). Simplifying the nanostructure as 12 parallel wire pairs, the capacitance can be estimated analytically as \( C_0 \approx 15 \text{ fF} \), increasing to \( \sim 20 \text{ fF} \) at the static switching voltage \( U_c \) due to the decreasing gap between the wires. The energy required to switch the device from the OFF state to the ON state can be estimated as the energy required to charge the capacitive nanostructure to the static switching point and was determined numerically as \( \sim 100 \text{ fJ} \), a very small amount of energy.

It is interesting to compare the metamaterial’s electro-optic properties to those of conventional electro-optic materials. Electro-optic modulation usually results from minute refractive index changes achieved by the application of an electric field across an electro-optic crystal, which is why applications require long crystals, high-voltage driving signals and polarizers to exploit birefringence-induced polarization effects. A similar solution using liquid crystals yields a slow response. In conventional electro-optic media such as perovskite-type ferroelectric lithium niobate, the electro-optic effect mainly comes from field-induced relative displacement of the central metal ion and the surrounding oxygen octahedron. This displacement changes the electronic band wavefunctions through electron-phonon coupling, which affects the refractive index of the lattice. Similarly, in the reconfigurable metamaterial an electro-optic effect arises from electric field-induced relative displacement of its constitutive parts. This displacement changes the structure’s collective plasmonic wavefunction, which affects the effective refractive index of the lattice. In light of these intriguing similarities in the microscopic mechanism and macroscopic manifestation, we estimated the reconfigurable metamaterial’s effective electro-optic coefficient. Full three-dimensional Maxwell calculations showed that OFF to ON switching of the 100-nm-thick structure changes the transmitted wave’s phase by up to \( \pi/5 \) at \( \sim 1.6 \mu \text{m} \), corresponding to an effective refractive index change of \( \Delta n = 1.6 \). This results...
from applying $U_c = 3$ V across $L = 35 \mu m$ of metamaterial. Thus, the effective electro-optic coefficient of the metamaterial is approximately $\Delta nL/\Delta U \approx 10^{-3} \text{m/V}^4$ in the non-volatile regime, and $\sim 10^{-7} \text{m/V}^4$ in a fully reversible regime, which is about five to four orders of magnitude greater than in typical electro-optic media such as lithium niobate ($3 \times 10^{-11} \text{m/V}^3$; ref. 22). This makes the metamaterial suitable for light modulation in small low-voltage devices without polarizers.

The novel technology presented here provides opportunities for further development, but it also has some limitations. Larger modulation depths can be achieved with metamaterial patterns that have narrower resonances. Even faster modulation would result from smaller reconﬁgurable elements, where gigahertz modulation can be anticipated for electrostatic actuation within the individual molecules. On the other hand, larger reconﬁgurable metamaterials based on longer strings will tend to be slower modulators, which can only be partially addressed by using stiﬀer materials. Also, bowing of the strings necessarily introduces some inhomogeneity, which can be reduced but not prevented by tapered string ends.

In summary, the novel class of reconﬁgurable nanostructures introduced here transfers electrically reconﬁgurable metamaterials from the terahertz to the optical part of the spectrum, while simultaneously increasing their modulation speed by three orders of magnitude. Such structures, with some modiﬁcations, are compatible with low-cost production using high-resolution complementary metal–oxide–semiconductor (CMOS) fabrication techniques and nanoimprinting. The approach, based on combining the elastic properties of a nanoscale-thickness dielectric membrane and nanoscale electrostatic forces in a planar plasmonic structure, provides a powerful generic platform for achieving tunable metamaterial characteristics in the optical spectral range. Such reconﬁgurable metamaterials can be operated at microwatt power levels and can provide continuous modulation of optical signals with megahertz bandwidth. A compact design integrating the actuation mechanism into the metamaterial, low-power consumption and direct control with a few volts makes electrostatically reconﬁgurable photonic metamaterials compatible with optoelectronic systems, for example as tunable spectral ﬁlters, switches, modulators and adaptable transformation optics devices. The low-energy, high-contrast, non-voltaile switching mode of these devices may also have applications in protective optical circuitry and reconﬁgurable optical networks.

**Methods**

Reconﬁgurable photonic metamaterial fabrication. A 50-nm-thick gold layer (for the plasmonic metamaterial and contact electrodes) was thermally evaporated onto a shadow mask onto a commercially available 50-nm-thick low-stress silicon nitride membrane. The gold-coated membrane was structured with a focused ion beam system (FEI Helios 600 Nanolab), with the contact electrodes connected to a source measurement unit (Keithley 2636) through a vacuum feedthrough for in situ electrical characterization. Using focused ion beam milling, the ‘meander near the wire’ pattern was ﬁrst milled. The membrane was then cut into suspended silicon nitride strings with tapered ends, and the terminals at the string ends were electrically separated by removing the gold ﬁlm in selected areas. The detailed dimensions of the nanostructure are given in the main text.

Experimental characterization. All imaging of the nanostructure was conducted using the scanning electron microscopy mode of the focused ion beam system (Figs 1,3 and 4). For the Supplementary Movie, the source measurement unit was used to induce switching. The transmission and reﬂection spectra of the reconﬁgurable metamaterial were recorded using a microspectrophotometer (CRAIC Technologies) while applying various DC voltages (via the source measurement unit) to tune the mechanical conﬁguration of the nanostructure (Figs 2 and 4).

High-frequency electro-optical modulation was studied by measuring the modulation of a 1.3-µm laser beam transmitted through the nanostructure, while modulating the metamaterial using a signal generator (Tabor 8551, rectangular modulation between 0 V and 1.1 V). The modulated signal was detected by an InGaAs photodetector (New Focus 1811) and a lock-in ampliﬁer (Stanford Research SR844) (Fig. 3).

In all optical experiments, the incident electric field was polarized parallel to the strings.