Nature Nanotechnology

Reconfigurable nanomechanical photonic metamaterials

Nikolay Zheludev[1,2] and Eric Plum[1]

[1] Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK
[2] The Photonics Institute & Centre for Disruptive Photonic Technologies, Nanyang Technological University, 637371, Singapore

The changing balance of forces at the nanoscale offers the opportunity to develop a new generation of opto-mechanical nanomembrane metamaterials in which electromagnetic Coulomb, Lorentz and Ampère forces, as well as thermal stimulation and optical signals can be engaged to dynamically change their optical properties. Individual building blocks of such metamaterials, the metamolecules, and their arrays fabricated on elastic dielectric membranes can be reconfigured and their optical characteristics modulated at high frequencies, potentially reaching the gigahertz range. Optical and mechanical resonances enhance the magnitude of actuation within these nanostructures, which can be driven by electric signals of only a few volts or optical signals with power of only a few milliwatts. Silicon nanofabrication technology compatible compact nonlinear, switchable, electro-optical and magneto-optical metamaterials with functionality surpassing natural media by orders of magnitude in some key design parameters can be envisaged.

Metamaterials, artificial electromagnetic media structured on a size scale smaller than the wavelength of external stimuli, were first developed to exhibit unusual properties, such as negative index of refraction, asymmetric transmission, invisibility or optical magnetism. They stimulated the development of devices such as optical cloaks and super-resolution lenses. Now widely researched, tuneable, nonlinear, switchable, gain-assisted, sensor and quantum metamaterials have large potential for practical device integration[1]. The next challenge is to develop random access metamaterials with on-demand optical properties, where every individual “metamolecule” may be independently controlled at any given point in space and at any moment of time. This will allow modulation of light’s intensity and phase, as well as control of the wavefront and the near-field of electromagnetic radiation, thus enabling reconfigurable electromagnetic space and multi-channel data processing in metamaterial systems[2]. In comparison to commercial spatial light modulators offering kHz modulation and pixel sizes of about 10x10 μm^2, random access metamaterials promise two orders of magnitude higher pixel densities and up to six orders of magnitude faster modulation frequency. However, the development of randomly accessible photonic metamaterials is challenging: the metamolecules must be sub-wavelength optical switches with a fraction of square micron footprint and a physical volume of only about 10^{-19} m^3. To have impact on telecommunications technologies such switches must be fast and consume energy at a level not prohibitive to their mass deployment.

Exceptional opportunities to address this challenge are provided by optomechanical systems that take advantage of the changing balance of forces at the nanoscale (Box 1). With the decrease in the physical dimensions of a system the electromagnetic forces between constituent elements grow, as may be illustrated by the repulsive force between electrons as their separation diminishes. In contrast, elastic forces, such as the force restoring a deformed beam, decrease with size (Box 2). At the sub-micron dimensions of the metamolecules in photonic metamaterials, electromagnetic Coulomb, Lorentz and Ampère forces compete with elastic forces and can thus be used to reconfigure the shape of individual metamolecules or to change their mutual arrangement. Here even small movements lead to a very substantial change of the metamaterial's optical properties (Figure 1). The nanoscale metamaterial building blocks can be moved very fast, potentially offering modulation at GHz frequencies. Elastic structured nanomembranes are the ideal platform for such nano-opto-mechanical reconfigurable metamaterials. Such structures can also be driven thermo-elastically or by light, through optical forces arising within illuminated metamolecules (Figure 2).

This new high-throughput and silicon compatible technology benefits from related advances in nano-opto-mechanics[3], which have led to the demonstration of thermally driven plasmonic nano-mechanical oscillators[4,5] and resonators[6]. It is being developed alongside other approaches for creating nonlinear, tuneable and switchable metamaterials from the microwave to the optical parts of the spectrum such as the phase change[7-9] and liquid crystal[10-13] hybrid metamaterial technologies, coherent control[14-19], structural reconfiguration[20,21] of metamaterials based on stretchable polymer substrates[22-26], MEMS[27-37], microfluidics[38,39] and magnetic forces[40,41]; carrier injection in semiconductor metamaterial substrates[42,43] and graphene[44,45]; and superconducting metamaterials[46,47]. A comprehensive overview of these approaches is available in recent reviews[1,48-53].

The technology for growing high-quality free-standing nanomembranes, such as ultra-thin films of silicon nitride[54,55], silicon[56], and diamond[57], that are supported by bulk semiconductor frames is well-established[58,59]. Such membranes are commercially widely available, packaged as individual membranes, arrays of membranes on silicon wafers or chip prototypes with prefabricated terminal wires[60-63]. Individual membranes, both poly-crystalline or nearly single crystal, typically have thickness from a few tens of nanometres to one micron with overall size up to a few square millimetres. They are mechanically robust, chemically stable and can support plasmonic metal films (gold, silver and other) deposited on them by thermal evaporation and sputtering. For prototyping work, focused gallium ion beam milling (FIB) is extensively used to fabricate plasmonic and dielectric metamaterial patterns on such membranes, including cutting through the membrane to form individual metamolecules and free-standing strips of them[64-69]. When using FIB the typical prototype fabrication time is between a few minutes to a few hours, depending on the complexity of the design, and faster lithographic fabrication of metamaterial patters on membranes is being developed. Supplementary video 1 shows FIB fabrication of an array of metamaterial samples.

THERMAL ACTUATION

Following the successful implementation of thermally switchable THz metamaterial[21] (Figure 2a), the first tuneable nanomembrane metamaterial for the optical part of the spectrum[64] exploited thermally-activated deformations of a multi-layered plasmonic structure that was built by sophisticated dual-side focused ion beam milling on a dielectric membrane. It consisted of arrays of plasmonic metamolecules supported by pairs of strings cut from the membrane and functionalized in a way that one string of the pair exhibited temperature-activated deformation while the other did not. The thermally-activated string was a two-layer sandwich of materials with different thermal expansion coefficients: a 50nm-thick gold layer and a 100nm-thick silicon-nitride layer. Upon increasing ambient temperature, this bimorph string bent towards its gold side as the thermal expansion coefficient of gold is five times larger than that of silicon nitride (Figure 2d). The other, thermally insensitive string of the pair had a symmetric 3-layered structure made of gold, silicon nitride and gold films. The alternating thermally active and thermally passive strings supported rows of C-shaped aperture resonators (split rings) with a 500nm x 500nm footprint. Upon change of the ambient temperature mutual displacement of neighbouring strings caused a change of the electromagnetic coupling of adjacent split rings. Such reconfiguration of the metamaterial, that involved nanoscale displacements of rows, strongly affected the transmission and absorption spectra of the entire array: a temperature increase from 76K to 270K caused a transmission change of up to 50% at plasmonic resonances in the spectral range from 1200nm to 1700nm. Potential applications of this thermally-activated metamaterial include temperature sensors, tuneable spectral filters, switches and modulators. However, this simple and robust technology is relatively slow: the reaction time τ depends on the thermal conductivity of the materials involved and the geometry of the string, and can be estimated as $\tau = L^2 C_L/(12Ak)$, where L is the string length, C_L the heat capacity per unit length, A the cross-section of the string, and k the thermal conductivity. For metamaterial arrays of overall size of tens of microns the response time is typically on the μs to ms scale, but the practically achievable response time is likely to be controlled by the rate at which the ambient temperature can be changed, unless the nanostructure's temperature is controlled directly using local resistive heating by electrical currents[66,67] or optical heating by pulses of light[69]. Supplementary video 2 shows actuation of nanomembrane chevron metamaterial.

ELECTROSTATIC ACTUATION

Engagement of the Coulomb force (Box 1a) allows for the development of membrane-based metamaterials controlled by electric signals, which work in the visible and near-infrared spectral bands[65]. They are orders of magnitude faster and far more compact than previously reported electrically reconfigurable THz MEMS comb-drive metamaterials (Figure 2b) and provide a much higher degree of control than metamaterials with opaque adjustable ground plane designs[27-37]. Furthermore, the membrane-based metamaterials can be used in transmission and reflection modes. Here, 'wire' and 'meander' parts of the metamolecules were fabricated on separate strings cut from a 100nm thick gold-coated silicon-nitride membrane in a way that two parts of each metamolecule were placed on neighbouring strings (Figure 2e). To increase flexibility of the strings, their ends, which are anchored in the unstructured membrane, were narrowed to about 200nm. The metamaterial was actuated by electrostatic forces arising from the application of only a few volts between each pair of parallel strings. These strings of picogram mass could be driven electromechanically to reconfigure the metamolecules synchronously across the entire array. This actuation changes dramatically the transmission and reflection spectra of the array. The array may be reconfigured in the static and dynamic regimes. In the static regime reversible changes of transmission and reflection spectra reaching 8% at the plasmonic resonances in the near-infrared spectral range were observed upon application of voltages up to 2.4V. Beyond that level of voltage the neighbouring strings come so close to one another that the electrostatic force grows more rapidly than the elastic restoring force; as a result, the strings came into contact and stuck to each other by the virtue of the surface (van Der Waals) forces, short-circuiting the device and fusing together. A dramatic, irreversible 250% transmission jump around the wavelength of 1200 nm and 110% reflectivity changes around 1600 nm occurred due to the change of electromagnetic coupling between the plasmonic wire and meander structures (Figure 1a). Below the critical switching voltage, the structure can also be driven dynamically up to megahertz frequencies (the main natural frequency of the strings is about 1MHz). Driving the array at mechanical resonance frequencies enhances the modulation of its optical properties. The metamaterial exhibits a complex dependence of its optical response on the frequency of electrical modulation with initial roll-off at the modulation frequency of 0.5 MHz and resonant peaks at 1.3 MHz and 1.6 MHz.

The electro-optical coefficient is on the order of 10^{-5}-10^{-6} m/V (at 1600 nm wavelength), which is about four to five orders of magnitude greater than in reference natural electro-optic media such as lithium niobate (3×10^{-11} m/V at 633 nm wavelength). Thus, electro-optical nanomembrane metamaterials could become a very compact alternative for applications at modulation frequencies well into the MHz range, where they can compete and complement conventional bulk modulators based on the fast electro-optical Pockels effect in crystals that are practically limited only by the speed of the driving electronics. The energy required to switch the metamaterial device from the OFF state to the ON state can be estimated as the energy required to charge the capacitive nanostructure and was found to be as little as ~100 fJ for the entire array. Such reconfigurable metamaterials can be operated at microwatt power levels making them suitable for applications in ultra-compact tuneable spectral filters, displays, switches, modulators, adaptable transformation optics devices, protective optical circuitry and reconfigurable optical networks Supplementary video 3 shows switching of nanomembrane electro-optical metamaterial with the Coulomb force.

MAGNETIC ACTUATION

Engaging the Lorentz force (Box 1c) provides another mechanism for reconfiguring nanomembrane metamaterials. In a recently demonstrated artificial “chevron” gold nanowire structure fabricated on an elastic dielectric nanomembrane, the Lorentz force drives reversible transmission changes of its optical properties on application of a fraction of a volt when the structure is placed in a magnetic field of less than 1T[66,67]. Such driving voltage typically corresponds to a current of less than 1 mA in each of the activated wires of the array. The chevron pattern was chosen because it is easy to fabricate and has good longitudinal elasticity due to its spring-like shape, while providing plasmonic optical resonances and continuous electrical paths for control currents (Figure 2f). The metamaterial was placed between the poles of permanent neodymium magnets in such a way that the field was directed along the surface of the array, but perpendicular to the nanowires. The electric current used as control signal is run through every second nanowire forcing out-of-plane motion of alternating strips. The magneto-electro-optical response of this metamaterial can be unambiguously separated from its thermal response caused by the resistive heating by observing modulation at different frequencies. Optical modulation up to frequencies of hundreds of kilohertz was observed. The response may be quantified in terms of change to the dielectric tensor ε_{ij} of the medium that is simultaneously proportional to the applied electric field $\boldsymbol{E}$ that drives the current and the magnetic field $\boldsymbol{B}$: $\delta\varepsilon_{ij} = \chi_{ijkl}E_kB_l$. Here the magneto-electro-optical susceptibility reaches a value of $\chi_{yyxy}/n \sim 10^{-4}$ (mV^{-}1 T^{-1}), where n is the refractive index. Remarkably, no natural media are known that show a noticeable magneto-electro-optical phenomenon of this type. This change of the dielectric properties is reciprocal as it does not depend on the wave propagation direction[67] and the phenomenon is therefore radically different from the conventional magneto-optical Faraday Effect. By engaging highly sensitive zero balance phase detection techniques, this magnetically actuated metamaterial can be used to realize micron size magnetic field sensors with sensitivity at nano-Tesla levels. We argue that a dedicated optimization of the metamaterial design can lead to the observation of stronger effects suitable for practical application in light-modulation devices controlled by electric signals and magnetic fields. Supplementary video 2 shows actuation of nanomembrane chevron metamaterial.

OPTICAL ACTUATION

Optical forces (Box 1d) also allow photonic metamaterial to be driven by light, leading to optical nonlinearity[41,70-73]. Building on the experimental demonstration of such a nonlinearity in magnetoelastic microwave metamaterial[41] (Figure 2c), this idea was introduced to nanomembrane metamaterials for the optical part of the spectrum, specifically a dielectric optomechanical metamaterial consisting of arrays silicon "nano-bricks" with sub-wavelength footprint and thicknesses alternating between 100 and 150 nm[68]. Pairs of such "bricks" support a high quality optical resonance due to a "trapped" mode. These bricks are mounted on 100 nm thick, 250 nm wide elastic silicon nitride strips running parallel and separated from each other by a gap of 200 nm. When the array is illuminated close to the trapped mode resonance, strong optical forces are generated, which act to change the spatial arrangement of the nano-bricks within each unit cell and thereby the optical properties of the array. Numerical Maxwell stress tensor analysis reveals that optomechanical forces, acting within and among the constituent cells of the dielectric metamaterial produce differential movements of neighbouring beams providing a strong nonlinear optical response that gives rise to high contrast, near-infrared asymmetric transmission and optical bistability at illumination intensity levels of only a few hundred $\mu W/\mu m^2$. All-dielectric metamaterial exhibiting an opto-mechanical nonlinearity that allows modulation of light with light at 150 MHz has recently been observed experimentally[74] (Figure 2h).

Moreover, a nano-opto-mechanical metamaterial was reported that realised a similar optical actuation, but using plasmonic resonators rather than dielectric ones[69] (Figure 2g). Here, as above, the nonlinearity was due to the reversible light-induced reconfiguration of the structure, although optical forces compete with bimorph deformation resulting from optical heating at low modulation frequencies. Modulation of light with light using continuous wave milliwatt power telecom diode lasers operating at wavelengths of 1310 nm and 1550 nm was demonstrated in a nanostructure of only 100 nm thickness. To allow mechanical reconfiguration of the 700 nm x 700 nm plasmonic metamolecules, their constituting parts were supported by different flexible silicon nitride strips of 28 µm length spaced by alternating gaps of 95 nm and 145 nm. Plasmonic resonances play a key role here. Indeed, a plasmonic resonance excited by the illuminating light increases the driving force that reconfigures the metamaterial. Moreover, a steep plasmonic resonance near the wavelength of detected light enhances transmission and reflection changes caused by the reconfiguration of the structure. Remarkably, although for the majority of media the magnitude of nonlinearity tends to be proportional to its response time, the nano-opto-mechnical plasmonically enhanced nonlinearity reaches an extremely high value of $\chi^{(3)}/n^2 \sim 10^{-12}\ m^2/V^2$, while remaining three orders of magnitude faster than could be expected from the otherwise universal trend linking response speed and magnitude of the nonlinearity[75]. The optical response of the structure can be modulated by light to up to a few MHz frequency as it exhibits a complex pattern of mechanical modes (see Box 2) that correspond to different oscillations of the strips. At such frequencies the viscosity of air damps oscillations: placing the metamaterial in a vacuum cell dramatically increases the quality factor of its mechanical resonances and thus the magnitude of the nonlinearity.

OUTLOOK

In conclusion we argue that the recent exploration of the nonlinear, switching, electro-optical and magneto-optical functionalities in nanomechanical systems offers a new direction for metamaterial research and applications. We expect that nano-opto-mechanical metamaterials will impact photonic technology significantly as they can provide light modulation in micron-size devices. Further improvements beyond the proof-of-principle stage are possible. Indeed, high index dielectric resonators[74,76-81] promise lower losses and larger optical forces than plasmonic structures[82]. Silicon and silicon nitride membranes as scaffolding materials may be complemented by diamond membranes that offer higher mechanical resonances and superior thermal properties. Moreover, the first generation randomly accessible metamaterials, providing control in a single spatial dimension, have already been realized using nanomembrane technology[83] (Figure 2i,j). Such devices can function as re-focusable lenses or dynamic dispersion elements and, most importantly, can be used for signal multiplexing in multi-mode or multi-core optical telecommunication technology. Supplementary video 4 shows actuation of individual wires in randomly reconfigurable nanomembrane metamaterial. Another exciting direction for nano-opto-mechanical metamaterial would be to exploit the peculiar properties of auxetic planar patterns to induce the expansion and contraction of surfaces with a negative Poisson's ratio[84].

AUTHOR CONTRIBUTIONS

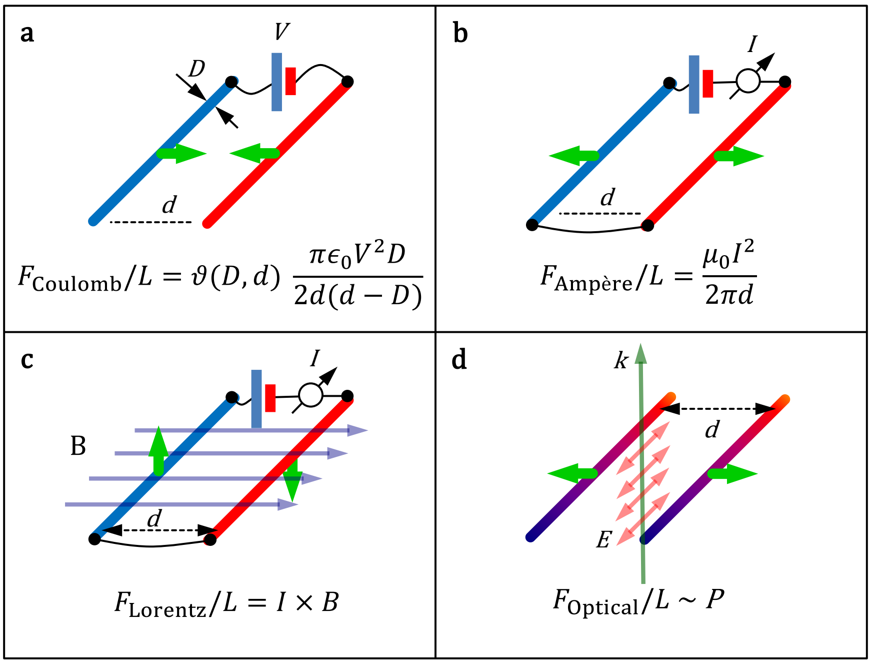
N.I.Z. and E.P. made equal contributions to the preparation of this review.

ADDITIONAL INFORMATION

Supplementary information accompanies this paper at www.nature.com/naturenanotechnology. Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/. Correspondence and requests for materials should be addressed to N.I.Z. and E.P. The data from this paper can be obtained from the University of Southampton ePrints research repository: http://dx.doi.org/10.5258/SOTON/378243.

COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.



Box 1. Electromagnetic forces at the nanoscale. Elements of reconfigurable metamaterials can often be represented as nanowires. At the nanoscale electromagnetic forces acting on such nanowires are comparable with elastic forces of the supporting structure (see Box 2) and therefore can be used to reconfigure metamaterials. Even small mutual motion of the elements of the metamaterial array can create substantial changes in their interaction with light and their optical proprieties (see Figure 1).

For simplicity let us consider cylindrical nanowires of diameter D spaced by the distance d and evaluate forces acting on the segment of nanowire of length L.

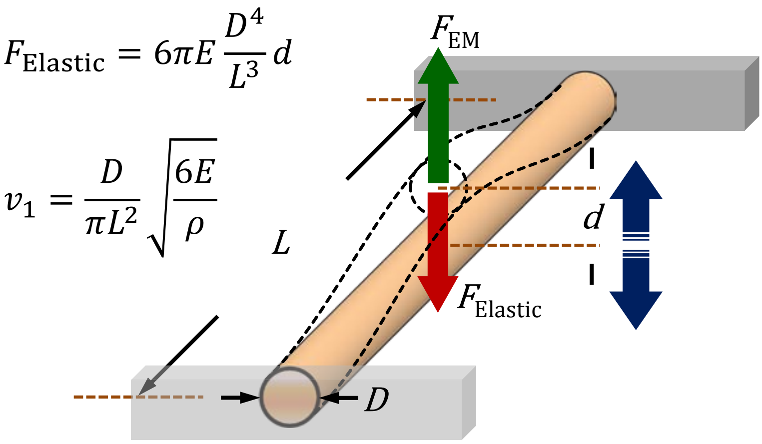
a) **The Coulomb force** F_{Coulomb} depends on the potential difference V between the nanowires, their diameter D and the distance d between them, where the dimensionless parameter $\vartheta(D,d)\approx 1$ for realistic geometries. For V=1V, D=100nm and d=500nm the Coulomb force is about 5pN per 1μm of nanowire length L. This corresponds to an electric field acting between the nanowires that is close to the electric breakdown of air, which takes place at about 3MV/m [85]. With decreasing distance between the nanowires the Coulomb force increases rapidly.

b) **The Ampère force** $F_{\mathrm{Ampère}}$ depends on the current I in the nanowires and distance d between them. It may be understood as the Lorentz force acting on the current in one nanowire due to the magnetic field caused by the current in the other. The achievable Ampère force tends to be smaller than the Coulomb force. For I =1mA and d=500nm the Ampère force is about 0.4pN per 1μm of nanowire length L. The Ampère force is limited by the current that a nanowire can sustain. A gold nanowire with diameter D=100nm cannot take more than 10mA continuous current due to the release of heat that causes melting[86], but much higher current can be sustained in the pulsed regime.

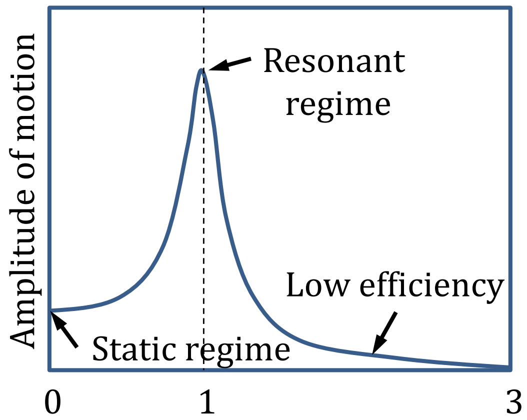
c) **The Lorentz force** F_{Lorentz} depends on the current I and magnetic field B and can be even stronger than the Coulomb force. The force is perpendicular to the current and magnetic field and moves wires apart. For I =1mA and B =100mT the Lorentz force is about 100pN per 1μm of nanowire length L. An external field B of about a Tesla can be easily achieved with permanent Neodymium and Samarium-Cobalt magnets.

d) **Optical force.** Nanowires can also be driven by illuminating them with light. Nanowires that have a length L of approximately half of the wavelength of incident radiation act as resonant antennas for light. Light-induced oscillating dipoles in a pair of parallel nanowires will repel with time-averaged optical force F_{Optical} that is proportional to the incident light intensity P, if the radiation is polarized with the electric field E parallel to the nanowires and the optical wavevector k is directed perpendicular to the plane defined by them. When such gold plasmonic nanowires of diameter D =100nm, length L=500nm and spacing d =300nm are illuminated by light with wavelength λ =925nm and intensity P =1mW/μm^2, the repelling optical force between them is about F_{Optical} =1.5pN.

a



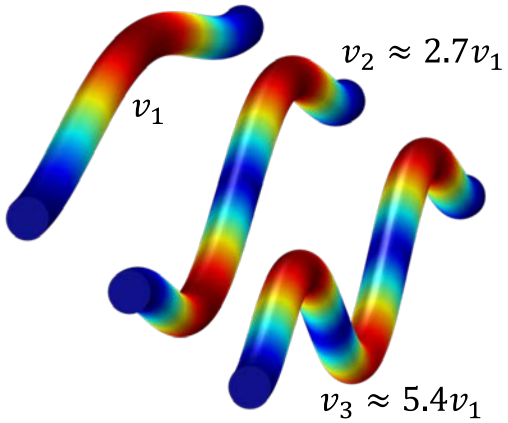
b



c

d	L	D	ν_1	F_{Elastic}
10 nm	100 µm	100 nm	60 kHz	3 pN
10 nm	10 µm	100 nm	6 MHz	3 nN
10 nm	1 µm	10 nm	60 MHz	300 pN
1 nm	100 nm	10 nm	6 GHz	30 nN

d



Box 2. Motion at the nanoscale. A combination of nanowires anchored at either one or two ends is a fundamental toolkit of reconfigurable nano-opto-mechanical metamaterials. (a) A nanowire anchored at both ends of length L, diameter D, Young's modulus E and density ρ will have a fundamental natural frequency ν_1 that will rapidly increase with decreasing size of the oscillator. Using an external electromagnetic force F_{EM} it will become possible to drive it to frequencies approaching the GHz range for sub-micron oscillators. Indeed, as can be seen from the generic resonance curve of a driven oscillator (b), driving at the mechanical resonance $\nu_{EM} \approx \nu_1$ will lead to enhanced motion that is controlled by the quality factor of the mechanical oscillator, but driving at frequencies far above the resonance is inefficient. (c) The force necessary to achieve a static displacement d of the nanowire's center against the elastic force $F_{Elastic}$ depends on the size and aspect ratio of the nanowire, as illustrated in the table for silicon nanowires: a much smaller force is needed to drive a displacement d=10nm in a nanowire of 100µm length and 100nm diameter, then in a short nanowire of 1µm length and 10nm diameter. The same nanowire anchored at only one end (a cantilever) will have an about 7 times lower resonance frequency and it will reach the same end displacement in response to a 48 times weaker force. (d) Often more complex movements are present in nanostructures that may be exploited for reconfiguration of nano-opto-mechanical metamaterials. For instance, depending on how the oscillator is driven, odd and even higher order modes can be excited, where in-plane and out-of-plane modes of oscillation are allowed that appear at different natural frequencies for nanowires with elliptical or rectangular cross-sections. Note that in a nanowire with finite aspect ratio the frequencies of higher modes (v_2 and v_3) are not integer multiples of the fundamental natural frequency v_1, as could be expected for an infinitely thin string, thus leading to a rich pattern of excitations that can be seen in nanostructures.

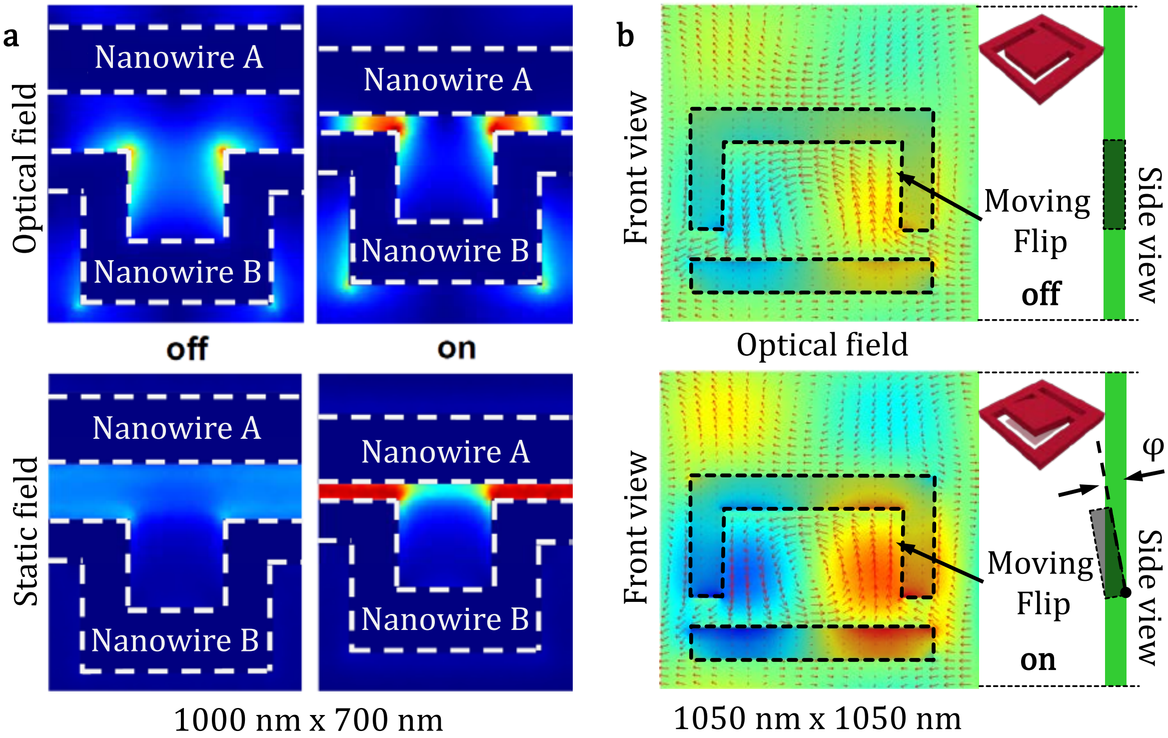


Figure 1. Nanoscale motion and fields. (a) In a **plasmonic reconfigurable metamaterial**[65] with a 1000nm x 700nm unit cell (see also Figure 2e) mutual displacement of electrically charged nanowires A and B towards each other by about 125nm driven by the Coulomb force leads to a strong change of the resonant optical field trapped in the structure around λ=1800 nm wavelength (upper row, colours indicate the magnitude of the optical electric field), and thus to a change in the optical reflectivity and transmission of the metamaterial array. The distribution of the static electric field that drives the reconfiguration also changes dramatically (lower row). (b) **Dielectric reconfigurable metamaterial**[74] with a 1050nm x 1050nm unit cell consisting of an asymmetric split-ring aperture in a silicon nanomembrane creating a moving flip (see also Figure 2h). Dashed lines indicate areas where the membrane was removed. The upper and lower images show optical field maps (colours indicate strength of the field along the symmetry axis of the unit cell) and displacement currents (arrows) for illumination at a wavelength of λ=1280nm. The field distribution changes dramatically when the flip is turned by an angle φ=10° out of the plane of the membrane. In-phase oscillations of the flips in the metamaterial array may be caused by optical forces and will lead to a change of optical properties of the metamaterial.

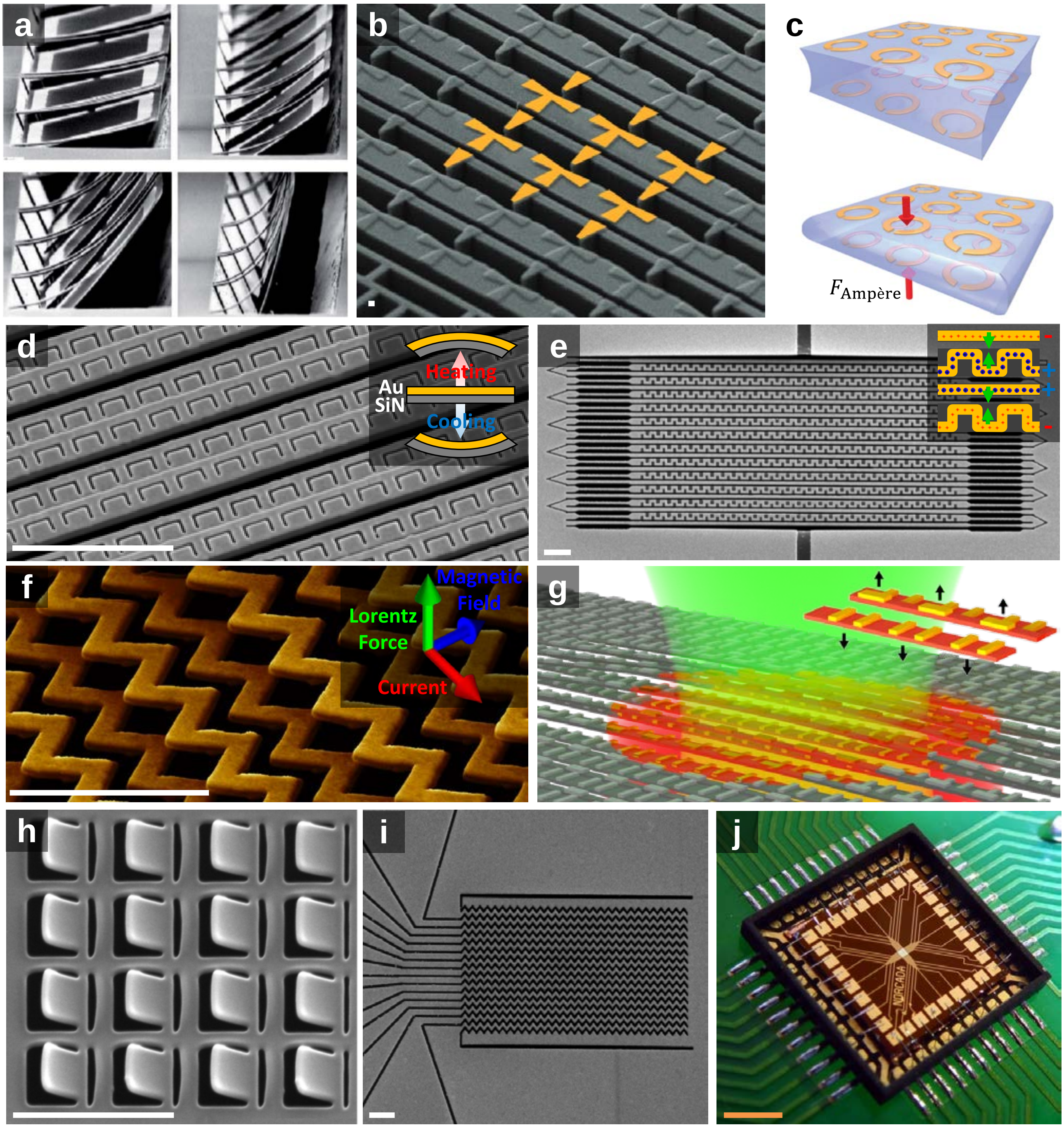


Figure 2. Implementations of reconfigurable nano-opto-mechanical nanomembrane metamaterials operating in the visible and near-infrared parts of the spectrum. (a-c) Earlier reconfigurable metamaterials exploiting opto-mechnical solutions included: (a) Thermally switchable terahertz metamaterial actuated by rapid thermal annealing[21]; (b) Terahertz metamaterial tuned by MEMS actuators[33]; (c) Magnetoelastic microwave metamaterial driven by Ampère's force $F_{\text{Ampère}}$ between excited metamolecules, shown in its relaxed (top) and actuated (bottom) states[41]. (d-j) Reconfigurable optical metadevices based on flexible strips or nanowires cut from membranes of nanoscale thickness supporting a thin film of plasmonic metal or high index dielectric. Structures controlled by various forces on the nanoscale have been reported recently. (d) Thermometer: Thermally reconfigurable metamaterial driven by differential thermal expansion between gold and silicon nitride layers[64]; (e) Electro-optical modulator: Electro-optical metadevice driven by electrostatic forces (green arrows) between oppositely charged nanowires (+, -)[65]; (f) Magnetic field sensor: Nanowire structure actuated by the Lorentz force that is controlled by currents and magnetic fields[67]; (g) All-optical modulator: Plasmonic metamaterial actuated by only a few milliwatt of light power at telecom wavelengths, a pump beam (red) reconfigures the nanostructure (inset) resulting in modulation of a probe beam (green)[69]; (h) Nonlinear device: All-dielectric metamaterial with a large opto-mechanical nonlinearity[74]; (i,j) Spatial light modulator: Randomly reconfigurable electrically addressable metadevice for providing optical properties on demand in one dimension. Panel (i) shows an array of individually controlled nanowires, while panel (j) shows the packaging arrangement for the device[83]. White scale bars are 2μm and the orange scale bar is 2mm in length.

REFERENCES

1 Zheludev, N.I. & Kivshar, Y.S. From metamaterials to metadevices. *Nat. Mater.* **11**, 917-924 (2012).
2 Zheludev, N.I. Obtaining optical properties on demand. *Science* **348**, 973-974 (2015).
3 Aspelmeyer, M., Kippenberg, T.J. & Marquardt, F. Cavity optomechanics. *Rev. Mod. Phys.* **86**, 1391-1452 (2014).
4 Thijssen, R., Verhagen, E., Kippenberg, T.J. & Polman, A. Plasmon nanomechanical coupling for nanoscale transduction. *Nano Lett.* **13**, 3293-3297 (2013).
5 Thijssen, R., Kippenberg, T.J., Polman, A. & Verhagen, E. Parallel Transduction of Nanomechanical Motion Using Plasmonic Resonators. *ACS Photonics* **1**, 1181-1188 (2014).
6 Thijssen, R., Kippenberg, T.J., Polman, A. & Verhagen, E. Plasmomechanical Resonators Based on Dimer Nanoantennas. *Nano Lett.* **15**, 3971-3976 (2015).
7 Dicken, M.J. *et al.* Frequency tunable near-infrared metamaterials based on VO_2 phase transition. *Opt. Express* **17**, 18330-18339 (2009).
8 Driscoll, T. *et al.* Memory Metamaterials. *Science* **325**, 1518-1521 (2009).
9 Sámson, Z.L. *et al.* Metamaterial electro-optic switch of nanoscale thickness. *Appl. Phys. Lett.* **96**, 143105 (2010).
10 Werner, D.H., Kwon, D.-H., Khoo, I.-C., Kildishev, A.V. & Shalaev, V.M. Liquid crystal clad near-infrared metamaterials with tunable negative-zero-positive refractive indices. *Opt. Express* **15**, 3342-3347 (2007).
11 Zhao, Q. *et al.* Electrically tunable negative permeability metamaterials based on nematic liquid crystals. *Appl. Phys. Lett.* **90**, 011112 (2007).
12 Minovich, A. *et al.* Liquid crystal based nonlinear fishnet metamaterials. *Appl. Phys. Lett.* **100**, 121113 (2012).
13 Buchnev, O., Ou, J.Y., Kaczmarek, M., Zheludev, N.I. & Fedotov, V.A. Electro-optical control in a plasmonic metamaterial hybridised with a liquid-crystal cell. *Opt. Express* **21**, 1633-1638 (2013).
14 Zhang, J., MacDonald, K.F. & Zheludev, N.I. Controlling light-with-light without nonlinearity. *Light Sci. Appl.* **1**, e18 (2012).
15 Fang, X. *et al.* Ultrafast all-optical switching via coherent modulation of metamaterial absorption. *Appl. Phys. Lett.* **104**, 141102 (2014).
16 Mousavi, S.A., Plum, E., Shi, J. & Zheludev, N.I. Coherent control of birefringence and optical activity. *Appl. Phys. Lett.* **105**, 011906 (2014).
17 Shi, J. *et al.* Coherent control of Snell's law at metasurfaces. *Opt. Express* **22**, 21051-21060 (2014).
18 Fang, X., MacDonald, K.F. & Zheludev, N.I. Controlling light with light using coherent metadevices: all-optical transistor, summator and invertor. *Light Sci. Appl.* **4**, e292 (2015).
19 Roger, T. *et al.* Coherent perfect absorption in deeply subwavelength films in the single-photon regime. *Nat. Commun.* **6**, 7031 (2015).
20 Lapine, M. *et al.* Structural tunability in metamaterials. *Appl. Phys. Lett.* **95**, 084105 (2009).
21 Tao, H. *et al.* Reconfigurable Terahertz Metamaterials. *Phys. Rev. Lett.* **103** (2009).
22 Pryce, I.M., Aydin, K., Kelaita, Y.A., Briggs, R.M. & Atwater, H.A. Highly strained compliant optical metamaterials with large frequency tunability. *Nano Lett.* **10**, 4222-4227 (2010).
23 Aksu, S. *et al.* Flexible plasmonics on unconventional and nonplanar substrates. *Adv. Mater.* **23**, 4422-4430 (2011).
24 Cui, Y., Zhou, J., Tamma, V.A. & Park, P. Dynamic Tuning and Symmetry Lowering of Fano Resonance in Plasmonic Nanostructure. *ACS Nano* **6**, 2385-2393 (2012).
25 Lee, S. *et al.* Reversibly stretchable and tunable terahertz metamaterials with wrinkled layouts. *Adv. Mater.* **24**, 3491-3497 (2012).
26 Walia, S. *et al.* Flexible metasurfaces and metamaterials: A review of materials and fabrication processes at micro- and nano-scales. *Appl. Phys. Rev.* **2**, 011303 (2015).
27 Chicherin, D. *et al.* MEMS-based high-impedance surfaces for millimeter and submillimeter wave applications. *Microw. Opt. Technol. Lett.* **48**, 2570-2573 (2006).
28 Hand, T. Characterization of Tunable Metamaterial Elements Using MEMS Switches. *IEEE Antenn. Wireless Propag. Lett.* **6**, 401-404 (2007).
29 Fu, Y.H. *et al.* A Micromachined Reconfigurable Metamaterial via Reconfiguration of Asymmetric Split-Ring Resonators. *Adv. Funct. Mater.* **21**, 3589-3594 (2011).

30 He, X., Lv, Z., Liu, B. & Li, Z. Tunable magnetic metamaterial based multi-split-ring resonator (MSRR) using MEMS switch components. *Microsys. Technol.* **17**, 1263-1269 (2011).
31 Zhu, W.M. *et al.* Switchable magnetic metamaterials using micromachining processes. *Adv. Mater.* **23**, 1792-1796 (2011).
32 Zhang, W. *et al.* Micromachined switchable metamaterial with dual resonance. *Appl. Phys. Lett.* **101**, 151902 (2012).
33 Zhu, W.M. *et al.* Microelectromechanical Maltese-cross metamaterial with tunable terahertz anisotropy. *Nat. Commun.* **3**, 1274 (2012).
34 Ho, C.P. *et al.* Electrothermally actuated microelectromechanical systems based omega-ring terahertz metamaterial with polarization dependent characteristics. *Appl. Phys. Lett.* **104**, 161104 (2014).
35 Lin, Y.-S. & Lee, C. Tuning characteristics of mirrorlike T-shape terahertz metamaterial using out-of-plane actuated cantilevers. *Appl. Phys. Lett.* **104**, 251914 (2014).
36 Pitchappa, P. *et al.* Micro-electro-mechanically switchable near infrared complementary metamaterial absorber. *Appl. Phys. Lett.* **104**, 201114 (2014).
37 Liu, A.Q., Zhu, W.M., Tsai, D.P. & Zheludev, N.I. Micromachined tunable metamaterials: a review. *J. Opt.* **14**, 114009 (2012).
38 Kasirga, T.S., Ertas, Y.N. & Bayindir, M. Microfluidics for reconfigurable electromagnetic metamaterials. *Appl. Phys. Lett.* **95**, 214102 (2009).
39 Zhu, W.M. *et al.* A Flat Lens with Tunable Phase Gradient by Using Random Access Reconfigurable Metamaterial. *Adv. Mater.* **27**, 4739-4743 (2015).
40 Ozbey, B. & Aktas, O. Continuously tunable terahertz metamaterial employing magnetically actuated cantilevers. *Opt. Express* **19**, 5741-5752 (2011).
41 Lapine, M., Shadrivov, I.V., Powell, D.A. & Kivshar, Y.S. Magnetoelastic metamaterials. *Nat. Mater.* **11**, 30-33 (2012).
42 Chen, H.T. *et al.* Active terahertz metamaterial devices. *Nature* **444**, 597-600 (2006).
43 Padilla, W.J., Taylor, A.J., Highstrete, C., Lee, M. & Averitt, R.D. Dynamical Electric and Magnetic Metamaterial Response at Terahertz Frequencies. *Phys. Rev. Lett.* **96** (2006).
44 Ju, L. *et al.* Graphene plasmonics for tunable terahertz metamaterials. *Nat. Nanotechnol.* **6**, 630-634 (2011).
45 Lee, S.H. *et al.* Switching terahertz waves with gate-controlled active graphene metamaterials. *Nat. Mater.* **11**, 936-941 (2012).
46 Ricci, M., Orloff, N. & Anlage, S.M. Superconducting metamaterials. *Appl. Phys. Lett.* **87**, 034102 (2005).
47 Savinov, V., Fedotov, V.A., Anlage, S.M., de Groot, P.A.J. & Zheludev, N.I. Modulating Sub-THz Radiation with Current in Superconducting Metamaterial. *Phys. Rev. Lett.* **109**, 243904 (2012).
48 Boardman, A.D. *et al.* Active and tunable metamaterials. *Laser Photon. Rev.* **5**, 287-307 (2011).
49 Keiser, G.R., Fan, K., Zhang, X. & Averitt, R.D. Towards Dynamic, Tunable, and Nonlinear Metamaterials via Near Field Interactions: A Review. *Journal of Infrared, Millimeter, and Terahertz Waves* **34**, 709-723 (2013).
50 Lapine, M., Shadrivov, I.V. & Kivshar, Y.S. Colloquium: Nonlinear metamaterials. *Rev. Mod. Phys.* **86**, 1093-1123 (2014).
51 Shadrivov, I., Lapine, M. & Kivshar, Y.S. *Nonlinear, Tunable and Active Metamaterials*. (Springer, 2014).
52 Turpin, J.P., Bossard, J.A., Morgan, K.L., Werner, D.H. & Werner, P.L. Reconfigurable and Tunable Metamaterials: A Review of the Theory and Applications. *Int. J. Antennas Propag.* **2014**, 1-18 (2014).
53 Fan, K. & Padilla, W.J. Dynamic electromagnetic metamaterials. *Mater. Today* **18**, 39-50 (2015).
54 Toivola, Y., Thurn, J., Cook, R.F., Cibuzar, G. & Roberts, K. Influence of deposition conditions on mechanical properties of low-pressure chemical vapor deposited low-stress silicon nitride films. *J. Appl. Phys.* **94**, 6915 (2003).
55 Zwickl, B.M. *et al.* High quality mechanical and optical properties of commercial silicon nitride membranes. *Appl. Phys. Lett.* **92**, 103125 (2008).
56 Petersen, K.E. Silicon as a mechanical material. *Proc. IEEE* **70**, 420-457 (1982).
57 Fairchild, B.A. *et al.* Fabrication of Ultrathin Single-Crystal Diamond Membranes. *Adv. Mater.* **20**, 4793-4798 (2008).
58 Rogers, J.A., Lagally, M.G. & Nuzzo, R.G. Synthesis, assembly and applications of semiconductor nanomembranes. *Nature* **477**, 45-53 (2011).
59 Lagally, M.G. *et al.* Semiconductor nanomembranes: a platform for new science and technology. *Proc. SPIE* **8031**, 803107 (2011).
60 *Norcada Inc.*, http://www.norcada.com/

61 *Silson Ltd*, http://www.silson.com/
62 *Ted Pella, Inc.*, http://www.tedpella.com
63 *SPI Supplies / Structure Probe, Inc.*, http://www.2spi.com
64 Ou, J.Y., Plum, E., Jiang, L. & Zheludev, N.I. Reconfigurable Photonic Metamaterials. *Nano Lett.* **11**, 2142-2144 (2011).
65 Ou, J.Y., Plum, E., Zhang, J. & Zheludev, N.I. An electromechanically reconfigurable plasmonic metamaterial operating in the near-infrared. *Nat. Nanotech.* **8**, 252-255 (2013).
66 Valente, J., Ou, J.Y., Plum, E., Youngs, I.J. & Zheludev, N.I. Reconfiguring photonic metamaterials with currents and magnetic fields. *Appl. Phys. Lett.* **106**, 111905 (2015).
67 Valente, J., Ou, J.Y., Plum, E., Youngs, I.J. & Zheludev, N.I. A magneto-electro-optical effect in a plasmonic nanowire material. *Nat. Commun.* **6**, 7021 (2015).
68 Zhang, J., MacDonald, K.F. & Zheludev, N.I. Nonlinear dielectric optomechanical metamaterials. *Light Sci. Appl.* **2**, e96 (2013).
69 Ou, J.Y., Plum, E., Zhang, J. & Zheludev, N.I. Modulating light with light via giant nano-opto-mechanical nonlinearity of plasmonic metamaterial. *arXiv.org*, 1506.05852 (2015).
70 Zhao, R., Tassin, P., Koschny, T. & Soukoulis, C.M. Optical forces in nanowire pairs and metamaterials. *Opt. Express* **18**, 25665-25676 (2010).
71 Zhang, J., MacDonald, K.F. & Zheludev, N.I. Optical gecko toe: Optically controlled attractive near-field forces between plasmonic metamaterials and dielectric or metal surfaces. *Phys. Rev. B* **85** (2012).
72 Slobozhanyuk, A.P. *et al.* Flexible helices for nonlinear metamaterials. *Adv. Mater.* **25**, 3409-3412 (2013).
73 Ginis, V., Tassin, P., Soukoulis, C.M. & Veretennicoff, I. Enhancing Optical Gradient Forces with Metamaterials. *Phys. Rev. Lett.* **110**, 057401 (2013).
74 Karvounis, A., Ou, J.Y., Wu, W., MacDonald, K.F. & Zheludev, N.I. Nano-optomechanical nonlinear dielectric metamaterials. *Appl. Phys. Lett.* **107**, 191110 (2015).
75 Boyd, R.W. *Nonlinear Optics*. 3rd edn, 211 (Academic Press, 2008).
76 Semouchkina, E.A., Semouchkin, G.B., Lanagan, M. & Randall, C.A. FDTD Study of Resonance Processes in Metamaterials. *IEEE Trans. Microw. Theory Tech.* **53**, 1477-1487 (2005).
77 Ginn, J.C. *et al.* Realizing Optical Magnetism from Dielectric Metamaterials. *Phys. Rev. Lett.* **108** (2012).
78 Zhang, J., MacDonald, K.F. & Zheludev, N.I. Near-infrared trapped mode magnetic resonance in an all-dielectric metamaterial. *Opt. Express* **21**, 26721-26728 (2013).
79 Chong, K.E. *et al.* Observation of Fano resonances in all-dielectric nanoparticle oligomers. *Small* **10**, 1985-1990 (2014).
80 Wang, Q. *et al.* 1.7 Gbit/in.^{2} gray-scale continuous-phase-change femtosecond image storage. *Appl. Phys. Lett.* **104**, 121105 (2014).
81 Wang, Q. *et al.* Optically switchable and rewritable phase-change (dielectric) metamaterials. *2015 MRS Spring Meeting* (San Francisco, CA, USA, 2015) http://eprints.soton.ac.uk/379172/.
82 Zhang, J., MacDonald, K.F. & Zheludev, N.I. Giant optical forces in planar dielectric photonic metamaterials. *Opt. Lett.* **39**, 4883-4886 (2014).
83 Cencillo-Abad, P., Ou, J.Y., Valente, J., Plum, E. & Zheludev, N.I. Randomly addressable reconfigurable photonic metamaterials. *Nanometa* (Seefeld, Austria, 2015) http://eprints.soton.ac.uk/375824/.
84 Valente, J., Plum, E. & Zheludev, N.I. Auxetic Nanomechanical Metamaterials. *MRS Fall Meeting* (Boston, MA, USA, 2015) http://www.mrs.org/fall-2015-program-s/.
85 Rigden, J.S. *Macmillan Encyclopedia of Physics*. 353 (Simon & Schuster Macmillan, 1996).
86 Karim, S., Maaz, K., Ali, G. & Ensinger, W. Diameter dependent failure current density of gold nanowires. *J. Phys. D: Appl. Phys.* **42**, 185403 (2009).

One Sentence summary of selected references

[20] This paper reports the first mechanically reconfigurable microwave metamaterial.
[21] This paper reports the first mechanically reconfigurable terahertz metamaterial.
[22] This paper reports the first mechanically reconfigurable optical metamaterial.
[41] This paper reports the first microwave metamaterial that is actuated by electromagnetic forces.
[64] This paper reports the first thermally actuated optical nanomembrane metamaterial.
[65] This paper reports the first electrostatically actuated optical nanomembrane metamaterial.
[67] This paper reports the first magnetically actuated optical nanomembrane metamaterial.

[68] This theoretical paper predicts giant nonlinear optical effects in nanomembrane metamaterials actuated by optical forces.
[69] This manuscript reports the first optically actuated nanomembrane metamaterial.
[83] This conference paper discusses the first randomly addressable reconfigurable nanomembrane metamaterial.

ACKNOWLEDGEMENTS

The authors are grateful to Artemios Karvounis and Vassili Savinov for helping in manuscript preparation. They are also grateful to Pablo Cencillo-Abad, João P. Valente and Jun-Yu Ou for preparing Supplementary Information video files and Kevin MacDonald for discussions. This work is supported by the Leverhulme Trust, the MOE Singapore (grant MOE2011-T3-1-005) and the UK's Engineering and Physical Sciences Research Council (grant EP/G060363/1).