Optical addressing of nanomechanical metamaterials with subwavelength resolution

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Abstract

Metamaterials that offer "on-demand" control of individual metamolecules are termed "randomly accessible metamaterials". They can be useful for manipulating the wavefront of electromagnetic radiation, tailoring of the nearfield, and ultimately for multichannel data processing. Here we demonstrate how light can be used to actuate individual metamaterial elements on demand. Selectivity is achieved by constructing the metamaterial from nanomechanical elements that are designed to have slightly different mechanical resonance frequencies. Actuation is controlled by modulation of the optical control signal at the mechanical resonance frequencies of targeted elements, providing an all-optical route to randomly accessible metamaterials with spatial resolution beyond the diffraction limit.

The ultimate vision of metamaterials is effectively continuous control over the properties of light at any point in time and space, i.e. with subwavelength pixelation [1]. The electromagnetic properties of metamaterials are determined by the composition and geometry of their subwavelength scale building blocks that are known as metamolecules. Therefore, metamolecule deformation [2] and modification of constituent materials via nonlinearities [3, 4] and phase transitions [5, 6] allow dynamic control over metamaterial properties. Selective control over individual metamaterial elements has been demonstrated using a microwave metamaterial based on mercury-filled microfluidic channels [7] and a photonic metamaterial based on electrothermal actuation of individual nanostructures [8]. However, such approaches are not scalable to large arrays of nanostructures as they require a separate control signal (channel or wire) to be physically routed to each element. In contrast, all-optical delivery of the control signal through free space enables scalable control over large metamaterial arrays. However, the spatial resolution of existing approaches is inherently limited by diffraction as they are based on imaging optical intensity or phase distributions on metamaterial arrays in order to induce phase transitions [6] or to form interference patterns that control the light-metamaterial interaction [9, 10].

Here we demonstrate how individual nanomechanical metamaterial elements, that are spaced by much less than the wavelength of the optical control signal, can be actuated with light. Our metamaterial consists of identical plasmonic metamolecules supported by dielectric structures with unique mechanical resonances. Illumination of the

metamolecules by near-infrared pump light leads to optically induced forces that cause resonantly enhanced displacement only if the pump is modulated at the element's unique mechanical resonance frequency.

The metamaterial, which is shown by Fig. 1, consists of an array of Π-shaped gold metamolecules supported by pairs of silicon nitride strings (nanowires) separated by 95 and 110 nm gaps to allow relative movement of the horizontal and vertical gold bars that make up the metamolecules. Both gold and silicon nitride are 50 nm thick and the metamolecule is 700 × 700 nm^2 in size. A metamaterial based on similar Π-shaped metamolecules supported by narrower nanowires of 28 μm length was previously shown to exhibit a large optomechanical nonlinearity, but did not allow addressing of individual metamaterial elements [11]. To realize addressable nanowire string pairs with different mechanical resonance frequencies in the present work, the string pairs supporting different rows of metamolecules were fabricated with different lengths from 24 μm to 28 μm in steps of 1 μm. The nanostructure was fabricated from a commercially available silicon nitride membrane of 50 nm thickness by thermal evaporation of a 50-nm-thick gold layer followed by focused ion beam milling (FEI Helios 600 NanoLab), where the plasmonic resonators were fabricated before the strings were separated.

Maxwell stress tensor calculations and experiments have demonstrated that illumination at pump wavelengths close to an optical resonance of such mechanically

reconfigurable metamolecules leads to light-induced actuation and an exceptionally large nonlinear optical response [11-16]. Fig. 2 shows both simulated (COMSOL) and measured (CRAIC microspectrophotometer) transmission, reflection and absorption spectra of the metamaterial for light polarized with the electric field parallel to the nanowire strings. Measurements and simulations are in close agreement and show that the metamaterial has an absorption resonance at a wavelength of about 1250 nm.

Light incident on the metamaterial will cause actuation due to thermal and electromagnetic optical forces. Absorption of light increases the temperature of the nanostructure, causing differential thermal expansion of gold and silicon nitride that will result in out-of-plane actuation of the nanowire strings. This actuation mechanism will be efficient for modulation that is slower that the structure's cooling timescale of tens of microseconds, i.e. up to modulation rates of tens of kHz. However, as discussed below, we observe resonant in-plane actuation of the nanostructure at MHz frequencies. Maxwell stress tensor calculations show that illumination of the nanostructure leads to significant optical forces that actuate strings within the metamaterial plane, see Fig. 2c. Such in-plane optical forces are permitted in terms of symmetry as each string is closer to one neighbour than the other due to the gap sizes of 95 and 110 nm. They can be understood as forces acting between the optically-induced oscillating dipole moments within the plasmonic metamolecules, time-averaged over the optical cycle [14]. In-plane optical forces on neighbouring strings have equal magnitude and opposite direction, thus, they are either attractive or repulsive and alter the gap between

neighbouring strings.

In order to actuate the metamaterial with light, we illuminated the nanostructure with an intensity modulated pump laser of 1550 nm wavelength (Fig. 3a), where the in-plane optical forces have a local maximum (Fig. 2c). The resulting modulation of the metamaterial transmission was measured using a CW probe laser at a wavelength of 1310 nm, where the "slope" of the nearby transmission resonance ensures high sensitivity to perturbations of the metamaterial structure (Fig. 2b). The probe signal was detected with a lock-in amplifier (Stanford Research SR844) that was locked to the modulation frequency of the pump laser. Both lasers were polarized with the electric field parallel to the nanowire strings and the pump and probe intensities were 466 W/cm^2 and 89 W/cm^2 on the metamaterial, which was placed in an evacuated vacuum chamber with a pressure of 9×10^{-2} torr to minimize air-damping of the nanomechanical oscillations. Figures 3b and 3c show the detected modulation of the metamaterial's transmission as a function of the pump modulation frequency alongside COMSOL simulations of the mechanical eigenmodes of the strings. Each string has two fundamental eigenmodes corresponding to oscillation parallel and perpendicular to the metamaterial plane. In the Π-resonator reconfigurable metamaterial, in-plane oscillation of the narrow strings leads to strong modulation of probe light and this is clearly seen as resonant peaks at 1.02, 1.13, 1.23 and 1.30 MHz, where the mechanical resonance frequencies are inversely proportional to the square of the string length. We note that only four of these mechanical resonances are observed as irreversible sticktion,

caused by charging and mechanical stress relaxation during focused ion beam milling, prevents in-plane oscillation of several strings including the 24 μm strings. The 2 leftmost and 5 rightmost narrow strings shown in Fig. 1 are free to move. Notably, resonance quality factors (Q-factors) of 300 are observed for string lengths of 25 and 26 μm, which are not affected by inhomogeneous broadening as only one narrow string of each of these lengths can oscillate freely. For string lengths of 27 and 28 μm, several narrow strings are free to move, which implies that slight differences between these strings result in inhomogeneous broadening of the transmission modulation associated with their mechanical resonances, which is likely to explain the lower observed Q-factors of 170 and 230, respectively. Much weaker light modulation associated with the out-of-plane oscillation eigenmode of the strings is seen around 800 kHz and evidence of the in-plane mode of the wide strings can be seen around 2.2 MHz. Furthermore, thermal actuation due to optical absorption is visible as low modulation frequencies up to tens of kHz.

In analogy with acoustics, our work may be described as playing a "metamaterial guitar" with light, where plectrum becomes photon, string becomes nanostring and kHz becomes MHz. What we report is essentially an optically addressable metamaterial array of optomechanical transducers [17-21]. The interaction with light is determined by the metamaterial unit cell that provides freedom to design the optical response at the pump and probe wavelengths. In particular, this allows engineering of the optical and thermal forces that drive the actuation and arise from metamaterial excitation and

absorption at the pump wavelength. Optical addressing of individual nanomechanical elements, strings in our case, becomes possible due to a slight size variation of the nanomechanical oscillators that results in different mechanical resonance frequencies for different oscillators while keeping the same optical resonators. This allows the amplitude of oscillation of each nanomechanical element to be controlled by the intensity of an optical control signal that is intensity-modulated at the element's mechanical resonance frequency. In our case, metamaterial strings spaced by 700 nm have been actuated independently with light of 1550 nm wavelength, demonstrating that the resolution of our optical method is determined by nanofabrication rather than diffraction. We argue that independent amplitude modulation of multiple carrier frequencies provides a route to independent optical actuation of 1D [11-13, 22], 2D [16, 23] and even 3D arrays of nanomechanical metamaterial elements with spatial resolution that is not limited by diffraction. Instead, the spatial resolution and the carrier frequencies that will drive resonant actuation are determined by the size of the nanomechanical elements. Mechanical resonance frequencies of cantilevers and nanowire strings as employed here are proportional to t/L^2, where L is length and t is thickness in the direction of oscillation, and reach GHz frequencies for sub-micron dimensions. We anticipate that the number of nanomechanical elements that can in principle be addressed independently with a single pump laser is on the order of the Q-factor of the mechanical resonance of an individual element, i.e. 300 in our case. This could be scaled up further by combining amplitude modulation with wavelength division multiplexing based on targeting distinct optical resonances of different

metamaterial nanostructures with different pump lasers. Selective optical actuation of individual metamolecules will require metamolecules that act as both mechanical and optical resonators [16, 23], such as a dielectric cantilever supporting a plasmonic resonator. Variation of either cantilever length or plasmonic resonator position on the cantilever could be used to realize metamolecules with unique mechanical resonance frequencies that could then be actuated individually with light.

As addressable nanomechanical metamaterials provide spatial and temporal control over electromagnetic waves, they are spatial light modulators, which can achieve subwavelength spatial resolution. Such control over metamaterial properties with subwavelength resolution is the basis for transformation optics [24] and could be used to realize devices that can be reconfigured dynamically to provide different optical functions. Furthermore, metamaterial arrays of nanomechanical elements with unique mechanical resonance frequencies could also be exploited for superresolution imaging and spectroscopy with a photodetector. For imaging, pump light illuminating each individual nanomechanical element would be detected by scanning the pump modulation frequency and reading the probe modulation at the corresponding mechanical resonance frequencies. For spectroscopy, each nanomechanical element would be covered with metamolecules that are sensitive to a different wavelength. A given pump wavelength would then be read with a probe beam while modulating incident pump light at the resonance frequency of the corresponding nanomechanical oscillator. In this case, the metamaterial would act as an array of optomechanical

sensors detecting different wavelengths. This approach could be adapted for sensing of anything that influences the oscillation of a nanomechanical oscillator.

In conclusion, we demonstrate an optical method for controlling metamaterials that exploits nanooptomechanics to circumvent the optical diffraction limit. We report selective actuation of metamaterial elements spaced by 700 nm using light of 1550 nm wavelength and we argue that our approach provides a route to optical control of individual nanostructures forming 1D, 2D and 3D metamaterial arrays. Further development of this concept could lead to superresolution spatial light modulators, transformation optics devices, reconfigurable optical components, parallel optomechanical sensor arrays, superresolution imaging devices and miniaturized spectrometers.

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Following a period of embargo, the data from this paper will be available from the University of Southampton ePrints research repository: http://doi.org/10.5258/SOTON/D0497

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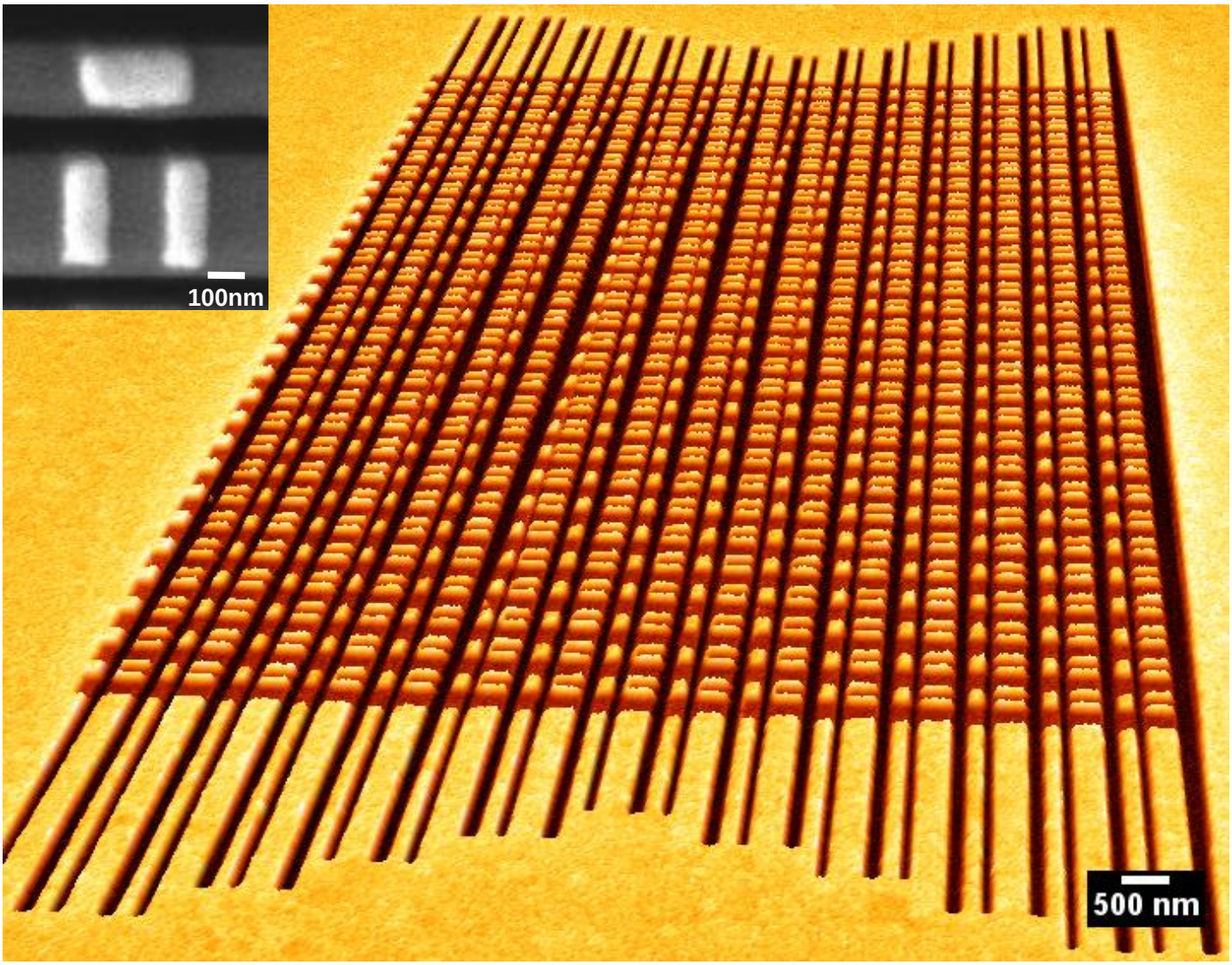
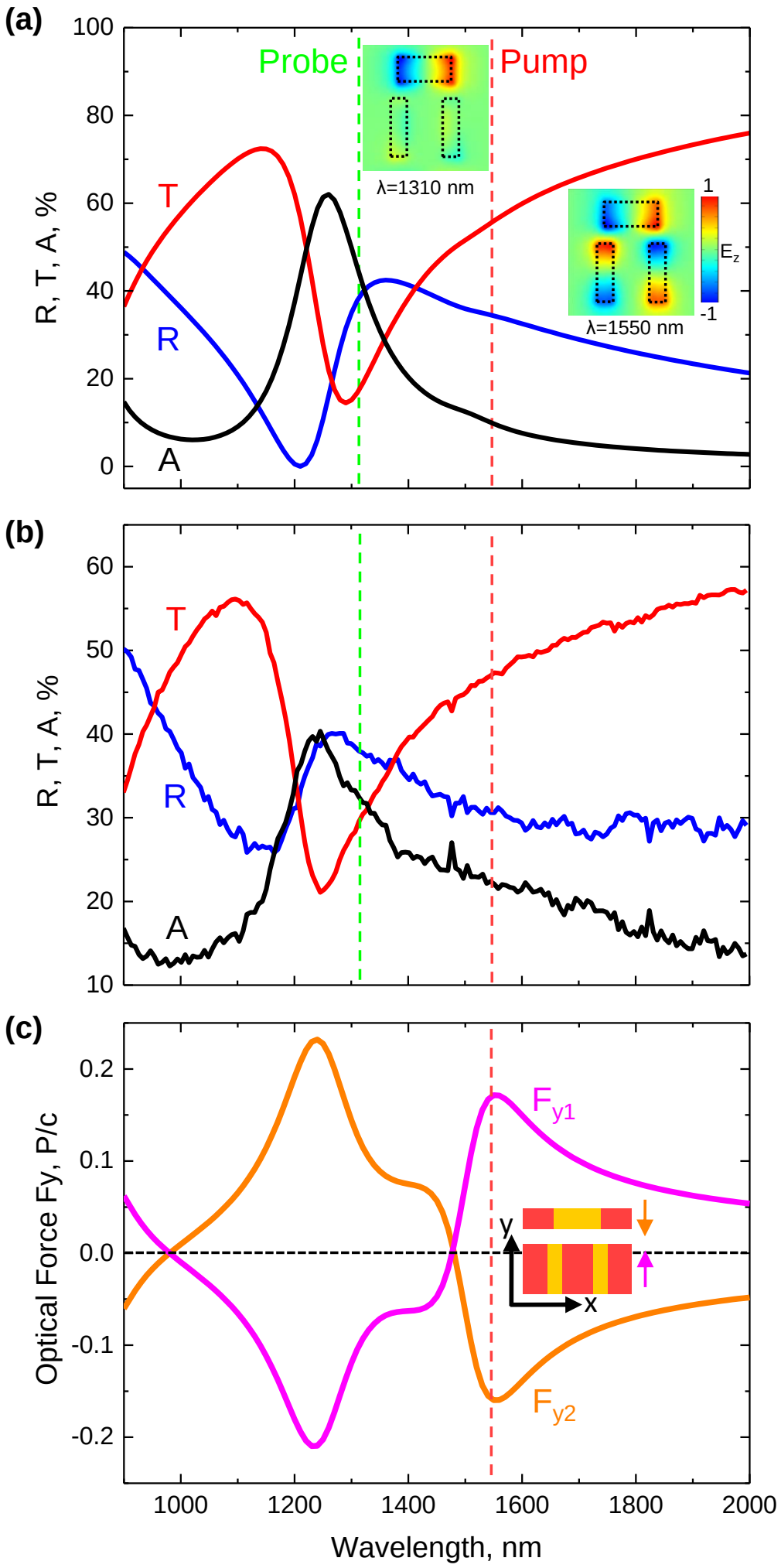
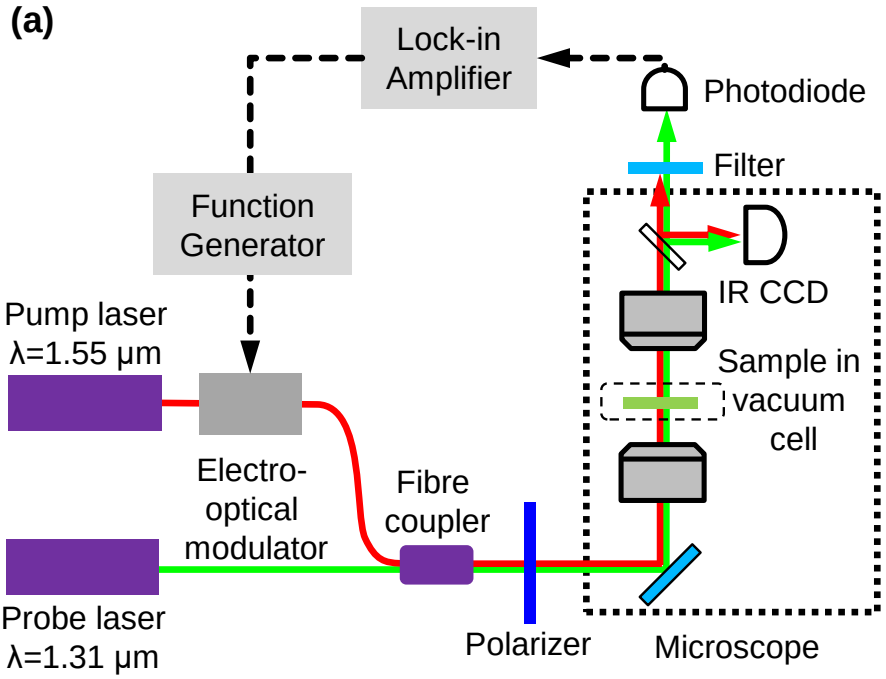
Figure 1: Optically addressable nanomechanical metamaterial. Scanning electron micrograph of the nanostructure and its unit cell (inset). Yellow represents gold and brown represents silicon nitride.

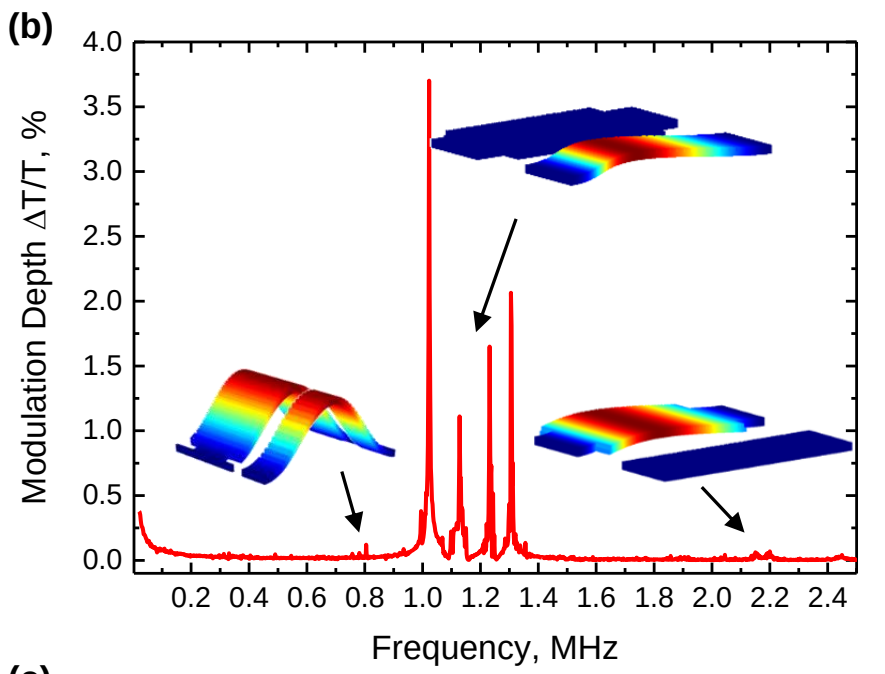
Figure 2: Optical properties of the reconfigurable metamaterial. (a) Simulated and (b) measured reflection (R), transmission (T) and absorption (A) spectra of the nanostructure. (c) In-plane optical forces per unit cell in units of P/c according to Maxwell stress tensor calculations, where P is the incident power and c is the speed of light in vacuum. Pump and probe wavelengths are indicated by dashed lines and the insets of panel (a) show the optically induced charge distributions at these wavelengths in terms of the normalized electric field perpendicular to the unit cell's surface.

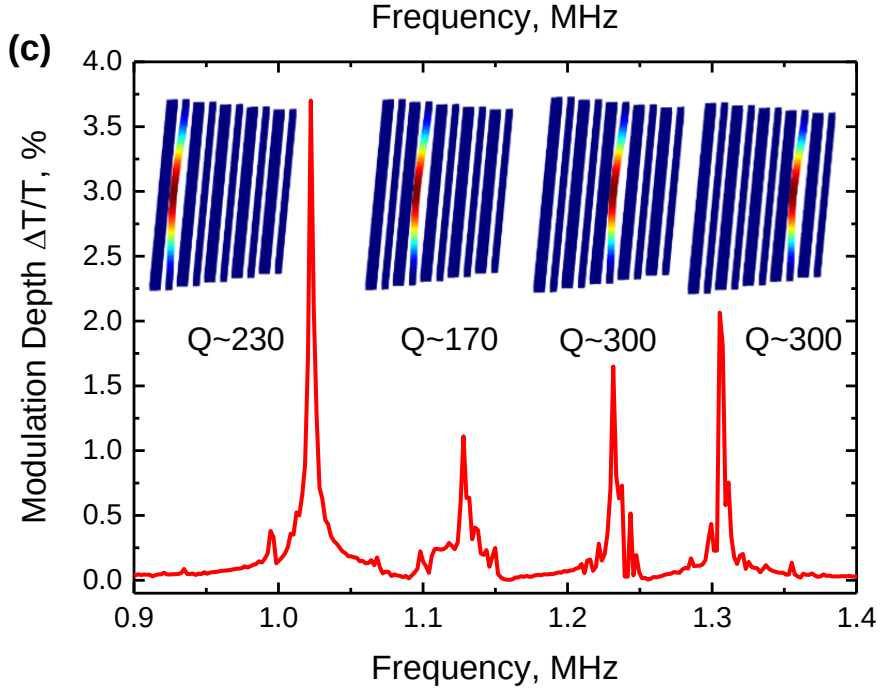
Figure 3: Selective actuation of metamaterial strings with light. (a) Schematic of the experimental setup for actuating individual nanostrings with a 1550 nm wavelength pump laser modulated at frequency f and detecting the resulting modulation of a transmitted 1310 nm CW probe laser with a lock-in amplifier locked to the same frequency. (b, c) Detected transmission modulation $\Delta T/T$ at the probe wavelength as a function of the pump modulation frequency f. Insets show COMSOL simulations of the mechanical eigenmodes corresponding to the observed resonances.


100nm
500 nm


(a)
Probe
Pump
T
R
A
λ=1310 nm
λ=1550 nm
1
E_z
-1
R, T, A, %
100
80
60
40
20
0
(b)
T
R
A
R, T, A, %
60
50
40
30
20
10
(c)
F_{y1}
F_{y2}
y
x
Optical Force Fy, P/c
0.2
0.1
0.0
-0.1
-0.2
1000
1200
1400
1600
1800
2000
Wavelength, nm


(a)
Lock-in Amplifier
Photodiode
Filter
Function Generator
IR CCD
Pump laser λ=1.55 μm
Sample in vacuum cell
Electro-optical modulator
Fibre coupler
Probe laser λ=1.31 μm
Polarizer
Microscope


(b)
Modulation Depth ΔT/T, %
Frequency, MHz


(c)
Modulation Depth ΔT/T, %
Q~230
Q~170
Q~300
Q~300
Frequency, MHz