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Random access actuation of nanowire grid metamaterial

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Abstract

While metamaterials offer engineered static optical properties, future artificial media with dynamic random-access control over shape and position of meta-molecules will provide arbitrary control of light propagation. The simplest example of such a reconfigurable metamaterial is a nanowire grid metasurface with subwavelength wire spacing. Recently we demonstrated computationally that such a metadevice with individually controlled wire positions could be used as dynamic diffraction grating, beam steering module and tunable focusing element. Here we report on the nanomembrane realization of such a nanowire grid metasurface constructed from individually addressable plasmonic chevron nanowires with a 230 nm × 100 nm cross-section, which consist of gold and silicon nitride. The active structure of the metadevice consists of 15 nanowires each 18 μm long and is fabricated by a combination of electron beam lithography and ion beam milling. It is packaged as a microchip device where the nanowires can be individually actuated by control currents via differential thermal expansion.

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Keywords: reconfigurable metamaterial, nanowire, metadevice, nanoelectromechanical system

(Some figures may appear in colour only in the online journal)

Full active control over diffraction and focusing of light, beam steering and video holography require dynamic control over amplitude and phase of light with sub-wavelength resolution, i.e. a device where optical properties of points spaced by less than the wavelength of operation can be controlled independently. However, sub-wavelength pixelation is out of reach for established spatial light modulator technologies based on digital micromirrors or liquid crystal cells that have a characteristic size of 10 μm [1–3] as well as deformable mirrors that have a typical actuator pitch of hundreds of microns. Opportunities for fast dynamic control over light with much higher resolution are now emerging in metamaterials, i.e. media that obtain enhanced or unusual optical properties from structuring with characteristic dimensions that are smaller than their wavelength range of operation. Approaches to achieving dynamic control over metamaterial properties can be grouped into three categories. (i) All-optical control over the light–matter interaction using multiple coherent light waves [4, 5], (ii) modification of the materials making up the metamaterial nanostructure, e.g. based on optical nonlinearities [6, 7], phase transitions [8] or electronic doping [9], and (iii) spatial rearrangement of

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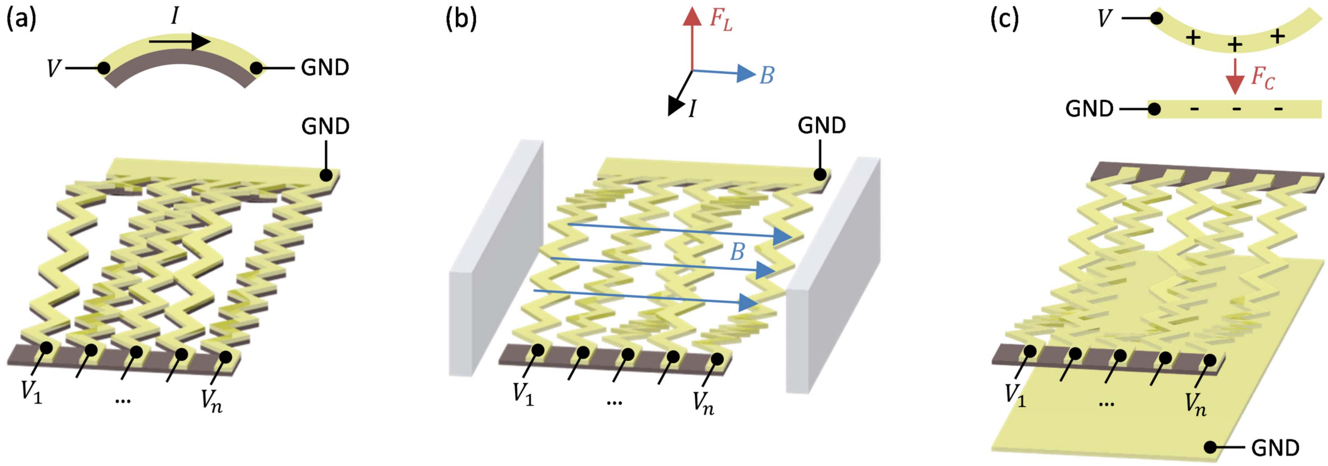

Figure 1. Random-access electrical actuation of reconfigurable nanowire metamaterials. (a) Electrothermal actuation, which is employed here, exploits differential thermal expansion of materials with different thermal expansion coefficients in response to resistive heating by a current I to displace a nanowire. (b) Magnetic actuation uses the Lorentz force F_L on moving charges to actuate a current-carrying metamaterial strip placed in an external magnetic field B. (c) Electrostatic actuation is driven by the Coulomb force F_C between charged nanowires or between a nanowire and a ground plane (GND). V_i indicate nanowire actuation voltages in all cases.

the metamaterial components [10–15]. However, dynamic control over metamaterial properties with sub-wavelength resolution remains a challenge. Spatial resolution of all-optical approaches involving coherent light–matter interactions, optical nonlinearities or phase transitions is limited by the ability to focus light, in contrast, this limitation is avoided by nanoelectromechanically actuated metamaterials, whose pixelation is determined by nanofabrication technology rather than light. It has been predicted that selective actuation of nanowires in nanowire grid metamaterials would enable spatial phase and intensity modulation with one-dimensional sub-wavelength pixelation providing focusing, diffraction and beam steering functionalities on demand [16, 17]. We refer to such metamaterials that allow selective control of each individual element as random access metamaterials.

Here we report the nanofabrication of a random access metadevice consisting of individually addressable plasmonic nanowire actuators. The nanowires are arranged in a grid, forming a metamaterial with a chevron-shaped unit cell. We demonstrate selective electrical actuation of individual nanowires, which allows the metamaterial nanostructure to be controlled with 620 nm pixelation in one dimension.

Reconfigurable metamaterials [14, 18–21] and similar optomechanical nanostructures [22–25] operating in the visible to near infrared part of the spectrum have been developed based on dielectric membranes of nanoscale thickness. Such membranes serve as a flexible support for a plasmonic metal or high index dielectric thin film, which can be structured by standard nanofabrication processes to create metamaterial nanostructures and actuators. Electrical actuation is most easily achieved by cutting a membrane with an electrically conductive layer into freestanding metamaterial strips. Deformation of such nanowires with microsecond scale response times can then be driven by Coulomb or Lorentz forces, or resistive heating, resulting in very large electro-optical and magneto-electro-optical effects [18–20].

Selective electrical actuation of individual nanowires requires the wires to be controlled by independent electrical signals. Bimorph nanowires can be actuated by resistive heating, where the same temperature change of materials with different thermal expansion coefficients causes nanowire deformation due to differential thermal expansion (figure 1(a)). Current-carrying nanowires can be actuated by the magnetic Lorentz force that acts on moving charges in a magnetic field (figure 1(b)). Electrically charged nanowires can be actuated by electrostatic forces due to a nearby plane (or neighboring wires) that has a different electric potential (figure 1(c)). Here we have chosen actuation of bimorph nanowires due to differential thermal expansion in response to resistive heating as this allows simultaneous nanowire observation by scanning electron microscopy. Prior work on electrically actuated nanowire grid metamaterials was limited to equal actuation of every second nanowire controlled by a total of two electrical terminals [18–20]. Here we report independent selective actuation of individual nanowires, which is required to enable spatial light modulation applications. In contrast to prior art, the number of nanoscale electrical terminals scales with the number of nanowires, and we address the resulting increase in complexity by combining multiple nanofabrication processes and introducing standard electronic packaging and standard electronic interfaces, as well as computer control.

We fabricated such an electrically addressable metamaterial nanostructure, starting with a commercially available (Norcada Inc, figure 2(a)) 250 × 250 μm^2 low stress silicon nitride membrane of 50 nm thickness. The membrane is supported by a 5 × 5 mm^2 silicon frame with 32 electrodes and contact pads consisting of 50 nm thick gold with a chromium adhesive layer that were made by standard photolithography, metal deposition and lift-off processes.

In order to create the plasmonic metal film for metamaterial fabrication on the membrane and to transition from the 30 μm electrode spacing at the membrane edge to the sub-

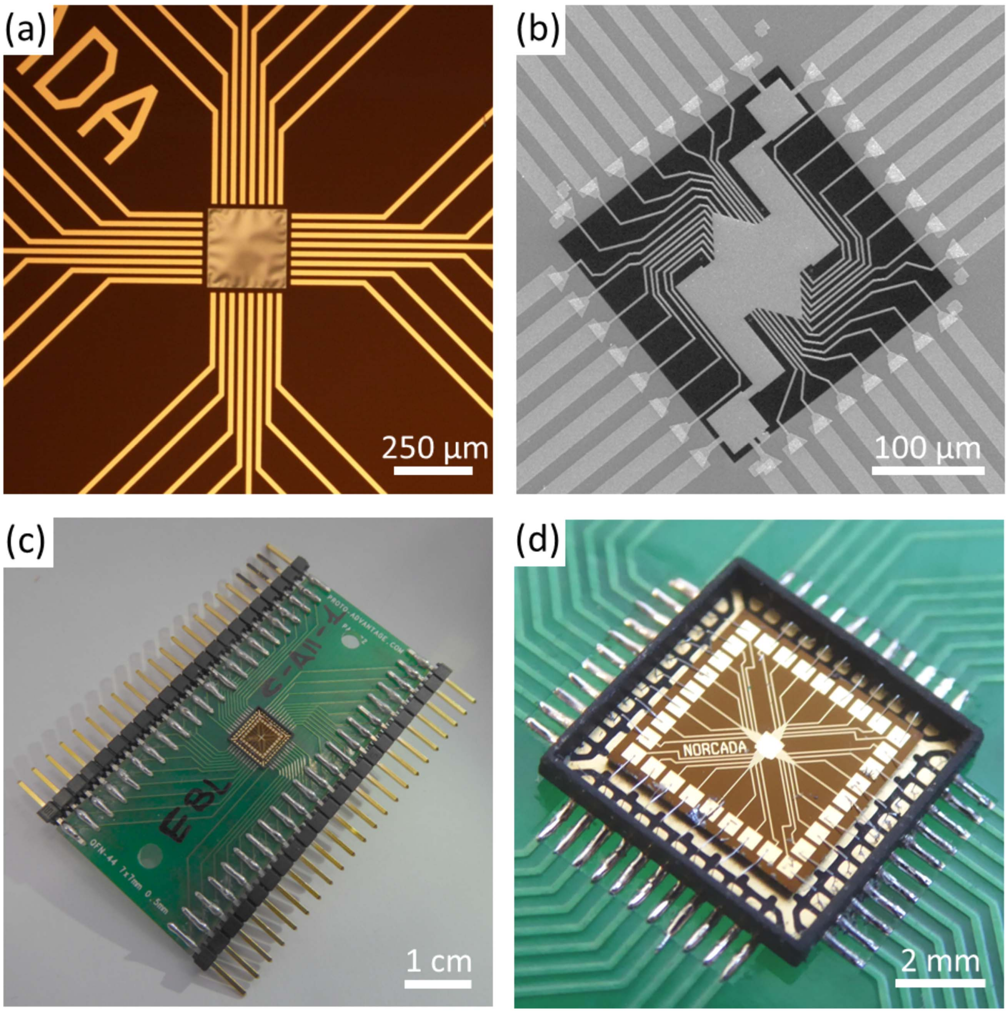

Figure 2. Contacting a nanomembrane. (a) Commercial 250 × 250 μm^2 silicon nitride membrane of 50 nm thickness on a 5 × 5 mm silicon frame with 32 electrodes. (b) Nanoscale gold contacts and gold areas for testing and metadevice fabrication made by e-beam lithography. (c) Addressable metamaterial device placed in a standard QFN to DIP package. (d) Close-up image of the metadevice in the QFN carrier.

micron electrode spacing that is required at the metamaterial edge, we performed electron beam lithography (figure 2(b)). A 1 μm thick layer of poly(methyl methacrylate) e-beam resist was spin-coated onto the membrane chip, then the electrode pattern and areas for metamaterial fabrication were exposed by standard electron beam lithography. The electrode pattern was developed for 60 s in a 1:3 MIBK:IPA solution at room temperature, rinsed with IPA and dried with N_2, followed by thermal evaporation of 50 nm of gold and subsequent lift-off.

In order to create a reliable and standardized electrical interface for the membrane chip, we used an open QFN (quad flat no-leads) chip carrier that had been surface-mounted by soldering to a QFN to DIP adapter (figure 2(c)). The membrane chip was attached inside the QFN chip carrier and the contact pads on the membrane frame were wire-bonded to the contacts of the chip carrier (figure 2(d)). The resulting chip assembly connects to a 16-way flat ribbon cable.

The metamaterial nanostructure was fabricated by gallium focused ion beam (FIB) milling and positioned relative to the e-beam lithography pattern using standard alignment techniques (figure 3(a)). Fifteen freestanding 18-μm-long chevron nanowires with a 230 nm × 100 nm cross-section were created by milling through both the gold and silicon nitride layers. Plasmonic chevron metamaterial strips were chosen for their suitability for electrothermal and magnetic actuation, their spring-like mechanical properties and their optical resonances [19, 20]. The chevron metamaterial unit cell is 600 × 620 nm^2 in size, corresponding to an active metamaterial area of 18 μm × 9 μm with a one-dimensional metadevice pixelation of 620 nm (figure 3(b)). Then the electrical connections of the 13 central nanowires to the contacts of the e-beam lithography pattern were separated by manual FIB milling at a reduced dose in order to remove the gold layer while keeping the silicon nitride membrane intact to ensure structural integrity of the device.

In order to realize a computer-controlled ‘programmable’ metadevice, the reconfigurable metamaterial was connected to a computer using a 16-channel digital-to-analog converter and a protective circuit that provides a 1 kΩ series resistor for each nanowire as well as grounding to avoid electrical shock to the nanostructure (figure 4(a)). A LabVIEW interface

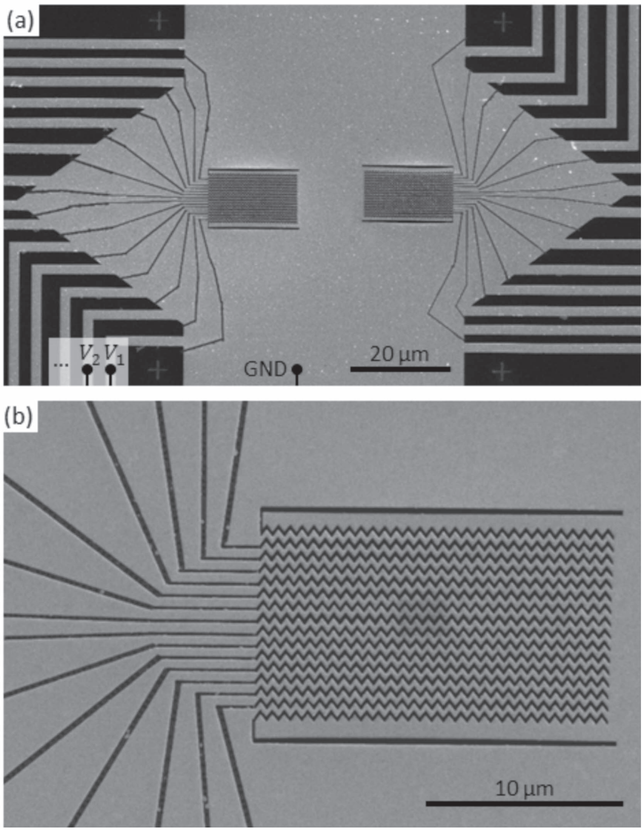

Figure 3. Addressable reconfigurable nanomembrane metadevices. (a) SEM image of the central membrane area with two contacted metadevices and alignment marks for automated FIB milling. V_i indicate electrical terminals for actuation of individual nanowires and GND indicates the common ground terminal. (b) High-resolution image of the nanowire grid metamaterial nanostructure.

allows computer-controlled actuation of individual metamaterial strips by setting the DAC output voltages.

Actuation of individual nanowires is illustrated by figures 4(b)–(d) and the online supplementary video, which show scanning electron micrographs of the central part of the metadevice at a viewing angle of 50° from the normal in order to visualize out-of-plane displacements of individual nanowires. The left and right panels show actuation of the third and fifth nanowires from the bottom with DAC control voltages of 3 V, while the middle panel shows a reference image without applied electrical signals. The nanowire resistance is small compared to the 1 kΩ protective resistor, therefore, the nanowire actuation current is almost 3 mA, with <9 mW (<1 mW) power dissipation per metamaterial strip including (excluding) the protective circuit. The movement of the actuated nanowires relative to their neighbors is clearly visible and corresponds to about 100 nm vertical displacement.

The actuation is caused by resistive heating of the nanowires, which leads to differential thermal expansion as the thermal expansion coefficient of gold (14.2×10^{-6} K^{-1}) is five times larger than that of silicon nitride (2.8×10^{-6} K^{-1}). Neglecting temperature variation along the wire for simplicity, the resulting displacement is proportional to $\Delta T \Delta\alpha L^2/t$, where the temperature change ΔT is proportional to the square of the applied current, the difference in thermal expansion coefficients $\Delta\alpha$ depends on the chosen materials, and L and t correspond to nanowire length and thickness, respectively [26]. Therefore, larger nanowire displacements and lower current operation are most easily achieved with longer nanowires or by placing the metadevice in a static magnetic field in order to combine electrothermal actuation with magnetic actuation driven by the Lorentz force. We found in our experiments that currents exceeding 3 mA (about 3×10^{11} A m^{-2} current density) are likely to damage our metadevice due to reaching the melting point of gold in positions where fabrication imperfections cause the nanowire to have a smaller gold cross-section. The exact nanowire damage threshold depends on the gold film quality, nanofabrication accuracy as well as the nanowire dimensions, see [27] for a detailed study. Therefore, an increased range of nanowire displacement due to a larger temperature range would require higher nanofabrication accuracy, a cooled environment or replacement of gold with a conductive material that has a higher melting point. Potential thermal issues such as heat transfer between nanowires still need to be investigated and the overall current applied to the metadevice may need to be limited to avoid possible overheating during simultaneous actuation of all nanowires. Such thermal issues can be minimized by fabricating the metadevice on a smaller membrane so that the thick supporting frame that acts as a heat sink is located at the nanowire ends. Reducing the size of the membrane will also enhance the mechanical stability of the structure. The device packaging could be improved with a transparent anti-reflection-coated protective lid to create a sealed unit. The speed of the thermal actuation process is determined by the cooling timescale of the nanowires, which is on the order of 10 μs and scales with L^2 according to conductive cooling estimates, while faster actuation could be driven by magnetic and electrostatic forces as illustrated by figures 1(b) and (c).

Potential optical functionalities of such programmable metadevices have been studied numerically by references [16] and [17], which show that similar metadevices can modulate the phase or intensity of reflected light in one dimension by controlling either the optical path length or light absorption separately with each nanowire, enabling functionalities of gratings, phase-gradient metasurfaces and curved mirrors on demand and without unwanted diffracted beams for wavelengths of operation that exceed the nanowire period, here 620 nm. Our metadevice design is intended to operate in the red to infrared band at wavelengths λ longer than the nanowire period, but small compared to the overall size of the nanowire array, i.e. 620 nm $< \lambda \ll 9$ μm. Beyond photonics, actuation of structured nanowires may also provide opportunities for manipulation of their thermal and phononic properties, which have been shown to depend on nanostructuring and strain [28].

In summary, we report the nanofabrication of an electrically addressable reconfigurable metadevice with 620 nm pixelation in one dimension. We demonstrate selective actuation of individual rows of metamaterial unit cells. Potential applications of such random access metadevices

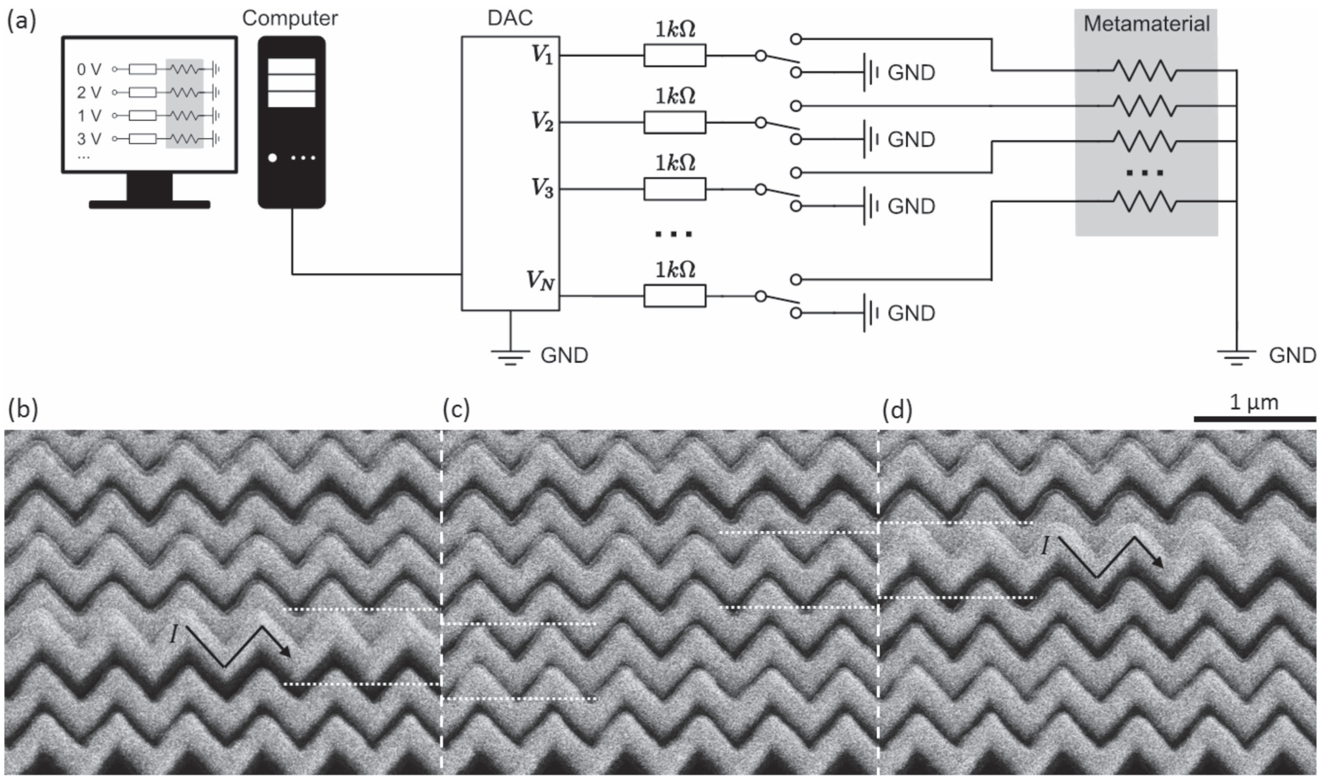

Figure 4. Selective electrical actuation of individual nanowires. (a) Schematic of the computer-controlled actuation circuit, where DAC indicates the digital-to-analog converter and GND indicates ground. (b)–(d) Strip actuation—SEM images showing the nanostructure at a viewing angle of 50° from the normal (b) with $V_3 = 3$ V applied to nanowire 3 from the bottom, (c) without voltage application and (d) with $V_5 = 3$ V applied to nanowire 5 from the bottom.

include spatial light modulators with sub-wavelength pixelation.

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