Nano-electromechanical switchable photonic metamaterials

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Abstract

We introduce mechanically reconfigurable electrostatically-driven photonic metamaterials (RPMs) as a generic platform for large-range tuning and switching of photonic metamaterial properties. Here we illustrate this concept with a high-contrast metamaterial electro-optic switch exhibiting relative reflection changes of up to 72% in the optical part of the spectrum.

1. Introduction

Switchable and tunable metamaterials are expanding research areas fueled by the development of nanophotonic all-optical data processing circuits, optical memory, smart surfaces, adaptable detection and imaging systems and transformation optics devices [1]. So far control over metamaterial properties at optical frequencies has been achieved by combining metal nanostructures with nonlinear materials, such as carbon nanotubes [2], or phase-change materials, such as chalcogenide glass [3] and vanadium dioxide [4]. However, these existing approaches are not without problems as optical nonlinearities require high intensities and phase transitions can be difficult to control.

Recently, it has been demonstrated that far-infrared metamaterials can be reliably and reversibly controlled by microelectromechanical (MEMS) actuators repositioning parts of specially-designed deformable meta-molecules [5, 6].

Here we demonstrate that reconfigurable photonic metamaterials provide a flexible platform for tuning and switching of metamaterial properties in the optical part of the spectrum. We illustrate this concept with a high-contrast metamaterial electro-optic switch operating in the telecommunications band from 1.3-1.7 μm.

2. Concept: reconfigurable photonic metamaterials

The properties of almost any metamaterial system strongly depend on coupling between metamaterial resonators. Therefore tuning and switching of metamaterial properties will be achieved if the distance between the metamaterial resonators can be controlled. This may be achieved by placing the meta-molecules on alternating reconfigurable and non-reconfigurable support structures. Compared to existing MEMS metamaterials for the far-infrared, this approach has two key advantages: (i) Being independent of the specific meta-molecule design it is applicable to a huge range of metamaterial patterns. (ii) There is no need for reconfigurable elements on the size scale of the meta-molecules, which would be extremely challenging to achieve for the optical part of the spectrum.

Reconfigurable support structures may be realized in the form of support beams with controllable spacing. Here we will focus on electrostatic control, where the beam spacing is controlled via attractive and repulsive electrostatic forces resulting from an applied voltage. However, we will also discuss alternative schemes for thermal and electrothermal control of reconfigurable nanostructures at the conference.

3. Experiment: metamaterial electro-optic switch

An example of an electrically controlled reconfigurable photonic metamaterial is shown by Fig. 1. It consists of 35 μm long silicon nitride bridges alternatingly covered with nanoscale "fishscale"-shaped plasmonic resonators and continuous gold wires. The entire structure was fabricated by focussed ion beam milling from a 50 nm thick silicon nitride membrane covered by a 50 nm thick thermally evaporated gold layer. The bridges were separated by 125 nm gaps for electrical isolation and pairs of bridges were alternatingly connected to two electrical contacts for electrostatic control of the device.

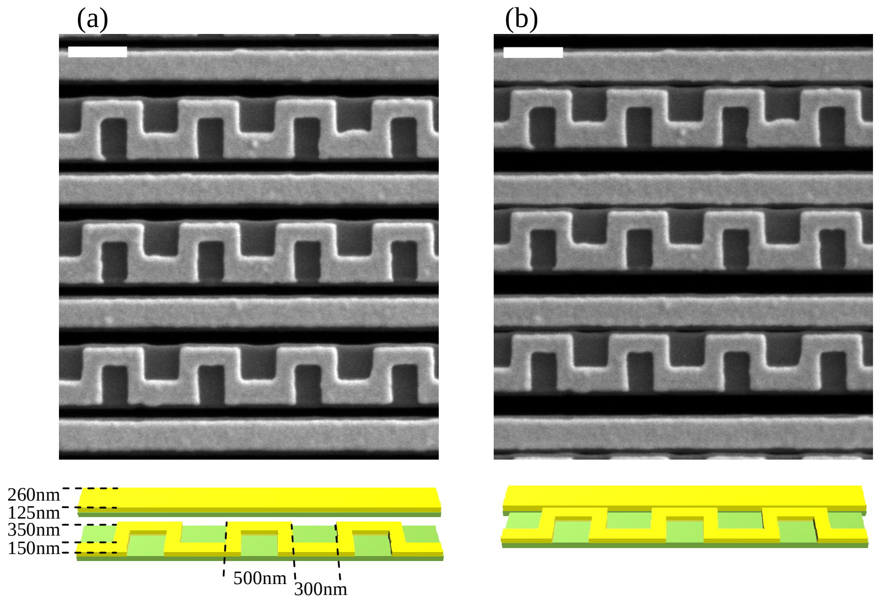

Fig. 1: Metamaterial electro-optic switch. (a) "Off" state and dimensions. (b) "On" state. The scale bar is 500 nm long.

A voltage applied to the metamaterial device leads to alternating attractive and repulsive electrostatic forces between "fishscale" and "wire"-bridges. At small voltages the electrostatic forces are in equilibrium with the restoring force of the elastic bridges, leading to only small displacements. However, as the restoring force is proportional to the bridge displacement, while the electrostatic forces are inversely proportional to the bridge separation, there is the threshold voltage where the electrostatic force overcomes the restoring force. At the threshold voltage U_{th} =5.7 V the structure switches into a brige-pair configuration, compare Figs. 1(a) and (b), showing the "off" and "on"-states respectively.

Switching of the metamaterial state leads to dramatic changes of its optical properties. Fig. 2 shows the metamaterial's reflection characteristics relative to the "off"-state. Switching the metamaterial to its "on"-state by applying a voltage above U_{th} increases its reflectivity by 72% in the telecommunications band around 1.5 μm. This remarkably large change in reflectivity is linked to a resonant mode of the coupled system of fishscale structure and straight wires. The resonant properties of this system strongly depend on coupling between neighboring bridges and switching the metamaterial to its "on"-state redshifts the resonance by about 15% as the plasmonic structures are moved together by electrostatic forces.

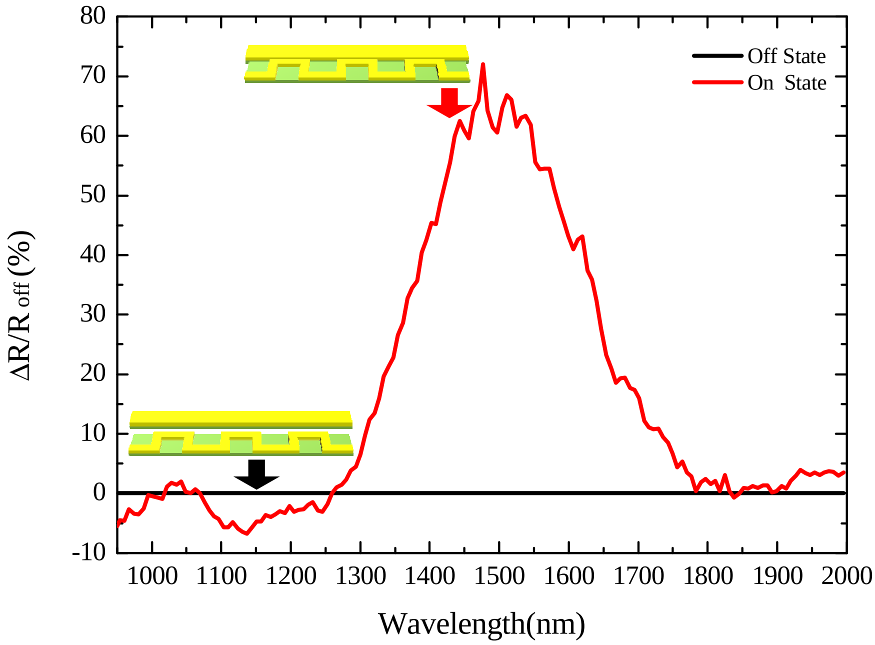

Fig. 2: Contrast between "on" and "off" states of the metamaterial electro-optic switch: $(R - R_{\text{off}})/R_{\text{off}}$.

4. Conclusion

In summary we demonstrate that reconfigurable photonic metamaterials provide a flexible platform for wide-range tuning and switching of metamaterial properties in the optical part of the spectrum. By placing nanoscale plasmonic resonators with useful functionalities on reconfigurable support structures their interactions can be controlled, leading to tuning of their electromagnetic properties. Potential applications of this generic approach include electro-optic sensors, tunable spectral filters, switches, modulators and any other planar metamaterial device where tunability is required or desirable. Specifically, we demonstrate a metamaterial electro-optic switch providing large contrast (up to 72%) between its reflective "off" an "on"-states in the telecommunications band around 1.5 μm.

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