Lorentz Force Metamaterial with Giant Optical Magnetoelectric Response

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Abstract: We demonstrate the first reconfigurable photonic metamaterial controlled by electrical currents and magnetic fields, providing first practically useful solutions for sub-megahertz and high contrast modulation of metamaterial optical properties.
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1. Electrooptical and magnetooptical metamaterial modulation

We introduce novel, practically useful solutions for adjusting metamaterial optical properties on demand. For the first time we demonstrate reconfigurable metamaterials controlled by currents and magnetic fields, offering solutions that provide high-contrast modulation of optical properties at up to 100s of kHz, while integrating easily in optoelectronic devices. We control metamaterial properties by dynamically rearranging the entire metamaterial array on the nanoscale. These nanoscale movements are driven by the magnetic Lorentz force associated with electrical charges moving in a magnetic field and differential thermal expansion of bimorph metamaterial components resulting from resistive heating. The associated optical manifestations correspond to an exeptionally large and novel optical magnetoelectric effect.

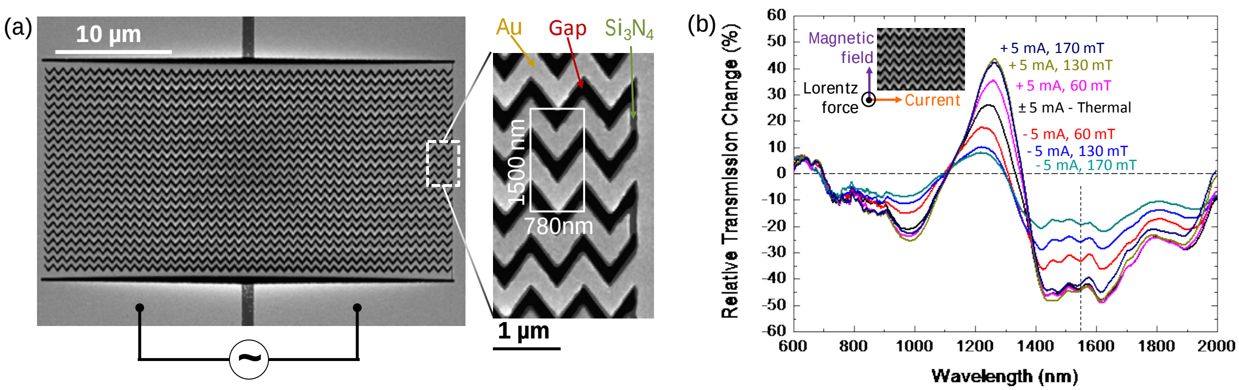

Fig. 1. (a) Structure of the reconfigurable photonic metamaterial consisting of free-standing plasmonic zig-zag shaped bridges, where every second bridge is connected to electrical terminals on both ends, see close-up of the bridges ends. (b) Magnetic tuning of the reconfigurable photonic metamaterial. Relative transmission change as a function of applied device current and magnetic field.

The metamaterial structure consists of elastic, spring-like zig-zag bridges, every second one of which is electrically connected to electrical terminals on both ends so that it can support currents, see Fig. 1(a). Application of a current of 5 mA to the nanostructure heats the electrically connected bridges, which bend due to differential thermal expansion of the plasmonic gold layer and the silicon nitride substrate causing relative transmission changes of up to 50%, see black curve in Fig. 1 (b). The optical changes observed in the metamaterial depend quadratically on the applied current and are independent of the current direction. Simultaneous application of a perpendicular magnetic field (170 mT) in the metamaterial plane leads to a Lorentz force that increases/decreases the mechanical deformation depending on the relative directions of the current flow and magnetic field, leading to an increase/decrease of the electrothermal transmission modulation, which is particularly apparent around 1250 nm wavelength, see Fig. 1(b).

While the speed of the electrothermal deformation that results from applied currents alone is limited by the thermal recovery timescale, the Lorentz force allows higher modulation speeds that are only limited by the fundamental mechanical resonance of the structure. As illustrated by Fig. 2, electric heating of the nanostructure with currents allows effective modulation of its optical properties at low frequencies, however, due to the bridge cooling timescale of about 10 μs, heating and cooling of the bridges becomes inefficient at modulation rates of 10s of kHz leading to a decreasing modulation amplitude, which becomes negligible around 100 kHz (black curve). The presence of a magnetic field leads to an increase/decrease of the modulation amplitude at low frequencies (blue/red), depending on whether Lorentz force and differential thermal expansion deform the nanostructure in the same or opposite directions. As the Lorentz force is not affected by thermal timescales, magnetic modulation dominates above about 30 kHz and can be seen up to the 400 kHz mechanical resonance of the bridges.

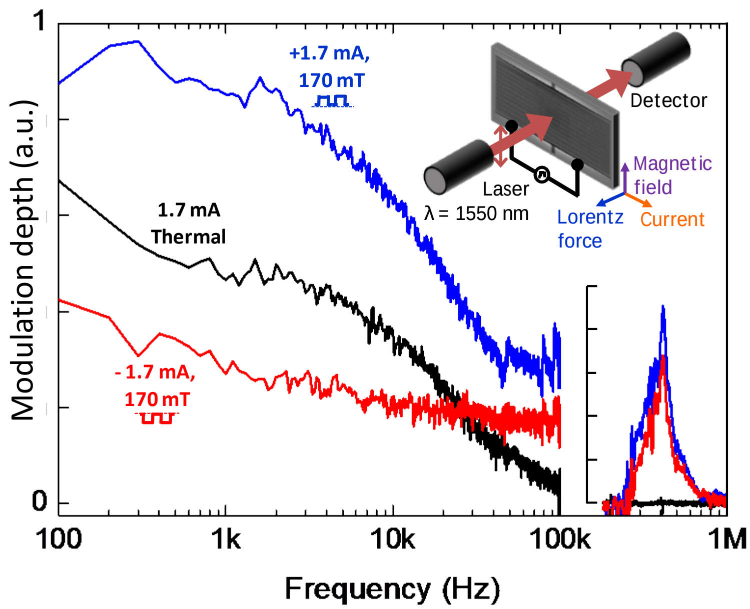

Fig. 2. High frequency modulation of metamaterial optical properties with electrical currents and magnetic fields. Modulation depth as a function of modulation frequency for purely electrothermal modulation (black, 1.7 mA modulated current only) and simultaneous application of a static magnetic field of 170 mT leading to a Lorentz force acting in the same (blue) or opposite (red) direction as the electrothermal deformation of the nanostructure.

2. Giant optical magnetoelectric effect

The dependence of the metamaterial's optical properties on magnetic field and electrical currents corresponds to a novel optical magnetoelectric effect. The optical magnetoelectric effect reported here is reciprocal and controls the metamaterial's linear dichroism (and linear birefringence) by changing the amplitude (and phase) of the metamaterial's transmitted (and reflected) linear eigenpolarizations. It is different from the conventional optical magnetoelectric effect, which causes nonreciprocal birefringence and dichroism. It is also different from conventional magneto-optical effects, i.e. the non-reciprocal Faraday effect and the magnetooptical Kerr effect, both of which cause magnetic circular birefringence (Faraday rotation, Kerr rotation) and dichroism at normal incidence and both of which vanish in our configuration where the magnetic field is parallel to the material surface. It resembles the Cotton-Mouton/Voigt effect, where magnetic linear birefringence and dichroism occur for propagation perpendicular to the magnetic field direction, however, while the Cotton-Mouton/Voigt effect has a quadratic magnetic field dependence, our effect is proportional to magnetic field as bridge deformation and Lorentz force are linearly dependent on magnetic field.

3. Summary

In summary, we demonstrate the fastest and most practical solutions for large-range tuning of reconfigurable photonic metamaterials so far: (i) Electrothermal modulation exploiting local resistive heating and differential thermal expansion to reconfigure the nanostructure and (ii) magnetic modulation exploiting the Lorentz force on current-carrying reconfigurable parts of the metamaterial which is placed in an external magnetic field. While effective electrothermal control of photonic metamaterials is limited by thermal timescales to 10s of kHz, magnetic modulation can be driven up to 100s of kHz and beyond. The observed magnetoelectric effect is exceptionally large and distinct from known magnetoelectric and magnetooptical phenomena.

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