Metamaterials Controlled with Light

Ilya V. Shadrivov,[1] Polina V. Kapitanova,[2] Stanislav I. Maslovski,[2,3] and Yuri S. Kivshar[1,2]
[1]*Nonlinear Physics Centre, Research School of Physics and Engineering, Australian National University, Canberra ACT 0200, Australia*
[2]*National Research University of Information Technologies, Mechanics and Optics (ITMO), St. Petersburg 197101, Russia*
[3]*Instituto de Telecomunicações, Universidade de Coimbra, Pólo II, 3030 Coimbra, Portugal*
(Received 12 April 2012; published 23 August 2012)

We suggest and verify experimentally the concept of functional metamaterials whose properties are remotely controlled by illuminating the metamaterial with a pattern of visible light. In such metamaterials arbitrary gradients of the effective material parameters can be achieved simply by adjusting the profile of illumination. We fabricate such light-tunable microwave metamaterials and demonstrate their unique functionalities for reflection, shaping, and focusing of electromagnetic waves.

DOI: 10.1103/PhysRevLett.109.083902 PACS numbers: 42.70.−a, 78.67.Pt, 81.05.Xj

Nature gives us more than a hundred elements listed in the periodic table, and thousands of their combinations in organic and inorganic substances, which allows for significant control over chemical, thermal, mechanical, and electrical properties of these materials. However, our ability to adjust the magnetic response of matter is still very limited. It is especially difficult to produce magnetic materials operating at GHz, THz, or optical frequencies, which would be highly desirable for wave manipulation in modern communication applications. Such a demand led to the emergence of a new field of physics—the electromagnetics of metamaterials, or materials whose structural elements (*meta-atoms*) are man-made subwavelength inclusions of various shapes optimized for the desired operation. The concept of metamaterials offers exceptional opportunities for tailoring macroscopic electromagnetic response through appropriate choice and arrangement of meta-atoms. This makes composite metamaterials remarkably different from natural materials, and opens exciting possibilities to change and control their parameters at will.

Electromagnetic metamaterials [1–3] already demonstrate many intriguing properties such as artificial magnetism at terahertz and optical frequencies, backward wave propagation and negative refraction, as well as enhanced chirality and optical activity (see, e.g., the recent review papers [4–6], and references therein). Metamaterials also find applications in subwavelength imaging and transformation optics [7,8]. Currently, a majority of demonstrated metamaterials possess fixed and often narrow-band response. Thus, there is a tremendous interest towards creating tunable metamaterials, whose local properties can be controlled externally, e.g., by photoexciting the carriers in the semiconductor parts of the structure [9–11], or by employing a nonlinear response [12]. Tunable metamaterials imply the ability to continuously change their properties through certain external influence or signal, with the mechanism of tunability being intrinsic to metamaterial. In resonant metamaterials, tunability may be achieved by affecting the system so as to change the parameters of the resonance. As a consequence, characteristics of a metamaterial can be varied, enabling tunable and controllable wave propagation, transmission, or reflection. It is also desirable to be able to control the meta-atoms of such materials individually and in a noncontact manner.

At microwave frequencies, a tunable nonlinear magnetic meta-atom can be realized as a split-ring resonator (SRR) loaded with a varactor diode [13,14]. A metamaterial formed by such elements allows for a power-induced control of wave propagation [15]. Moreover, with such artificial nonlinear media it is possible to demonstrate a number of interesting phenomena accessible at low powers, for example, nonlinear metamaterial mirror [16,17].

In this Letter we suggest and verify experimentally a novel practical approach for dynamic noncontact tuning of composite structures. This approach allows metamaterials to acquire almost any desirable spatially inhomogeneous properties by interacting with visual light patterns projected onto the metamaterial, which may lead to a new generation of electromagnetic composites whose local properties can be tuned continuously. More specifically, our approach works by applying a handcrafted light profile to an array of light-tunable magnetic meta-atoms. The illumination affects the magnetic resonances of the meta-atoms individually. Thus, for the first time we achieve a practical design of a metamaterial in which the constitutive parameters may be changed at will and gradually within a material volume. We fabricate the first reconfigurable light-tunable metamaterial that under different illumination profiles can operate as a controllable beam deflector or/and focusing or defocusing reflector.

The light-tunable metamaterial mirror that we study experimentally is formed by an array of 24 broadside-coupled SRRs placed perpendicular to a metallic screen [see Fig. 1(b)]. The broadside-coupled SRR is made of two copper broken rings with the oppositely oriented gaps. The rings are placed on the opposite sides of a 1.6 mm FR4 printed circuit board (PCB). The inner radius of the SRR is 3.25 mm, the width of the metal strip is 0.5 mm, the copper thickness is 30 μm and the gap size is 1 mm. Each ring has an extra gap of the width of 0.4 mm for a variable capacitance diode (Skyworks SMV1405 varactor). The biasing of the varactors in each SRR is provided by a pair of photodiodes that generate a voltage that increases with illumination intensity. By illuminating the array with light of varying intensity, we are able to change the properties of the structure inhomogeneously. Thus, by changing the applied light pattern, the properties of the metamaterial can vary in such a way that, e.g., the electromagnetic wave incident on the metamaterial experiences a locally varying phase shift being reflected at different angles, as schematically illustrated in Fig. 1(a).

To estimate the performance of the SRR-based reflector, we start by simulating numerically the response of split-ring resonators in the CST MICROWAVE STUDIO™. In our simulations, the SRR is placed in a waveguide formed by two horizontal perfectly conducting (PEC) walls and two vertical magnetic walls. The waveguide is terminated by a wave port at one end, and by a metal screen (emulated as PEC) at the opposite end. We adjust the waveguide dimensions and the SRR orientation so that the electric and magnetic fields of the main mode are, respectively, parallel and perpendicular to the plane of the SRR. In this configuration, the SRR is characterized by a magnetic response that creates a minimum in the reflection coefficient of the loaded waveguide. To simulate varactors in CST, we use capacitive lumped elements with adjustable value of the capacitance. The simulated phase of the reflection coefficient is shown in Fig. 2 for different values of the varactor capacitance.

In our experiments the structure is made using the standard PCB technology. The measurements are performed in a parallel plate waveguide. The bottom plate of the waveguide is placed on the computer-controlled translation stage, so that the source antenna, the collimating dielectric lens and the metamaterial sample move with respect to the receiving probe, which is fixed to the stationary top plate of the waveguide. The spacing between the waveguide plates is 13 mm. The emitting probe is a short monopole antenna, with 12 mm long central conductor of the diameter of 1.3 mm surrounded by 1.4 mm thick Teflon coating. This antenna produces cylindrical wave, partially focussed by the dielectric lens onto the sample. The delrin lens is designed in such a way that in the range from 3 to 5 GHz it creates a Gaussian-like beam of the width of approximately 15 cm. The edges of the waveguide are filled with microwave absorber in order to minimize reflections from the sides of the waveguide, and to stop the ambient light affecting the photodiodes. The transmitting and receiving probes are connected to the two ports of the Rohde and Schwartz vector network analyzer, model ZVB20.

The generated microwave beam is scattered by the metamaterial. Since the size of the scanning area is limited, at the frequencies of interest we can only observe the region where incident and reflected beams strongly overlap. To visualize only reflected (scattered) wave, we subtract the incident field measured without a metamaterial sample from the field measured in the presence of the metamaterial.

For the spatially inhomogeneous light illumination, we have developed a controllable light source comprised of an array of red light-emitting diodes (LEDs) which is placed next to the sample. The integrated lens of each LED ensures that each LED illuminates almost exclusively one corresponding photodiode. The voltage on each set of four LEDs is computer controlled. Using such a relatively simple setup, we are able to create arbitrary illumination patterns along the metamaterial mirror without a need to develop an optical light projection system. However, such a system may be required for metamaterial structures of higher dimensions.

The reflection coefficient of the metamaterial mirror measured with a local electric field probe features several resonances arising from the interaction of multiple SRRs in the structure. We focus on the lowest resonances with the

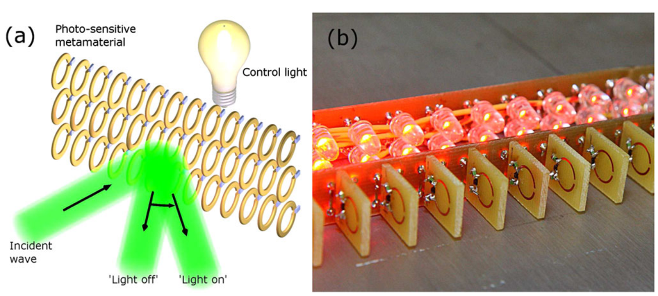

FIG. 1 (color online). (a) Operation of light-tunable metamaterial. Electromagnetic wave incident on metamaterial is reflected at different angles depending on the control light illumination. (b) Photograph of the microwave light-tunable metamaterial mirror made of an array of broadside-coupled SRRs. Each resonator contains a pair of varactors (one in each ring), and the biasing of the varactors is provided by photodiodes, which are located on the back side of the metamaterial. Also shown is the light source composed of an array of LEDs, which provide the required control light patterns.

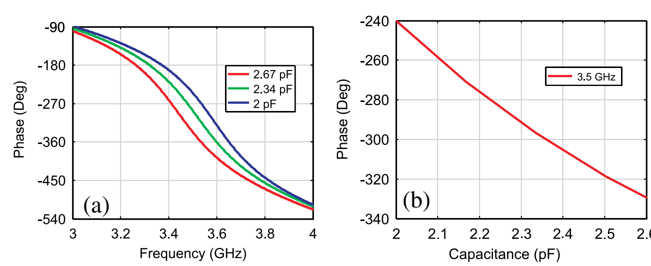

FIG. 2 (color online). (a) Simulated phase of the reflection coefficient as a function of frequency for different values of capacitance; (b) the same phase as a function of the varactor capacitance for the frequency of $f = 3.5$ GHz.

central frequency around 3 GHz. First, we study the dependence of the resonant frequency on the illumination intensity. Because the light intensity produced by LEDs monotonically increases with the applied voltage, and since it is difficult to measure the light intensity in the vicinity of photodiodes in our setup, we can unambiguously characterize the illumination by the voltage applied to the LEDs, which we call control voltage in what follows. The measured reflection coefficient versus frequency is shown in the inset of Fig. 4(a) for zero and for maximum applied illumination. One can clearly see that the resonance (the minimum of the reflection coefficient) shifts, indicating that the properties of the metamaterial in the vicinity of the probe significantly change under illumination, as predicted previously for one SRR [18], with a difference that the resonant frequency decreases with the illumination because of the opposite polarity of the photodiodes used in this setup.

In the uniformly illuminated structure the resonant frequency depends on the control voltage as is shown in Fig. 4(a). We observe a shift of about 150 MHz, which is comparable to the width of the resonance. This suggests that at an appropriate frequency slightly above or below the resonance the reflection properties of the metamaterial are strongly affected by the illumination.

Because the effects that we study in this work are mostly related to the local *phase* changes in the field reflected by the structure, the phase of the reflection coefficient and its dependence on the illumination are of the crucial importance. Dependence of the phase of the reflection coefficient on the control voltage is shown in Fig. 4(b). We see that the available phase control range of the metamaterial is on the order of 30°. This range can be substantially increased, e.g., by using arrays of photodiodes generating higher voltage.

To demonstrate the flexibility of the light-tunable metamaterial mirror, we now apply inhomogeneous light illumination patterns. First, we apply such illumination that the resonant frequency of the SRRs changes linearly along the structure. At a given frequency of operation this corresponds to a linear gradient in the reflection phase, which leads to the reflected beam deviation, so that the angle of reflection is not equal to the angle of incidence. When the gradient of illumination changes sign we observe reflected beam steering by 11°, as shown in Fig. 3.

Next, we demonstrate that with a specifically crafted profile of illumination we may achieve focusing and defocusing by a planar structure, as schematically shown in Figs. 5(a) and 5(b). To obtain the corresponding spatial variation of the reflection phase, the illumination profile should resemble the parabolic phase distributions in concave and convex mirrors. The photographs of the corresponding illumination patterns are shown in Figs. 5(c)

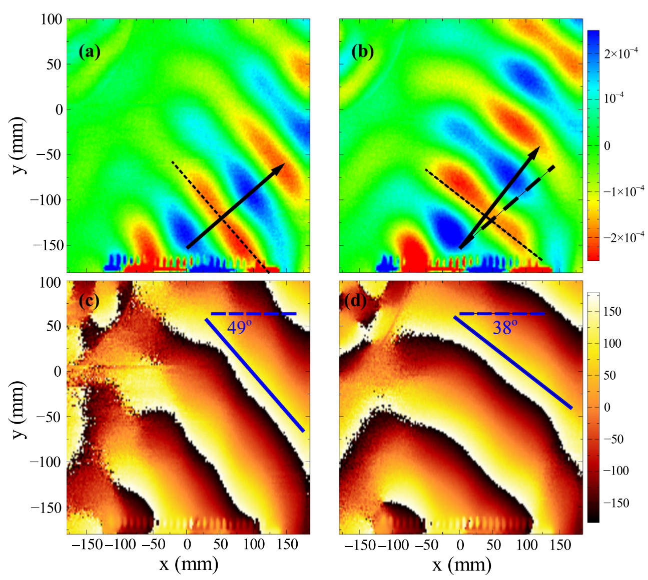

FIG. 3 (color online). (a),(b) Real part, and (c),(d) phase of the measured scattered field distribution at $f = 3.06$ GHz for two different control light illumination patterns. The wave incident is reflected from the top-left corner by the metamaterial mirror located at the bottom of the presented figures. (a),(c) Light illumination decreases from left to right; (b),(d) light illumination decreases from right to left. By changing the illumination pattern the metamaterial mirror can steer the reflected beam by at least 11°.

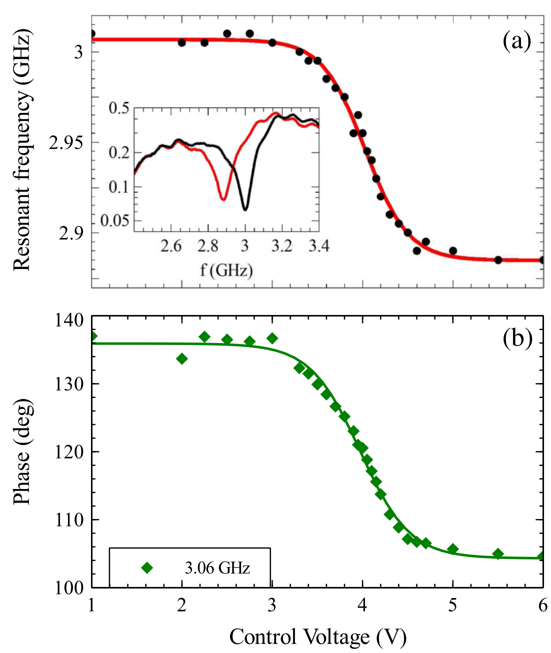

FIG. 4 (color online). (a) Measured (dots) and fitted (solid) data for the resonant frequency (corresponds to the minimum of the reflection coefficient) of the metamaterial mirror as a function of the control voltage applied to the LEDs. Inset in (a) shows the measured reflection coefficient as a function of frequency around $f = 3$ GHz. (b) Example of the dependence of the reflection coefficient phase on the control voltage for the case of the monotonically increasing light intensity.

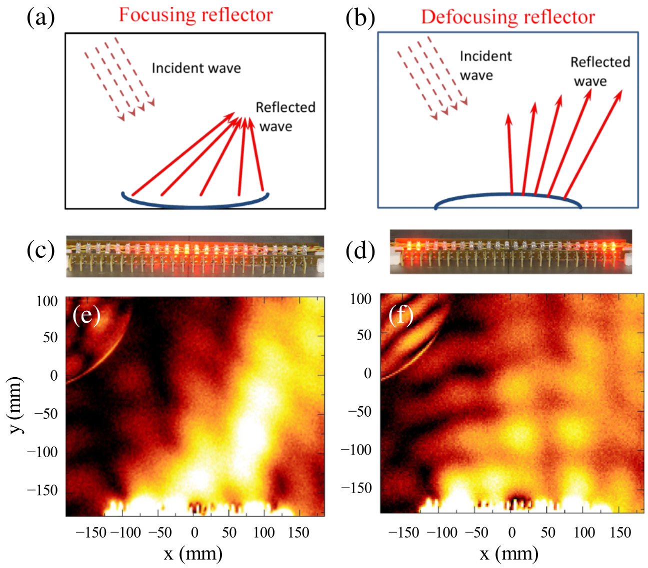

FIG. 5 (color online). Metamaterial mirror operating as (a) focusing or (b) defocusing reflector, depending on the light illumination pattern (c) and (d). Measured scattered field amplitudes at $f = 3.075$ GHz are shown for (e) focusing and (f) defocusing reflectors. Focusing of the scattered field is observed when the illumination is stronger in the middle [see panel (c)]. However, when the illuminated is stronger at the edges of the metamaterial mirror [as shown in panel (d)], the structure acts as a defocusing reflector.

and 5(d). The resulting amplitude distributions of the field scattered by the inhomogeneously illuminated mirror are shown in Figs. 5(e) and 5(f). Focusing of the incident electromagnetic wave is clearly observed in Fig. 5(e), while Fig. 5(f) shows a defocusing wave pattern.

With these examples, we have demonstrated that the proposed light-tunable metamaterial has a great flexibility, so that its resonant properties can be changed arbitrarily within a sample. This allows for designing reconfigurable mirrors or lenses in which switching between focusing and defocusing configurations, or between beam deflection directions is just a matter of adjusting the light illumination profile which may be done in a fraction of a second. Such control can be performed remotely, by projecting required light patterns on a photo-sensitive elements of the metamaterial. Moreover, the approach can be extended to electromagnetic structures of higher dimensions, where the light can be delivered to each control element by using optical fibers, and we believe that this can lead to novel and exciting applications of the light-tunable metamaterials. Importantly, this type of metamaterial tunability can be applied to shorter wavelengths, at least up to THz frequencies. For example, one can use spatially inhomogeneous photoexcitation of the semiconductor components even without metamaterials [19] to control THz beams, and the use of metamaterials can potentially extend this functionality further [9].

Metamaterials are prominent for delivering exceptional opportunities they offer in tailoring macroscopic properties of materials through appropriate choice and arrangement of their structural elements. We believe that the approach suggested here will open novel possibilities to implement tunability. Indeed, the ability to control the local material properties by applying light patterns may lead to unprecedented flexibility in confining, guiding or redirecting the flow of electromagnetic radiation. This will make possible to fabricate dynamically tunable structures such as lenses and waveguides, as well as demonstrate the first fully reconfigurable cloaking device.

This work was supported by the Ministry of Education and Science of the Russian Federation and by the Australian Research Council. The authors acknowledge useful discussions with P. A. Belov and M. Lapine, as well as the help of P. V. Voroshilov and D. S. Filonov at the initial stage of this project.

[1] V. G. Veselago, Sov. Phys. Solid State **8**, 2854 (1967); Sov. Phys. Usp. **10**, 509 (1968).
[2] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[3] R. A. Shelby, D. R. Smith, and S. Schultz, Science **292**, 77 (2001).
[4] N. Zheludev, Science **328**, 582 (2010).
[5] C. M. Soukoulis and M. Wegener, Science **330**, 1633 (2010).
[6] A. D. Boardman, V. V. Grimalsky, Yu. S. Kivshar, S. V. Koshevaya, M. Lapine, N. M. Litchinitser, V. N. Malnev, M. Noginov, Yu. G. Rapoport, and V. M. Shalaev, Laser Photonics Rev. **5**, 287 (2011).
[7] U. Leonhardt, Science **312**, 1777 (2006).
[8] J. B. Pendry, D. Schurig, and D. R. Smith, Science **312**, 1780 (2006).
[9] W. J. Padilla, A. J. Taylor, C. Highstrete, M. Lee, and R. D. Averitt, Phys. Rev. Lett. **96**, 107401 (2006).
[10] A. Degiron, J. J. Mock, and D. R. Smith, Opt. Express **15**, 1115 (2007).
[11] A. Rose and D. R. Smith, Phys. Rev. A **84**, 013823 (2011).
[12] A. A. Zharov, I. V. Shadrivov, and Yu. S. Kivshar, Phys. Rev. Lett. **91**, 037401 (2003).
[13] I. V. Shadrivov, S. K. Morrison, and Yu. S. Kivshar, Opt. Express **14**, 9344 (2006).
[14] B. Wang, J. Zhou, T. Koschny, and C. M. Soukoulis, Opt. Express **16**, 16058 (2008).
[15] I. V. Shadrivov, A. B. Kozyrev, D. W. Van Der Weide, and Yu. S. Kivshar, Opt. Express **16**, 20266 (2008).
[16] I. V. Shadrivov, A. A. Zharov, and Yu. S. Kivshar, J. Opt. Soc. Am. B **23**, 529 (2006).
[17] A. Rose, D. Huang, and D. R. Smith, Phys. Rev. Lett. **107**, 063902 (2011).
[18] P. V. Kapitanova, S. I. Maslovski, I. V. Shadrivov, P. V. Voroshilov, D. S. Filonov, P. A. Belov, and Yu. S. Kivshar, Appl. Phys. Lett. **99**, 251914 (2011).
[19] S. Busch, B. Scherger, M. Scheller, and M. Koch, Opt. Lett. **37**, 1391 (2012).