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Electromagnetic wave analogue of an electronic diode

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Abstract. An electronic diode is a nonlinear semiconductor circuit component that allows conduction of electrical current in one direction only. A component with similar functionality for electromagnetic waves, an electromagnetic isolator, is based on the Faraday effect of rotation of the polarization state and is also a key component in optical and microwave systems. Here we demonstrate a chiral electromagnetic diode, which is a direct analogue of an electronic diode: its functionality is underpinned by an extraordinarily strong nonlinear wave propagation effect in the same way as the electronic diode function is provided by the nonlinear current characteristic of a semiconductor junction. The effect exploited in this new electromagnetic diode is an intensity-dependent polarization change in an artificial chiral metamolecule. This microwave effect exceeds a similar optical effect previously observed in natural crystals by more than 12 orders of magnitude and a direction-dependent transmission that differs by a factor of 65.

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The Lorentz reciprocity lemma dictates that *linear* transmission of certain polarization states must be identical for forward and backward directions, unless the medium is statically magnetized or causes polarization conversion. In optics, the simplest isolator exploiting nonreciprocal transmission of circularly polarized light consists of a pair of polarizers and a Faraday rotator and it requires a static magnetic field [1]. A similar approach is also used for microwave devices. As another example, asymmetric transmission in metamaterial structures is allowed if propagation is accompanied by polarization conversion [2]–[4].

The Lorentz lemma is not applicable to nonlinear effects, thus allowing asymmetric transmission of intense electromagnetic waves. Asymmetric nonlinear distributed Bragg gratings [5, 6], metamaterial structures [7] and even disordered layered structures [8] were predicted theoretically to show directionally asymmetric responses for linearly polarized light. In this paper, we introduce and verify experimentally the concept of *a nonlinear electromagnetic diode for circularly polarized waves*. It is analogous to an electronic diode that transmits electric current in only one direction due to its nonlinear current–voltage characteristics, see figure 1. The nonlinear element in our nonreciprocal structure is an *artificial chiral metamolecule*. By introducing nonlinearity into the metamolecule, we experimentally demonstrate that it exhibits unidirectional transmission for one circular polarization while remaining transparent for the polarization of opposite handedness (see figure 1).

Nonlinear asymmetric transmission can only occur in the presence of a strong intensity-dependent propagation effect. Our idea is to exploit the intensity dependence of the gyrotropy in chiral media, which manifests itself as differential circular birefringence and dichroism. It has been known for nearly 200 years that many natural media exhibit strong optical activity; however, theoretical estimates predicted that nonlinear optical activity would be small and difficult to observe [9]–[11]. The first mention of this effect was made by S I Wawilow [12] who concluded that the necessary light intensities could only be found inside stars. The subsequent invention of the laser made it possible to study this effect with experimentally achievable power levels, and it was first observed in 1979 in $LiIO_3$ crystals [13]. In such materials the nonlinear optical activity was smaller than its linear counterpart by a factor of 10^{-6}, and this required samples several centimeters in length and light intensities of $100\,\mathrm{MW\,cm^{-2}}$, which is close to the optical breakdown of the crystal. Such a small level of nonlinearity is not sufficient for demonstrating any practically important electromagnetic diode functionality. In artificial media, however, much higher levels of optical activity can be achieved through the engineering of chiral properties of metamolecules. For instance, the polarization rotation in microwave chiral metamaterials can be nearly a million times stronger than in natural quartz for optical frequencies, once the sample thickness is normalized to the wavelength of radiation [15]. Moreover, in contrast to natural media, high levels of nonlinearity can be readily achieved in metamaterials through the inclusion of nonlinear electronic components for microwave applications [19]–[21] or by exploiting the local-field enhancement effects in the optical range [22, 23]. This leads to the opportunity to observe *extremely strong nonlinear gyrotropy* and thus to develop an electromagnetic diode.

We demonstrate the electromagnetic diode effect in a nonlinear chiral metamolecule consisting of a pair of wire strips, which are separated by a dielectric layer and twisted with respect to each other by angle ϕ, as shown in the inset to figure 2(a) (see Methods for more details). The resonant mode of this structure interacts both with the electric and magnetic fields due to the inductive chiral coupling between the wires, resulting in strong gyrotropy [24]. Adding a nonlinear element, a lumped varactor, to the center of one of the wires allows for

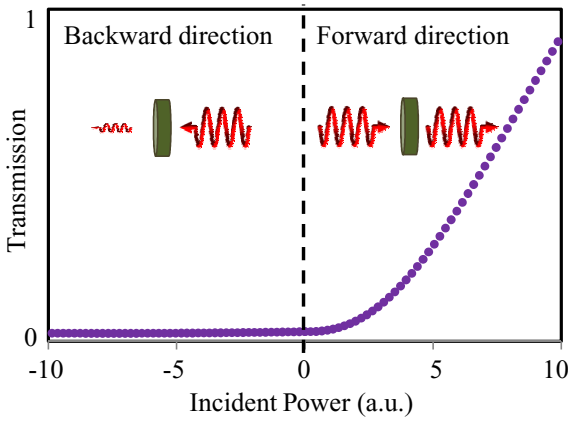

Figure 1. Operating principles of a metamaterial diode. The device shows different levels of transmission for circularly polarized waves propagating in the opposite directions due to the nonlinearity of a chiral metamolecule. This is similar to an electronic diode exhibiting different resistance for currents propagating in opposite directions due to the nonlinearity of the p–n junction.

the creation of the metamaterial diode with high contrast between forward and backward transmission in the high-power regime—see schematics in figure 2, and the more detailed description in Methods.

The results of our measurements for the left-handed circularly polarized wave scattering on a left-handed chiral metamolecule are shown in figure 2. When the amplitude of the incident wave is small, the structure shows a linear response, and the transmission coefficients in both directions are equal. However, in the nonlinear regime, with high intensity of the impinging wave we observe considerably different transmission properties in opposite directions with the maximal intensity contrast between the two directions of 18 dB. Our numerical modeling shows that such behavior results from significantly different current amplitudes induced in the two-wire strips by the waves entering the metamolecule from one direction, in comparison with a much smaller excitation difference produced by a wave entering from the opposite direction. The 'polarity' of the metamaterial diode depends on the operating frequency: in the range 5.9–6.0 GHz the transmission for the left-handed circularly polarized wave is greater in the forward direction (see figure 2(a)), i.e. when the wave hits the strip with the nonlinear element first. However, in the range from 6.0 to 6.3 GHz the 'polarity' reverses and the diode transmits the same polarization in the opposite direction only.

Figure 2(b) demonstrates the dependence of the transmittance on the incident power for both directions. The transmission curves are asymmetric with respect to zero incident power indicating a remarkable similarity with the I–V response of an electronic diode, while switching 'polarity' depends on the frequency of operation. We note that the response time of the structure is below 1 s for increasing incident power, and it is of the order of 10 s for decreasing microwave power. The nature of the nonlinear response of a diode in a resonant system was discussed before in [25, 26], and it is caused by rectification of the alternating current on the diode, which induces a self-bias voltage.

To study the nonlinear polarization properties of the chiral metamolecule, we also measured its polarization rotatory power for the symmetric case, with the central sections of both

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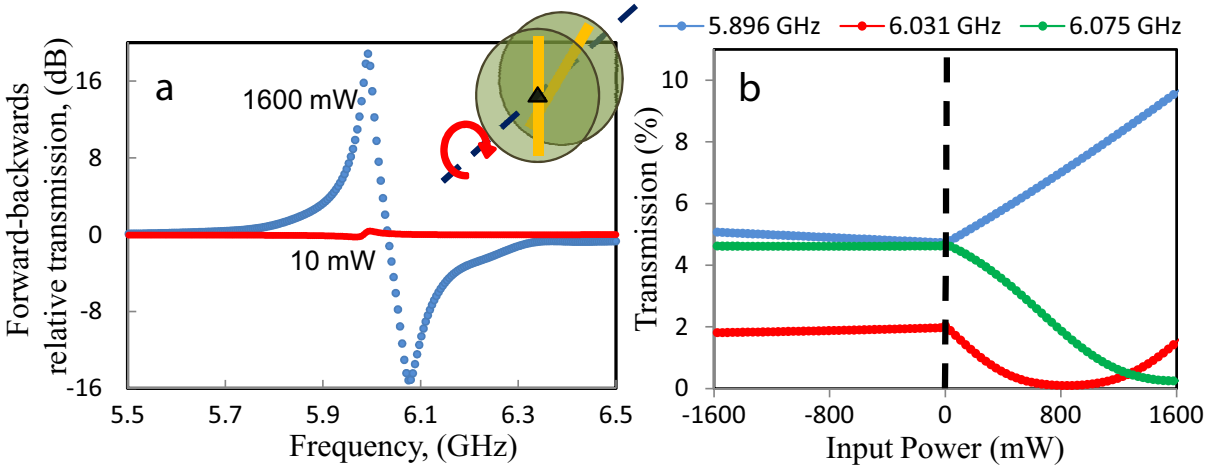

Figure 2. Transmission properties of an asymmetric chiral metamolecule. (a) Ratio of the transmission coefficients in forward and backward directions (in dB). For low power (red curve), the transmission is equivalent in both directions for left-handed circularly polarized waves. For large power (blue curve), the transmission is strongly asymmetric. It is larger in the forward direction for frequencies below 5.97 GHz, and it is larger in backward direction for higher frequencies. The difference reaches 18 dB, or a factor of approximately 65. Inset shows schematic of the metamolecule. (b) Transmission as a function of incident power. Positive incident power corresponds to the forward propagation, while negative values describe backward propagation. Depending on the frequency, the diode can change polarity, so that it is 'open' in the forward direction (blue curve) or in the backward direction (green curve). Additionally, the diode can suppress transmission in a certain range being open only for higher- or lower-wave intensities (red curve). The spectra were obtained using time-gating.

wires loaded with varactors. We notice that the angle of twist is an important parameter, which not only determines the magnitude of the gyrotropy [15, 24], but also changes the resonant frequency of the metamolecule due to strong near-field interactions (see [27] and references therein).

In general, chiral and anisotropic structures have elliptically polarized eigenmodes, leading to a complex dependence of the polarization state of the transmitted wave on the incident polarization state. We observed no change in our results when the metamolecule was rotated along its axis in the cylindrical waveguide. This indicates that anisotropic, birefringence effects are negligible and the polarization change is dominated by the circular dichroism and circular birefringence of the sample. This allows us to describe the transmission in terms of the transmission of the left- and right-handed circularly polarized waves, T_{--} and T_{++}.

Figures 3(a)–(c) show circular birefringence and polarization rotation for different incident intensities. The rotatory power of our sample is comparable to that obtained earlier in an artificial structure [14, 15], and it is two orders of magnitude stronger than the rotatory power of cholesteric liquid crystals [16], sculptured thin films [17] and chiral metamaterials for optical wavelengths [18]. The resonant feature observed in the circular dichroism comes from the resonant excitation of currents in the left-handed metamolecule by the left-handed circularly

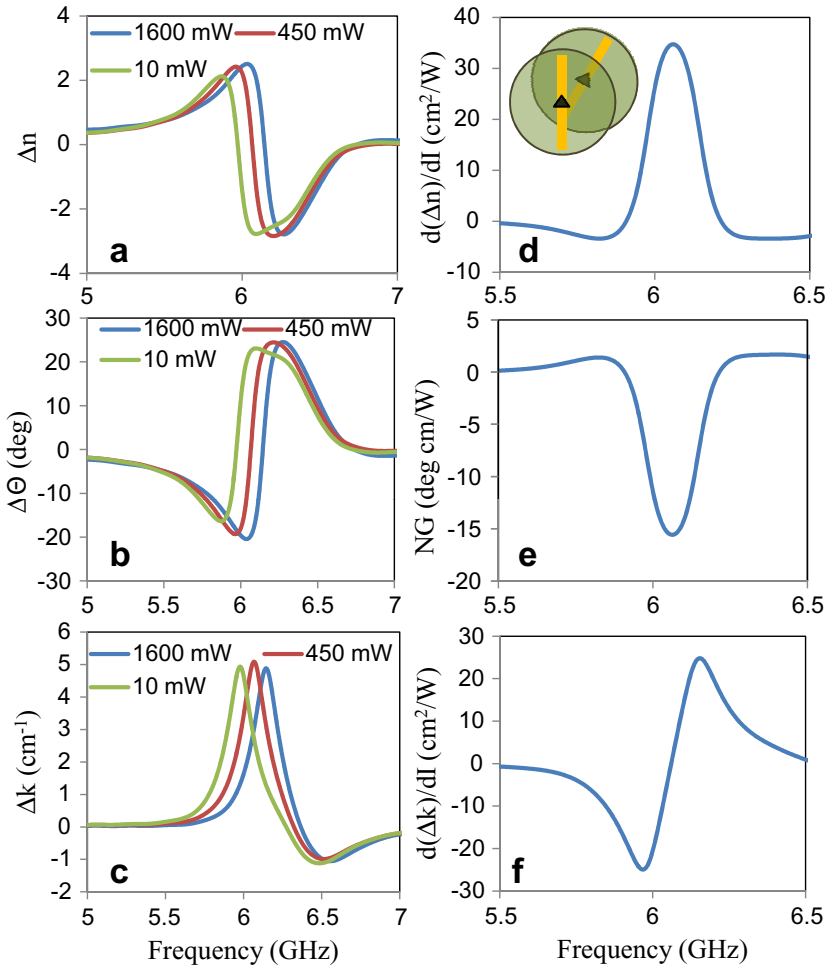

Figure 3. Giant nonlinear polarization rotation in a symmetric chiral metamolecule. (a)–(c) Circular birefringence $n_+ - n_-$, angle of polarization rotation and wavenumber difference versus frequency for several values of incident power. (d)–(f) Nonlinear gyrotropy shown as power-driven variation of (d) circular birefringence, (e) polarization azimuth rotation, and (f) wavenumber difference. The inset shows a schematic of the left-handed chiral metamolecule composed of twisted wires identically loaded with nonlinear elements. The angle between the wires is 49°.

polarized wave. Our numerical simulations confirm that the excited resonance corresponds to out-of-phase currents in the wires. At the same time, the right-handed circularly polarized wave does not noticeably excite any resonances in our structure.

Changing the power of the incident wave shifts the resonance of the gyrotropic response to a higher frequency, see figures 3(a)–(c). Importantly, such a shift of the polarization rotation resonance leads to *giant nonlinear gyrotropy*—see figures 3(d)–(f). The nonlinear gyrotropy coefficient is calculated as $\mathrm{NG} = \Delta\Theta / \Delta I / h$ deg cm W^{-1}, where $\Delta\Theta$ is the change in polarization rotation caused by the intensity change ΔI and $h = 3.2$ mm is the sample thickness. We see that close to the resonant frequencies, the nonlinear gyrotropy reaches the value of 15 deg cm W^{-1}. There are no previous data available for microwave frequencies that we can

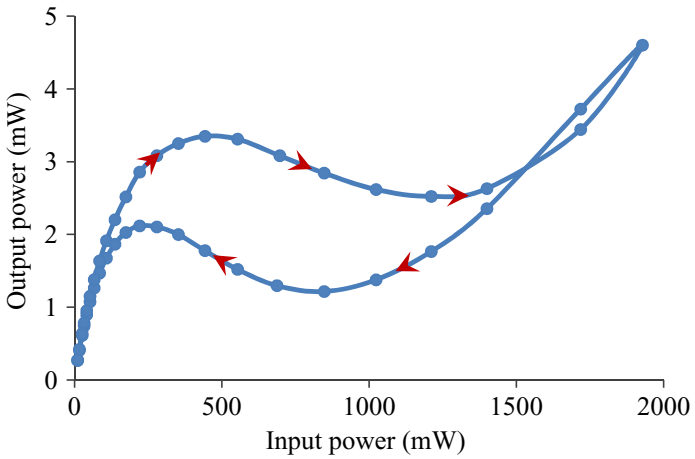

Figure 4. Characteristic bistability and hysteresis response of the chiral metamolecule composed of two nonlinear wires illuminated by a left-handed circularly polarized wave of frequency 6.11 GHz. Each experimental point is obtained in the continuous wave regime after the system reached the steady state.

compare our results with, but in natural optical media, e.g. in $LiIO_3$, the electronic nonlinear optical activity is 12 orders of magnitude weaker [13, 28].

One of the important features of a nonlinear resonant system is the possibility of a bistable response. In order to study this effect, we use the continuous wave regime of the vector network analyzer. We selected the frequency of excitation to be 6.11 GHz, near the dip of the transmission curve obtained in the large intensity regime. We performed the measurements by first increasing the input power and measuring the steady-state transmission amplitude for several values of input intensity (figure 4, top branch) and then similarly decreasing the power (figure 4, lower branch). We observe that the transmitted power may take different values that vary by a factor of three, depending on the history of the excitation.

Methods

Structure. Copper strips forming the chiral metamolecules were engraved on one side of 1.6 mm-thick standard FR4 printed circuit boards, as schematically shown in the inset to figure 2(a). The boards were circular to fit conveniently into the circular waveguide of the polarimeter. The wire pairs were formed by stacking two boards together such that the overall separation between the wires was 3.2 mm. The metal strips had the following dimensions: width = 1 mm, length = 15 mm and thickness = 30 μm. We denote the metamolecule shown in the inset of figure 2 as a left-handed metamolecule, whereas its mirror-symmetric metamolecule is denoted as right handed. The nonlinearity was added to the metamolecules by inserting a semiconductor varactor diode (model Skyworks SMV-1405), see figure 2, in the middle of either one (asymmetric metamolecule) or both (symmetric metamolecule) wires. To match the resonance frequency of the varactor-loaded wire with that of the unloaded one (which changes due to the internal capacitance of the varactor) the former was shortened to 14.3 mm. The introduction of the varactor also decreased the quality factor of the resonances due to its internal resistivity. A similar approach based on the use of a varactor diode was previously employed for creating nonlinear metamaterials [19, 20] as well as for tunability of epsilon-near-zero structures [29].

Measurements. Experiments were performed in the 5.5–7.0 GHz frequency range using a vector network analyzer (VNA, Agilent model E8364B) and a microwave waveguide polarimeter hosting the sample. The polarimeter was built around circular waveguide sections producing and guiding left-handed circularly polarized waves (series 64 by Flann Microwave). In order to provide sufficient microwave power to observe nonlinear effects, we used an external power amplifier (HP 83020A). To eliminate the contribution of the microwave cables and the waveguides, the measurements were normalized to the transmission coefficient of the empty waveguide. The effect of multiple reflections from the waveguide components on the measured spectra of the nonlinear structures was suppressed by using time-gating with a 15 ns gating window; this allows much smoother experimental curves to be obtained. The intensity of the wave fed into the waveguide was measured using a 10 dB directional coupler connected to the input port of the waveguide. The power is measured with a Rohde and Schwarz power sensor, model Z23.

Similarly to [15], all our measurements were performed using left-handed circularly polarized waves only. The excitation of the samples with a right-handed circularly polarized wave is equivalent to the excitation of the corresponding mirror-reflected structures with a left-handed circularly polarized wave.

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References

[1] Brown Th G *et al* (ed) 2004 *The Optics Encyclopedia: Basic Foundations and Practical Applications* (New York: Wiley)

[2] Fedotov V A, Mladyonov P L, Prosvirnin S L, Rogacheva A V, Chen Y and Zheludev N I 2006 Asymmetric propagation of electromagnetic waves through a planar chiral structure *Phys. Rev. Lett.* **97** 167401–4

[3] Menzel C, Helgert C, Rockstuhl C, Kley E-B, Tunnermann A, Pertsch T and Lederer F 2010 Asymmetric transmission of linearly polarized light at optical metamaterials *Phys. Rev. Lett.* **104** 253902–4

[4] Hwang J, Hoon Song M, Park B, Nishimura S, Toyooka T, Wu J W, Takanishi Y, Ishikawa K and Takezoe H 2005 Electro-tunable optical diode based on photonic bandgap liquid–crystal heterojunctions *Nature Mater.* **4** 384–7

[5] Scalora M, Dowling J P, Bowden C M and Bloemer M J 1994 The photonic band edge optical diode *J. Appl. Phys.* **76** 2023–6

[6] Tocci M D, Bloemer M J, Scalora M, Dowling J P and Bowden C M 1995 Thin-film nonlinear optical diode *Appl. Phys. Lett.* **66** 2324–6

[7] Feise M W, Shadrivov I V and Kivshar Yu S 2005 Bistable diode action in left-handed periodic structures *Phys. Rev.* E **71** 037602–4

[8] Shadrivov I V, Bliokh K Y, Bliokh Yu P, Freilikher V and Kivshar Yu S 2010 Bistability of Anderson localized states in nonlinear random media *Phys. Rev. Lett.* **104** 123902–4

[9] Akhmanov S A and Zharikov V I 1967 Nonlinear optics of gyrotropic media *JETP Lett.* **6** 137–40

[10] Kielich S 1967 Natural and magneto-optical rotation in the presence of an intense light beam *Phys. Lett.* A **25** 517–8

[11] Atkins P W and Barron L D 1968 Quantum field theory of optical birefingence phenomena: linear and nonlinear optical rotation *Proc. R. Soc.* **304** 303–17
[12] Wawilow S I 1950 *Mikrostruktura Sveta* (*Microstructure of Light*) (Moscow: USSR Academy of Sciences Publishing) p 73
[13] Akhmanov S A, Zdanov B V, Zheludev N I, Kovrigin A I and Kuznetsov V I 1979 Nonlinear optical activity in crystals *JETP Lett.* **29** 264–8
[14] Hollinger R D, Varadan V V, Ghodgaonkar D K and Varadan V K 1992 *Radio Sci.* **27** 161
[15] Rogacheva A V, Fedotov V A, Schwanecke A S and Zheludev N I 2006 Giant gyrotropy due to electromagnetic-field coupling in a bilayered chiral structure *Phys. Rev. Lett.* **97** 177401–4
[16] deGennes P G 1974 *The Physics of Liquid Crystals* (Oxford: Clarendon)
[17] Hodgkinson I, Wu Q H, Knight B, Lakhtakia A and Robbie K 2000 *Appl. Opt.* **39** 642
[18] Kuwata-Gonokami M, Saito N, Ino Y, Kauranen M, Jefimovs K, Vallius T, Turunen J and Svirko Y 2005 *Phys. Rev. Lett.* **95** 227401
[19] Shadrivov I V, Kozyrev A B, van der Weide D W and Kivshar Yu S 2008 Tunable transmission and harmonic generation in nonlinear metamaterials *Appl. Phys. Lett.* **93** 161903–3
[20] Powell D A, Shadrivov I V and Kivshar Yu S 2009 Nonlinear electric metamaterials *Appl. Phys. Lett.* **95** 084102–3
[21] Huang D, Poutrina E and Smith D R 2010 Analysis of the power dependent tuning of a varactor-loaded metamaterial at microwave frequencies? *Appl. Phys. Lett.* **96** 104104
[22] Klein M W, Enkrich C, Wegener M and Linden S 2006 Second-harmonic generation from magnetic metamaterials *Science* **313** 502–4
[23] Nikolaenko A E, De Angelis F, Boden S A, Papasimakis N, Ashburn P, Di Fabrizio E and Zheludev N I 2010 Carbon nanotubes in a photonic metamaterial *Phys. Rev. Lett.* **104** 153902–4
[24] Svirko Yu, Zheludev N and Osipov M 2001 Layered chiral metallic microstructures with inductive coupling *Appl. Phys. Lett.* **78** 498–500
[25] Powell D A, Shadrivov I V, Kivshar Yu S and Gorkunov M V 2007 *Appl. Phys. Lett.* **91** 144107–3
[26] Wang B, Zhou J, Koschny T and Soukoulis C M 2008 Nonlinear properties of split-ring resonators *Opt. Express* **16** 16058
[27] Lapine M, Powell D, Gorkunov M, Shadrivov I, Marques R and Kivshar Y 2009 Structural tunability in metamaterials *Appl. Phys. Lett.* **95** 084105
[28] Svirko Yu P and Zheludev N I 1998 *Polarization of Light in Nonlinear Optics* (New York: Wiley)
[29] Powell D A, Alu A, Edwards B, Vakil A, Kivshar Yu S and Engheta N 2009 Nonlinear control of tunneling through an epsilon-near-zero channel *Phys. Rev.* B **79** 245135