Chiral Metamaterials

by David A. Powell, Ilya V. Shadrivov, Vassili A. Fedotov, Nikolay I. Zheludev and Yuri S. Kivshar

Unlocking Nonlinear Optical Activity

We demonstrate a chiral metamaterial exhibiting nonlinear optical activity – polarisation rotation which depends on the magnitude of the incident field. This effect is almost negligible in natural materials, but can be made very strong using artificially structured metamaterials. We utilise this effect to create an optical diode for circularly polarised waves – a device which allows transmission only in one direction.

Chirality has important implications in many areas of physics and chemistry, including optics. A chiral structure is one which has distinct left and right-handed forms which are the mirror images of each other. It is known that the interaction of circularly polarised light with chiral molecules depend on the relative handedness between the two. This is the basis of the well-known optical activity in sugar solutions, whereby a linearly polarised input wave has its polarisation rotated at the output. The microscopic origin of this effect is the excitation of a magnetic response by the electric component of the light and vice versa. Although the effect exists in natural media, it can be orders of magnitude stronger in artificially structured media - metamaterials. In place of molecules, one can engineer tiny, sub-wavelength elements such as resonant spirals that act as magneto-electric dipoles. Figure 1 shows an example of a chiral metamaterial, showing a linearly polarised incident plane wave, which undergoes polarisation rotation by angle θ.

The polarisation rotation in microwave chiral metamaterials can be nearly a million times stronger than in natural quartz for optical frequencies, once the sample thickness is normalised to the wavelength of radiation [1]. For such chiral metamaterials, the effect of optical activity can be so strong that the refractive index becomes negative for one circular polarisation. There are many other examples in the literature of how metamaterials can be engineered to achieve linear material parameters far beyond those of natural media. An even more exciting feature of metamaterials is that they can achieve exotic nonlinear parameters. Previous results have shown that a nonlinear inclusion in an optical or microwave metamaterial can result in a nonlinear response much stronger than that in the corresponding bulk nonlinear media [2]. This occurs due to the resonant enhancement of fields, and the local hot spots which develop within the structure.

Nonlinear Chiral Metamaterial

Our aim is to combine the strong chirality and nonlinearity of metamaterials to develop a structure with nonlinear optical activity - polarisation rotation which depends on the strength of the incident field. This effect has previously been proposed [3], and subsequently observed in LiIO3 crystals [4], however in such materials the nonlinear optical activity was smaller than its linear counterpart by a factor of 10-6. This required samples several centimetres in length and light intensities of 100 MW/cm2, which is close to the optical breakdown of the crystal. Such a small level of nonlinearity is not sufficient for demonstrating any practically important functionality. Using metamaterials, we can overcome these difficulties, by engineering the chiral response and carefully placing the nonlinear elements within the structure. The metamaterial is designed to operate at microwave frequencies, and consists of a pair of metallic wires, twisted so that they are no longer parallel, as shown in Figure 2. We can see that the structure is chiral, because if we take its mirror image, we end up with a non-identical object. Nonlinearity is introduced by cutting each wire and inserting a varactor diode. The structure is placed inside a circular waveguide, and excited with a high power microwave source in the 5-7GHz range.

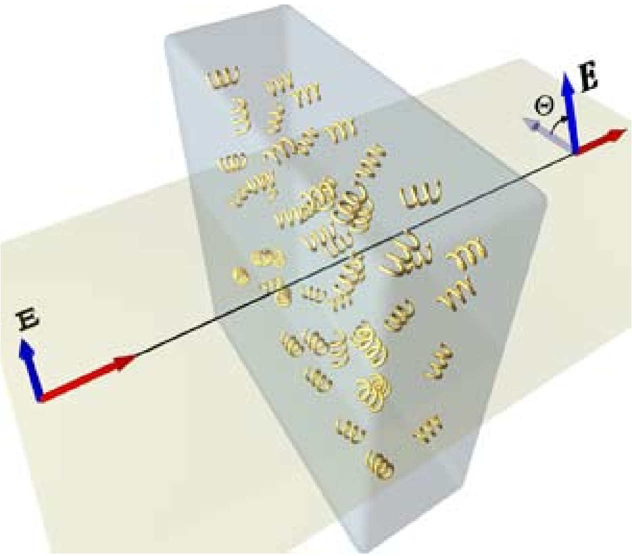

Figure 1. Example chiral metamaterial showing polarisation rotation.

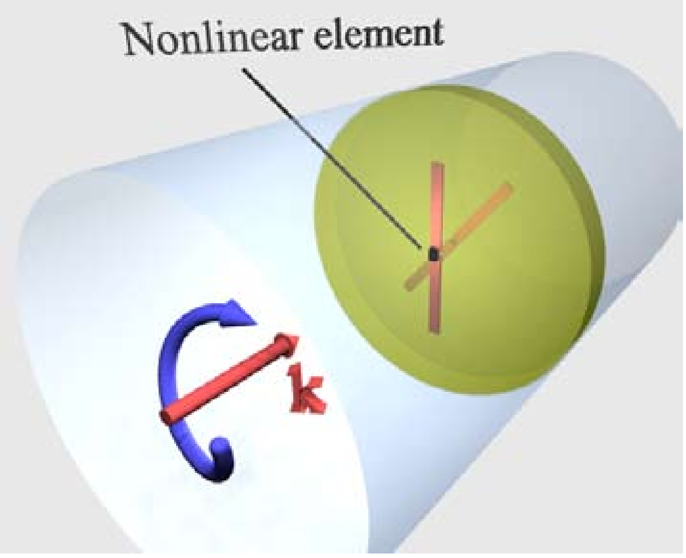

Figure 2. Schematic of the nonlinear chiral metamaterial.

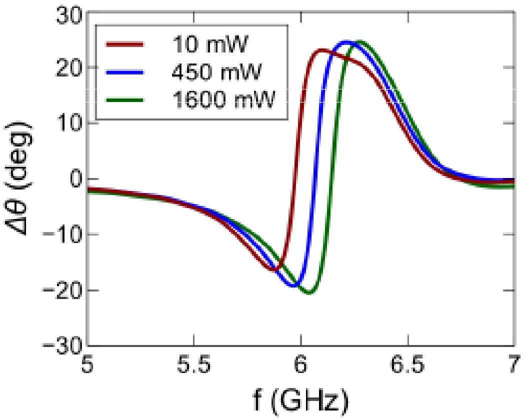

Figure 3. Polarisation rotation as a function of input frequency and power.

Further details of the design and the experimental techniques can be found in [2].

We note that the angle of twist is an important parameter, which not only determines the magnitude of the gyrotropy [1], but also changes the resonant frequency of the metamolecule due to strong near-field interactions [5]. In general chiral and anisotropic structures have elliptically polarised eigenmodes, leading to a complex dependence of the polarisation state of the transmitted wave on the incident polarisation state. We observed no change of our results when the metamolecule was rotated along its axis in the cylindrical waveguide. This indicates that anisotropic, birefringence effects are negligible and the polarisation 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 polarised waves, T-- and T++.

Figure 3 show polarisation rotation of a linearly polarised wave for different incident intensities. The resonant feature comes from the resonant excitation of currents in the left-handed metamolecule by the left-handed circularly polarised 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 polarised 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. Importantly, such a shift of the polarisation rotation resonance leads to giant nonlinear gyrotropy. This can be calculated as achieving a peak value of 15 deg°/W, which is 12 orders of magnitude stronger than results previously observed for LiIO3, at optical wavelengths [4].

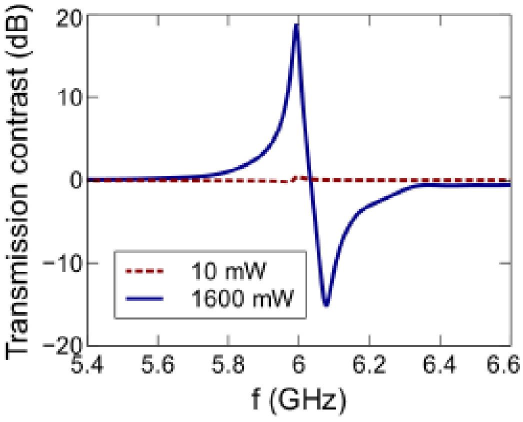

Figure 4. Difference between forward and backward transmission for the optical diode.

Optical Diode for Circularly Polarised Waves

If we modify the structure such that only one wire contains a nonlinear inclusion, then it will have a lower symmetry, and we can use this feature in order to allow the propagation of left-handed circularly polarised waves in one direction only. This relies on the non-reciprocity of nonlinear components, which becomes significant at higher input powers. The results of our measurements for the left-handed circularly polarised wave scattering on a left-handed chiral metamolecule are shown in Figure 4. 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 modelling shows that such behaviour results from significantly different current amplitudes induced in the two wire strips by the waves entering the metamolecule from one direction, in comparisons 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 polarised wave is greater in the forward direction, i.e. when the wave hits the strip with the nonlinear element first. However, in the range from 6.0 GHz to 6.3 GHz the 'polarity' reverses and the diode transmits the same polarisation in the opposite direction only.

Conclusion

We have demonstrated a metamaterial showing significant nonlinear optical activity, an effect which is extremely weak in natural materials. We then modified this structure to create an asymmetric version, which acts as an optical diode for circularly polarised waves, allowing transmission of the left-handed circular polarisation only in one direction.

Acknowledgements

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David A. Powell, Ilya V. Shadrivov and Yuri S. Kivshar are with the Nonlinear Physics Centre and CUDOS@ANU, Research School of Physics and Engineering, ANU, Canberra. Vassili A. Fedotov and Nikolay I. Zheludev are with the Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, United Kingdom.