Novel way for constructing flexible metamaterials with chiral conformational nonlinearity

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Abstract

We investigate nonlinear behavior of metamaterial, where responses of a different nature are intrinsically coupled within its spiral structural elements. We provide an experimental demonstration of the electromagnetically induced compression of the metamaterial, which leads to a remarkable shift of the resonance frequency. We believe that these results are useful for a variety of important applications and for the future development of nonlinear and tunable metamaterials.

1. Introduction

Metamaterials — artificial materials designed to deliver an unusual electromagnetic response — have already established a prominent area of theoretical and experimental physics with applications ranging from super-imaging and transformation optics to tunable and active materials, photonics and plasmonics. In particular, nonlinear properties of metamaterials currently attract growing interest [1], however existing approaches offer a nonlinear response achieved with an effect of one physical nature, typically, electric nonlinearity of a dielectric host [2,3,4], or that of a semiconductor within specific insertions [5,6], or elastic medium between the resonators [7]. Naturally, a link between electromagnetic, mechanical and thermal properties offers great application capabilities, as demonstrated, e.g., by mechanically tunable [8] or thermally reconfigurable [9] metamaterials. Those methods, however, did not offer a dynamic interaction, required for nonlinear response.

Recently, we put forward an approach to achieve a self-action by combining the effects of a different physical nature in a single element, providing an intrinsic connection between electrodynamic, mechanical and thermodynamic responses [10]. The element we propose for this purpose, is a thin wire wound into a spiral resonator (Fig. 1a). Indeed, this particle is at once an electromagnetic resonator and a mechanical spring. Furthermore, its electromagnetic and mechanical properties are sensitive to heat through its thermal expansion. Therefore, all these characteristics become mutually coupled, providing self-active feedback and efficient nonlinear behavior. With our novel approach, the nonlinear response involves different physical mechanisms, and it can be tailored by adjusting the structure. This offers further flexibility in the design, and a rich spectrum of nonlinear phenomena.

2. Results

To give a practical example, we consider a metamaterial assembled with such resonators arranged in

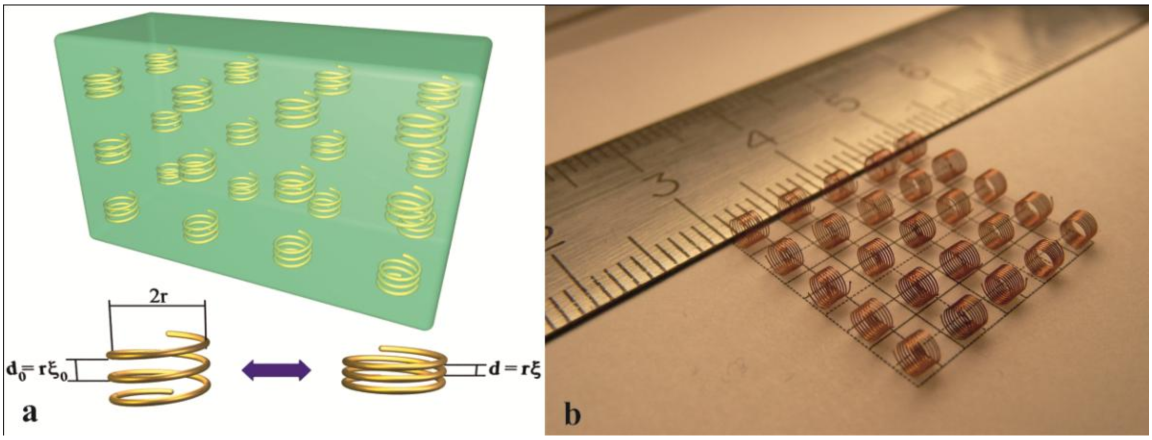

Fig. 1: a) General schematic of a self-active metamaterial and its “meta-molecule” in different conformations. Flexible spring resonators have variable pitch ξ and radius r, which change upon spiral contraction and expansion; b) Photograph of the experimental lattice of spiral elements.

an anisotropic lattice, as shown in Fig. 1b, and analyse nonlinear phenomena resulting from the self-induced conformational changes. An external electromagnetic wave induces a current along each spiral conductor, but this current causes an attractive force between the windings. The spiral will therefore contract until that force is balanced by the spring force, however the corresponding change in spiral geometry will shift the resonance and thus alter the current amplitude in a self-consistent manner. In addition, the thermal expansion of the spiral, resulting from its heating with the increasing incident power, provides a relevant contribution, further shifting the resonance — importantly, in the same direction. With our approach, the nonlinear response involves different physical mechanisms, and it can be tailored by adjusting the structure. This offers further flexibility in the design, and a rich spectrum of nonlinear phenomena.

We show that the dependence of spiral pitch (Fig. 2a), temperature (Fig. 2b) and magnetization (Fig. 2c) on the incident field intensity is remarkably nonlinear reflecting a transition through the “conformational states” of the “meta-molecules” [10].

For the experiments in the microwave range, we fabricate spirals with several windings and metamaterial based on chiral "meta-molecules" (Fig. 1b), which provide a resonant response to an incident electromagnetic wave with appropriate polarization (with the magnetic field being parallel to the spiral axis). To achieve an efficient mechanical response, we use a thin wire and arrange the windings of the spiral close to each other. By optimizing the geometric parameters, we obtain a configuration where mechanic response of the spiral dominates over its thermal expansion. We demonstrate a significant shift of the resonance frequency depending on the incident power (Fig. 3).

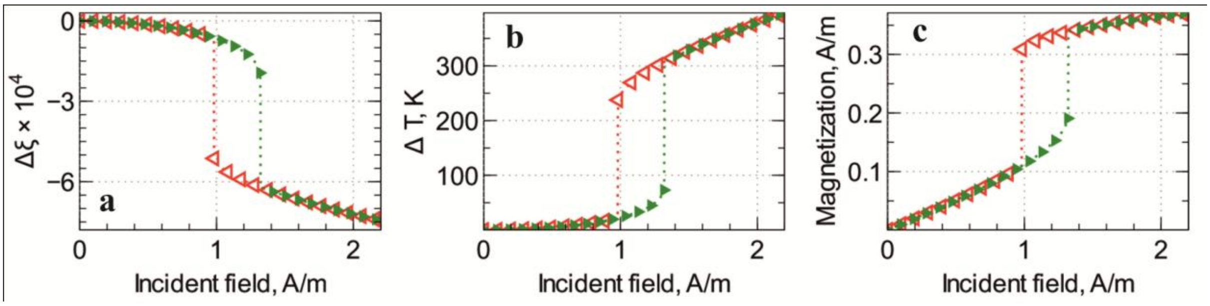

Fig. 2. Various characteristics of the conformational nonlinearity: dependence of the spiral pitch, temperature and effective magnetization on the incident field.

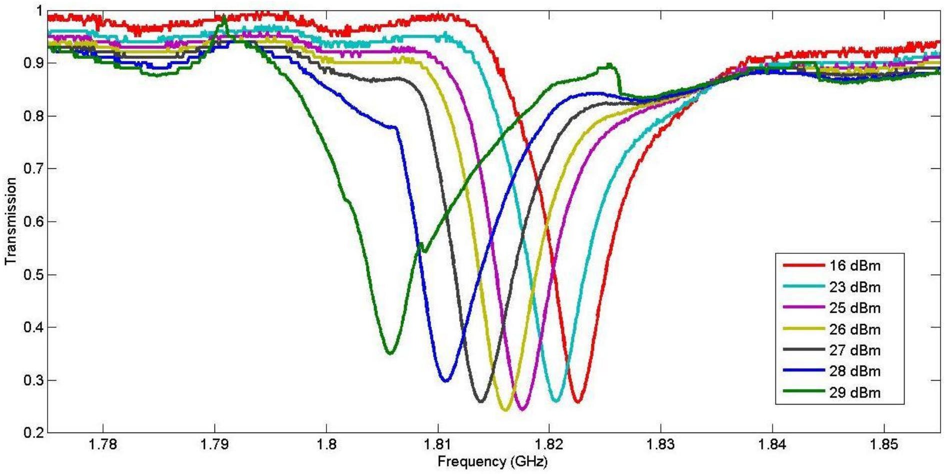

Fig. 3. Experimental results. The spectra obtained with various power, as indicated in the legend.

3. Conclusion

Our results provide a further step towards improvement and development of nonlinear metamaterials based on chiral "meta-molecules". While a lot of peculiar features will be provided for wave propagation in a large array of nonlinear chiral particles, the essence of nonlinear response is determined by the properties of an individual spiral particle and can be reliably assessed within a relatively small experimental sample. Therefore, our results form an clear basis for the research on the new class of conformationally nonlinear metamaterials and their applications.

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