MTT-S Undergraduate/Pre-Graduate Scholarship Project Report

Nonlinear chiral metamaterials

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***Abstract*— We report on a novel metamaterial design based on multi-turn spiral resonators which strongly enhance nonlinear coupling between electromagnetic and mechanical response. The robust fabrication procedures allowed to produce a large number of resonators, suitable for assembling large metamaterials arrays. We experimentally demonstrate a remarkable self-tuning of the electromagnetic resonance, achieved via power-dependent mechanical reconfiguration, dominating over thermal effects. The corresponding compression of the spirals provides a nonlinear chiral response.**

Index Terms—Nonlinear metamaterials, flexible spirals, electromagnetic resonator.

I. Introduction

Metamaterials are artificial media characterized with effective permittivities and permeabilities, not commonly available in Nature. Metamaterials demonstrate fascinating fundamental physics and they are very promising for engineering pure electromagnetic devices and for tailoring the electromagnetic field-matter interaction.

Nonlinear metamaterials established a new research direction giving rise to fruitful ideas for tunable and active artificial materials [1]. Typical approaches offer a nonlinear response achieved with an effect of one physical nature, typically, electric nonlinearity of a dielectric host [2], or that of a semiconductor within specific insertions [3], or elastic medium between the resonators [4]. However, a direct interplay of electromagnetic, mechanical and thermal properties offers interesting possibilities, as demonstrated by the recent proposal [5] to combine such effects. Both the mechanical and thermal response can be coupled to electromagnetic properties through the structure of a chiral metamaterial element, a well-known helical spiral

The spiral demonstrates a unique duality being both an electromagnetic resonator and a mechanical spring. It is therefore a very attractive "meta-atom" of electromagnetic metamaterials. The link between the responses of a different nature is provided through the dependence of resonance parameters on the spring geometry, with the sensitivity to heat through thermal expansion and temperature-dependent resistance. With an increasing incident power, the spring undergoes compression forced by the attracting currents in the neighbouring windings, while the growing temperature leads to

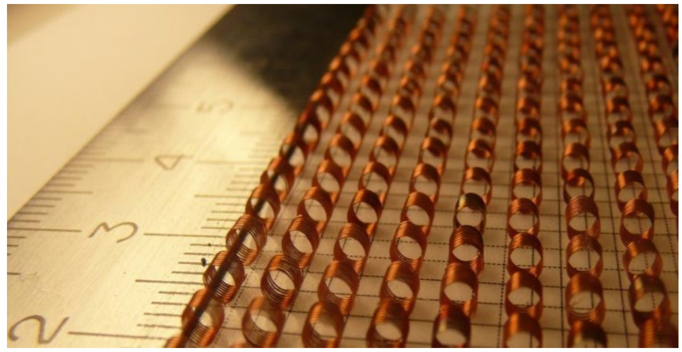

Figure 1. A photo of the experimental lattice of spiral resonators. A large number of resonators with a very good adjustment of the individual resonances, so that no significant resonance broadening is observed in the lattice.

an overall increase in size. Both the effects act in the same way, changing the spiral conformation such that the electromagnetic resonance shifts to a lower frequency. This provides a nonlinear feedback making self-tuning processes possible, and promises an interesting range of nonlinear phenomena.

In this contribution, we report an advanced design which enhances mechanical self-tuning, making the latter stronger than the thermal contribution, and dramatically increasing the nonlinear response. With the improved manufacturing procedures, we are able to fabricate a large number of nearly identical elements for creating bulk metamaterials in the form of a lattice of helical meta-atoms (Fig. 1). Our results open up a road to exploit the effect of nonlinear chirality for polarization conversion, beam splitting and modulation.

II. Results

We use compact multi-turn spirals made of thin copper wire with closely spaced windings (Fig. 1). High temperature annealing increases mechanical stability and minimises thermal effects, while the large number of turns enhances its mechanical response to electromagnetic excitation. Indeed, the earlier spiral element [5] had only two turns for the ease of analytical description. But for multi-turn spirals, there are clear reasons to expect a stronger current-induced compression as the compressing force increases through the interaction of multiple wire turns. This expectation is confirmed with our experiments over a piece of metamaterial excited with magnetic field at various power (Fig. 2). With an increase of supplied power to nearly 1W, the resonance was shifted by 24MHz from the original value. For the experiment, we have used 16 spirals with identical resonant frequencies, and arranged them into a

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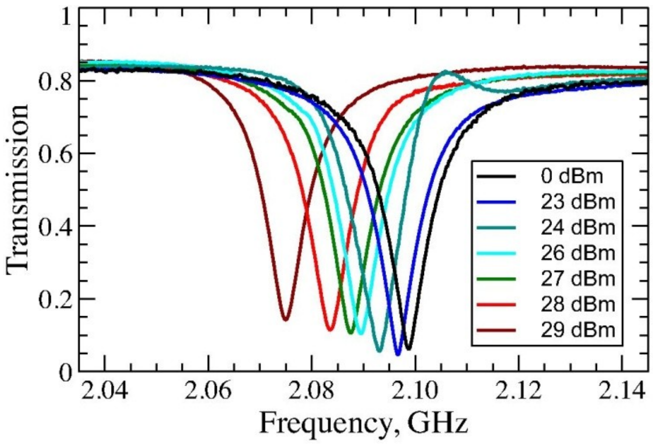

Figure 2. Experimental spectra of the lattice of spiral resonators observed at various levels of input power. The resonators were arranged in a 4x4 lattice, and placed in the center of a loop antenna which is used for excitation. Input power was varied between 0 and 29 dBm as shown in the legend.

two-dimensional 4x4 lattice, with their axes parallel to each other and also parallel to the magnetic field created by an exciting loop antenna. We have controlled that the temperature of the spirals did not increase by more than 80˚, which would contribute to a frequency shift of about 3MHz, suggesting that a possible thermal contribution in our experiments does not exceed 15% of the total effect.

We note that the particular polarization selected in our experiment is not crucial for the nonlinear behavior: as a chiral particle, the spiral can be excited with either electric or magnetic field directed along its axis. We have tested with numerical simulations that a plane-wave incidence with either polarization leads to the induced magnetic (and electric) moments of comparable magnitude. This makes our design convenient for nonlinear wave propagation in large chiral arrays: regardless of the expected rotation of the polarization plane, the nonlinear response will not change except for an attenuation due to the dissipation.

Chiral properties of the spiral are directly proportional to its pitch, and can be characterized [6] with the normalised ratio between the spiral electric p and magnetic m dipole moments along its axis. In Fig. 3, we present the change in the chiral response [$\gamma = |p_z/m_z| = \xi/\omega\pi r$], where $\xi = d/r$ is the spiral pitch, r is the radius of the spiral and d is the vertical distance between windings.

III. CONCLUSION

In summary, we present the first experimental demonstration of self-tunable nonlinear chiral metamaterial with the response governed by structural changes in the helical spirals. We believe that our results establish a road to exploit nonlinear chirality for nonlinear optical activity, circular polarisation conversion, beam splitting and for adding nonlinearity to the chiral route to negative refraction. Results of this study are published in Advanced Materials [7].

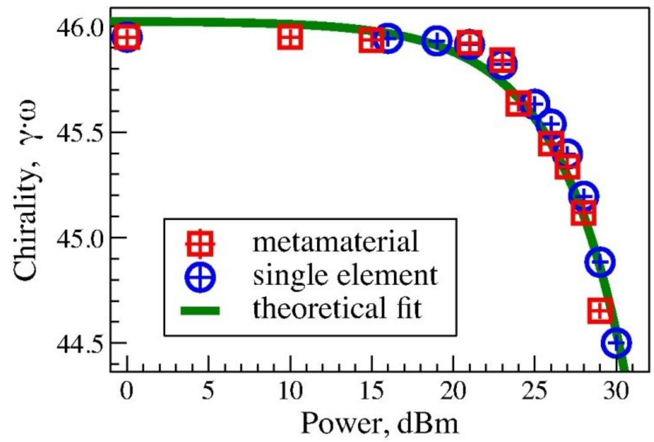

Figure 3. Change of the chirality (shown as $\gamma \cdot \omega$) with power, recalculated from the experimental data on the resonance shift with power (see Fig. 2). Blue circles represent the data obtained for a single resonator, and red squares for the lattice. Green solid curve shows the theoretical fit to the corresponding dependence, obtained with an approximate circuit theory [7].

ACKNOWLEDGEMENTS AND CAREER PLANS

I am extremely grateful to my advisor, Prof. Pavel Belov for giving me the opportunity to work in his group, for his guidance and patience. I would also like to thank Dr. Mikhail Lapine, Dr. David Powell, Dr. Ilya Shadrivov, Prof. Ross McPhedran and Prof. Yuri Kivshar, for their comments and assistance over the last three years. Futher, I would like to thank IEEE and MTT-S for possibilities to increase my own research potentials, the amount of time I can devote to research and for opportunity to presented and discussed my results at MTT-S sponsored conference (IMWS-Bio 2013) - that was very fruitful. Finally, the MTT-S scholarship motivated me to further pursue my Master's degree and stimulated me to further my graduate education in the related field.

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