Strong chiral properties of helically-structured metamaterials in THz range

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Abstract

In this paper on an example of the sample developed by a group from Institute of Semiconductor Physics(Novosibirsk), analytical simulation and numerical modeling of chiral properties of artificial anisotropic structure formed by microhelices is carried out. It is shown, that such artificial periodic structure can show giant chirality in THz range. The rotation angle of polarization plane of transmitted electromagnetic wave and circular dichroism of structure are compared with experimental results.

1 Introduction

Basic novelty and scientific importance of creation of metamaterials from the three-dimensional shells formed from strained nanofilms [1-4], consists in transition from two-dimensional elements-resonators to three-dimensional, in a variety of possible forms and materials of elements-resonators (dielectrics, metals, semiconductors). The principle of formation of the 3D-shells from the strained films is illustrated on Fig.1.

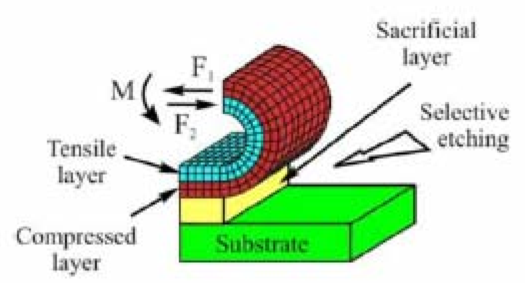

Fig.1: Schematic illustration of the detaching from the substrate and bending of the strained bifilm.

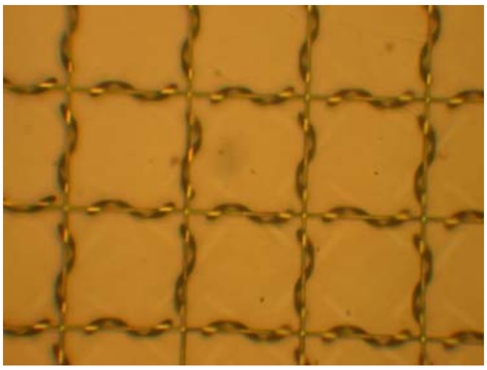

Fig. 2: Photo of the helices array (a square grid on a photo is a negative photo resist from a polymeric material, thickness is about 1 micron).

By means of three-dimensional designs of shell-resonators the electromagnetic response of a metamaterial is tailored in all three dimensions that is a new step in the field of metamaterials for THz range and allows one to create metamaterials with essentially new properties. The given technology now is a unique nanotechnology which can provide mass formation of THz-metamaterials on the basis of smooth resonant three-dimensional helices, including bulk metamaterials.

2 Helical model of molecules with reference to artificial structure with strong chirality

For artificial electromagnetic media the linear sizes of helix can be small in comparison with the wavelength. The length of a wire from which the helix is made, can be the order of length of a wave that provides a condition of a resonance. In this case chirality is not a small parameter and properties of chiral medium can cardinally differ from properties of mirror symmetric medium not only due to accumulation of small effect, as in the phenomenon of optical activity [5,6].

At studying of artificial anisotropic structures with special properties, so-called metamaterials, not only the phenomenological approach based on the basic physical laws (the law of conservation of energy of an electromagnetic field, a principle of symmetry of kinetic coefficients Onzager-Kazimir, the account of crystallography symmetry of medium) is important. At the analysis of properties of metamaterials the role of the microtheory increases. It allows to consider the specific mechanisms of resonant excitation of elements of structure.

We have obtained the modified expressions for effective parameters of structure with strong chirality considering the frequency dispersion and determined complex input impedance of one turn helix as:

$$Z = \frac{U}{I} = -j\sqrt{\frac{\mu_0}{\varepsilon_0}}\pi r^2 h \frac{1}{\alpha^{(11)}{}_{me}} \tag{1}$$

where $U=E_x h$ is the voltage at the helix ends, I is the current intensity in the helix, j is the imaginary unit, ε_0 and μ_0 are the electric and magnetic constants, r is the radius of helix, h is the helix pitch distance, $\alpha^{(11)}{}_{me}$ is the component of pseudotensor describing the chiral properties of the helix and index 1 designates the axis OX, which is oriented along the axis of helix. Then the coefficient of field decay inside metal can be written in the following form:

$$\tau = j\sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{\rho}{\pi r^2 S \sin\psi}\alpha^{(11)}{}_{me} \tag{2}$$

where S is the cross-section area of the conductor, ψ is the helix pitch angle, ρ is the specific resistance of the conductor.

3 Comparison of experimental results and numerical modeling

Experimental realization of the described metamaterials on the basis of helices for THz range is possible by the method of precise 3D nano-structuring recently developed by the Russian scientists [1-4].

The samples in the form of a square lattice of helices fixed on a substrate by a grid of resist were made in the Institute of Semiconductor Physics (Novosibirsk). The helices are rolled up from the strips with following parameters: length is 77 microns, width is 6 microns. Strips are made from four-layer metal-semiconductor film (InGaAs/GaAs/Ti/Au). The central part of helix adjoins to the substrate with semiconductor layer and to resist with metal layer, other part of a helix is in air (Fig.2). The pitch angle is 52-53 degrees, which is optimal for fabrication of the samples with maximal gyrotropic properties, as shown in [7, 8]. The helix diameter is 11 microns. The square lattice period is 84 microns. Substrate is made of undoped GaAs, the thickness of the substrate is 400 microns.

The properties of the fabricated samples in THz range were studied experimentally in Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Science.

On fig. 3,4 results of experiment and numerical modeling of properties of artificial anisotropic structure are presented.

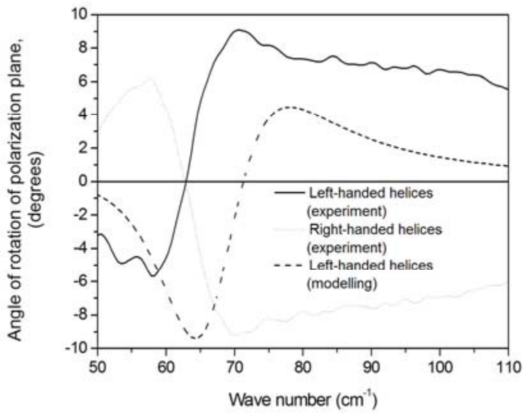

Fig.3. The angle of rotation of polarization plane of the transmitted wave by the array of helices. Continuous and dot lines are experimental data for the arrays of left- and right-handed helices accordingly. Dashed line is the result of modeling for the array of left-handed helices.
For the observer looking towards a wave, a clockwise rotation is taken as positive.

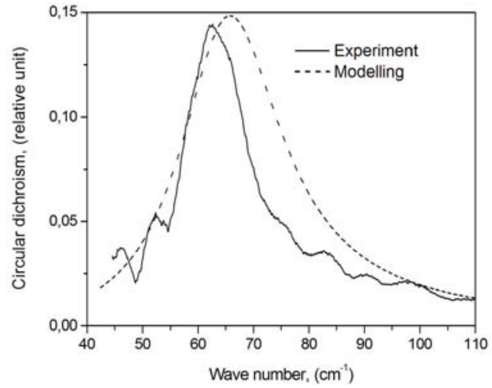

Fig.4. Circular dichroism for the left-handed helices array: experimental data (continuous line) and results of modeling (dashed line).

4. Conclusion

The theoretical simulations and numerical modeling of properties of artificial chiral structure are carried out and compared with experimental results for the fabricated structure in THz range.

As a result of comparison of experimental curves and results of modeling it is possible to draw a conclusion, that the offered model well describes properties of artificial structure with strong chirality. The maximal values of the angle of rotation of polarization plane of wave and circular dichroism, calculated on the basis of the offered model, correspond to the experimental data. Frequency dependence of the calculated chiral characteristics of medium near resonance qualitatively corresponds to the experimental data.

This work was supported by the Belarusian Republican Foundation for Fundamental Research (project F10R-230), the Russian Foundation for Basic Research (projects 08-02-01434, 09-02-12303-ofi_m, 10-02-90050-Bel_a), programs of SB RAS (project 24) and program of Department of Physical Science of RAS (project 12-2).

References

1. V.Ya. Prinz, V.A. Seleznev, A.K. Gutakovsky et al. *Physica E*. 2000. V.6 P.828
2. E.V. Naumova, V.Ya. Prinz. Patent of Russian Federation № 2317942. 2008
3. E.V. Naumova, V.Ya. Prinz , V.A. Seleznev et. al., in Proc. *Metamaterials 2007*, Rome, Italy. 2007. P. 74.
4. E.V. Naumova V.Ya. Prinz, S.V. Golod et. al. *Optoelectronics, Instrumentation and Data Processing*. 2009. V.45. No.4. P. 292.
5. L.D. Landau, E.M. Lifshitz, *The Classical Theory of Fields* (Nauka, Moscow, 1973; Pergamon, Oxford, 1975)
6. F.I. Fedorov, *Theory of Gyrotropy,* Minsk: Nauka i Tekhnika, 1976, p. 456. (in Russian)
7. I.V. Semchenko, S.A. Khakhomov, A.L. Samofalov, in *Bianasotropics' 2004*, 10th International Conference on Complex Media and Metamaterials, Het Pand, Ghent, Belgium. 22-24 September 2004. P. 74.
8. I.V. Semchenko, S.A. Khakhomov, A.L. Samofalov. *Electromagnetics*. 2006. V. 26. No. 3-4. P. 219.
9. I.V. Semchenko, S.A. Khakhomov, E.V. Naumova, V.Ya. Prinz, S.V. Golod, V.V. Kubarev. *Crystallography Reports*, 2011, Vol. 56, No. 3, *Kristallografiya*, 2011, Vol. 56, No.3, pp. 404–411. (accepted for publication)