2D isotropic metamaterial with equal permittivity and permeability in THz range

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Abstract

2D isotropic metamaterial with equal permittivity and permeability and compensated chirality was created by the original method of 3D nanostructure formation. Metamaterial consists of optimal helical elements. It is shown that this artificial structure can have the advantage over other metamaterials, for example, the ones based on straight wires and split-ring resonators.

1. Introduction

In the previous work [1], we focused on the characteristics of an individual optimal helix. It was demonstrated that this helix has equal dielectric, magnetic, and chiral susceptibilities. This property provides wide application of the optimal helices. The main frequency resonance arises when the helix length is equal to half of the incident radiation wavelength. For radiation of the circularly polarized wave in the direction perpendicular to the helix axis (*Ox* axis), the main role is played by the electric dipole and magnetic moment components p_x and m_x. The helix parameters are adjusted so that the circularly polarized wave is formed only by radiation of the p_x and m_x components. In this case, the moment components along the *Oy* and *Oz* axes can only distort radiation of the circularly polarized wave, and their influence must be minimized. Since the current distribution over the helix is symmetric about its center, the p_z and m_z components vanish, when the helix axis and ends are in *xOy* plane.

The condition of circular wave emission has the following form [1–3]

$$|p_x| = \frac{1}{c}|m_x| \tag{1}$$

Here *c* is the velocity of light in free space.

In this case, the electric dipole moment components p_y and p_z and the magnetic moment components m_y and m_z, which are orthogonal to the helix axis, do not contribute to the radiated wave. This condition can be fulfilled for an odd number of helix turns. For this configuration, $p_z = 0$ and $m_z = 0$ due to the symmetric current distribution along the helix. The components p_y and m_y do not vanish; however, these components of the electric and magnetic moments do not radiate in the direction of the *Oy* axis and hence, do not distort the circularly polarized wave. In [1–3], the optimal parameters of helices were calculated from the universal relationship [3]

$$p_x = \frac{2i}{\omega r^2 q} m_x \tag{2}$$

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Here r is the radius of the helix, q is the specific helix torsion related to the helix pitch h by the formula $h = 2\pi/|q|$, ω is the cyclic frequency of wave, i is the imaginary unit, all values depend on time as follows: $exp(-i\omega t)$. Formula (2) is valid for arbitrary current distribution along the helix, and the current can be induced by an incident wave or fields created by other helices. Therefore, the optimal properties are characteristic not only for individual helices but also for artificial structures in which the helix concentration can be high. Using the condition of main resonance $\lambda/2=L$ and relationship between the geometrical parameters of helix [3]

$$L\cos\alpha = 2\pi r N_t, \qquad (3)$$

where L is the length of a helix, we can obtain the equation for pitch angle α of helix:

$$4N_t tg\alpha = \cos\alpha \quad \text{or} \quad \sin^2\alpha + 4N_t \sin\alpha - 1 = 0. \qquad (4)$$

The optimal helix angle calculated in the main frequency resonance can be written as [1–3]

$$\alpha = \arcsin\left(-2N_t + \sqrt{4N_t^2 + 1}\right) \qquad (5)$$

where N_t is the number of the helix turns.

Table 1. Optimum values of the helix pitch angle α that correspond to radiation of a circularly polarized wave for different values of the number of turns N_t

N_t	1	2	3	4
α, degrees	13.65	7.1	4.75	3.6

Obtained results allow to optimize the geometry parameters of helix for manufacture of 2D isotropic metamaterial with equal permittivity and permeability in THz range. Each helix is characterized simultaneously by the dielectric, magnetic, and chiral susceptibilities. Hence, its behavior in an electromagnetic field can be described by the coupling equations [4,5]

$$\mathbf{p} = \varepsilon_0\alpha_{ee}\mathbf{E} + i\sqrt{\varepsilon_0\mu_0}\,\alpha_{em}\mathbf{H}, \quad \mathbf{m} = \alpha_{mm}\mathbf{H} - i\sqrt{\frac{\varepsilon_0}{\mu_0}}\,\alpha_{me}\mathbf{E}. \qquad (6)$$

Here α_{ee} and α_{mm} are the dielectric and magnetic susceptibility tensors, α_{em} and α_{me} are the pseudotensors describing the chiral properties of the helix, and ε_0 and μ_0 are the electric and magnetic constants, respectively. From the principle of symmetry of the kinetic coefficients it follows that the relationship [4]

$$\alpha_{em} = \alpha_{me}^T$$

is fulfilled, where T denotes tensor transposition, and the imaginary unit i is in an explicit form in material equations (6). Hence, the pseudotensor α_{em} has only real components for the nonabsorbing helix. From Eqs. (2) and (6) we obtain near the main frequency resonance

$$\alpha_{ee}^{(11)} = \alpha_{mm}^{(11)}, \quad \alpha_{ee}^{(11)} = \pm\alpha_{em}^{(11)} \qquad (7)$$

where $\alpha^{(ik)}$ are the components of the examined tensors and pseudotensors, the plus sign corresponds to the right-handed helix, and the minus sign corresponds to the left-handed helix. Equations (7) demonstrate that the helices with the optimal parameters are characterized by three equal susceptibilities: dielectric, magnetic, and chiral.

The equality of all the three susceptibilities for the optimal helices is confirmed by the available experimental data, in particular, by observation of a circularly polarized wave radiated by the optimal helix in the direction perpendicular to the helix axis.

The isotropic metamaterial with equal permittivity and permeability on the basis of optimal helices for THz range was made by the method of precise 3D nanostructure formation from strained heterofilms [6-8]. Chirality of the metamaterial was compensated with pairs of helices of opposite handedness. The fabricated samples are shown in Fig.1.

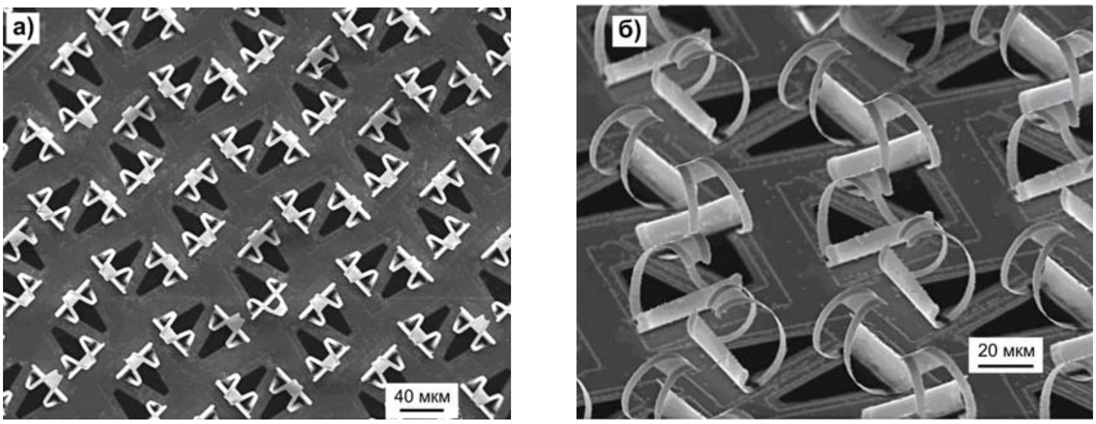

Fig.1 Scanning electron microscopy images of arrays of InGaAs / GaAs / Ti / Au single-turn helices: a) top view and b) oblique view

4. Conclusion

The optimal helices can find wide application, for example, for the development of reflectionless coatings and metamaterials with negative electromagnetic wave refraction. The examined helices have optimal characteristics upon exposure to both electric and magnetic fields, that is, for arbitrary orientation of the incident wave polarization plane. This is the advantage of the optimal helices over other possible metamaterial elements, for example, straight wires and split-ring resonators.

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