Resonant features of planar Faraday metamaterial with high structural symmetry

Study of properties of a 4-fold array of planar chiral rosettes placed on a ferrite substrate

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Abstract. The transmission of electromagnetic wave through a planar chiral structure, loaded with the gyrotropic medium being under an action of the longitudinal magnetic field, is studied. The frequency dependence of the metamaterial resonance and the angle of rotation of the polarization plane are obtained. We demonstrate both theoretically and experimentally a resonant enhancement of the Faraday rotation. The ranges of frequency and magnetic field strength are defined, where the angle of polarization plane rotation for the metamaterial is substantially higher than that one for a single ferrite slab.

1 Introduction

It is known, that bulk chiral artificial structures \cite{1, 2} manifest a reciprocal optical activity. The typical constructive object of 3D chiral media is a spirally conducting cylinder. The concept of chirality also exists in two dimensions. A planar object is said to be 2D chiral if it cannot be superimposed on its mirror image unless it is lifted from the plane. For instance, an array of metallic rosettes is an example of such an object. Hetch and Barron \cite{3, 4}, Arnaut and Davis \cite{5, 6} were the first who introduced planar chiral structures into the electromagnetic research. However, 2D chirality does not lead to the same electromagnetic effects which are conventional for 3D chirality and, so, it became a subject of special intense investigations \cite{7, 8, 9}.

Planar chiral materials are quite simple structures in manufacturing. However, in contrast to traditional fre-
frequency selective surfaces, they provide an additional twist parameter to control electromagnetic properties. Besides, in some particular cases, quasi-2D planar chiral metallic structures can be asymmetrically combined with isotropic substrates to distinct a reciprocal optical response inherent to true 3D chiral structures. In such metamaterials, at normal incidence of the exciting wave, an optical activity appears only in the case, when their constituent metallic elements have finite thickness, which provides an asymmetric coupling of the fields at the air and substrate interfaces [10].

From the viewpoint of possible applications in microwave and THz frequency bands, it is known that the thinner metallic elements of planar structures, so they are easier in fabrication. Thus, knowledge about optical properties of metamaterials based on the thin planar chiral structures are especially important.

The results of a detailed study of polarization transformations caused by an array of the perfectly conducting infinitely thin planar chiral elements are presented in [11]. In this work, the optical response of planar chiral metamaterials with four-fold symmetry was studied in the case, when the arrays are placed on an isotropic dielectric substrate. One of the results obtained in this study is an argue that the 2D chiral planar structures do not change the polarization state of the normally incident wave in the main diffraction order. This theoretical conclusion was confirmed with numerical data obtained by a simulation in the case of arrays made of infinitely thin metallic rosettes placed on a dielectric substrate.

From both fundamental and application points of view, the planar metamaterials placed on a ferrite substrate [12] and layered ferrite-dielectric structures [13,14] are quite interesting objects because they can be used successfully to design non-reciprocal magnetically controllable microwave devices based on the Faraday effect. On the other hand, magneto-optically active substrate can be serve as a sensitive element for THz magnetic near-field imaging in metamaterials [15]. The polarization rotation of a near-IR probe beam revealed in the substrate measures the magnetic near-field.

A general theoretical approach is used in [2] to predict electromagnetic properties of uniaxial composites with four-fold inclusions in the form of planar chiral gammadions combined with ferrite ellipsoids. It needs two pseudo-vectors to describe the system. The first vector is a bias magnetic field and the second one is a vector defining the handedness of the gammadion shape. They are pseudo-vectors (axial vectors) because being time-odd. As a result of the theory, these composite systems are bi-anisotropic non-reciprocal media described by specific constitutive equations of the same kind as that ones used in the moving chiral media.

However, it is necessary to clarify the effect of the particles handedness (and the corresponding pseudo-vector in the theory) on the system properties and the degree of reciprocal rotation. As it has been mentioned above, it is important at least in the case of metallic planar chiral particles which have small thickness in comparison with the wavelength. The theoretical and experimental studies
of the particle handedness effect are extremely important in this point and are the subject of the present research.

Thus, the purpose of this paper is to study both theoretically and experimentally the resonant properties of planar gyrotropic metamaterials (arrays of metallic rosettes placed on a ferrite substrate) depending on the value of static magnetic field strength. The field is applied normally to the structure plane, i.e., the systems are considered in the Faraday geometry. The periodic cell size of the studied metamaterials is chosen in such a way that the high-quality factor resonances appear in the structures spectra in the millimeter waveband. We consider metamaterials based on a 4-fold symmetry array which consisted of thin metallic rosettes. As a main result of our study the essential resonant enhancement of the Faraday rotation is demonstrated both theoretically and experimentally for the metamaterial. This effect is substantially higher than that one for a single ferrite slab.

2 Structures under study and theoretical approach

The metamaterial being under investigation is designed as a layered structure, which consists of a planar chiral periodic structure placed on a ferrite plane-parallel slab with thickness 0.5 mm. The chiral structure is made of fiberglass ($\varepsilon' = 3.67$, tan $\delta = 0.06$) with a thickness 1.5 mm, one side of which is covered with copper foil. The foil side of this layered structure is patterned with a periodic array which square unit cell consists of a planar chiral rosette (see Fig. 1). The ferrite slab is leaned to this array of metallic elements. Two samples of each kind (i.e. right-handed and left-handed elements) of gyrotropic planar metamaterial $60 \times 60$ mm$^2$ which are differed by the period of the rosette array have been performed. Sample 1 of both right-handed and left-handed kinds has the period $d = 5$ mm and the radius of rosette arcs $a = 1.66$ mm, whereas sample 2 has $d = 4$ mm and $a = 1.33$ mm, respectively. The angular size $\phi$ and the width $w$ of the copper strips which form the rosettes for all samples are identical.

We applied the ‘resonant model’ of ‘saturated’ ferrite [16,17] to calculate the ferrite constitutive parameters in the case when the static magnetic field $H_0$ is more strong than the field of the saturation magnetization $4\pi M_S$, and the ‘non-resonant model’ of ‘non-saturated’ ferrite [18,19] if the field $H_0$ is less than $4\pi M_S$.

When the field strength is larger then $4\pi M_S$ we use common expressions for permittivity and permeability for z-axis biased ferrite [16,17], assuming the ferrite material is magnetically saturated and taking into account the dielectric and magnetic losses

$$
\varepsilon_f = \varepsilon, \quad \hat{\mu}_f = \begin{pmatrix}
\mu & i\beta & 0 \\
-i\beta & \mu & 0 \\
0 & 0 & \mu_z 
\end{pmatrix}, \quad (1)
$$

where

$$
\mu = 1 + 4\pi(\chi' - i\chi''), \quad \beta = 4\pi(K' - iK''), \quad \mu_z = 1, \quad (2)
$$

$$
\chi' = \omega_0\omega_m[\omega_0^2 - \omega^2(1 - \alpha^2)]D^{-1}, \quad (3)
$$

$$
\chi'' = \omega_0\omega_m\alpha[\omega_0^2 + \omega^2(1 + \alpha^2)]D^{-1},
$$
Fig. 1. (Color online) The periodic array of planar chiral elements placed on a dielectric substrate: (a) the photo; (b) the square unit cell of the periodic array ($d$ is the period of the structure) with a metallic element shaped as the planar chiral right-handed rosette ($a$ is the radius of arc, $\phi = 120$ deg is its angular size, $w = 0.267$ mm is the width of copper strips which form the rosette).

\[
K' = \omega \omega_m [\omega_0^2 - \omega^2(1 + \alpha^2)]D^{-1},
\]
\[
K'' = 2\omega^2 \omega_0 \omega_m \alpha D^{-1},
\]
\[
D = [\omega_0^2 - \omega^2(1 + \alpha^2)]^2 + 4\omega_0^2 \omega^2 \alpha^2,
\]
\[
\omega_m = \gamma 4\pi M_S,
\]
\[
\omega_0 = \gamma |H_0 - 4\pi M_S|.
\]

we use the Gaussian system of units. The ferrite material of brand L14H is characterized by the following set of parameters: $\varepsilon = 13.2 - i0.0697$, $\alpha = 0.0285$, $\omega_m/2\pi = 14.2$ GHz. The value $\omega_m$ corresponds to the saturation magnetization field of $4\pi M_S = 4800$ Oe.

When the field strength $H_0$ is smaller than $4\pi M_S$, the experiment can be well described using the non-resonant 'non-saturated' ferrite model [18-19]. Let us note that in the non-saturated model, the current magnetization $M$ is a function of the static magnetic field strength $M = M(H_0)$. The elements of the tensor $\tilde{\mu}_f$ are represented by empirical expressions [19]:

\[
\mu = \mu_{\text{dem}} + (1 - \mu_{\text{dem}})(M/M_S)^{3/2},
\]
\[
\mu_z = (\mu_{\text{dem}})^P, \quad P = (1 - M/M_S)^{5/2},
\]
\[
\beta = -\gamma 4\pi M/\omega, \quad \mu'' = \mu_z'' = 0,
\]
where $\mu_{\text{dem}}$ is the permeability of completely demagnetized ferrite, which properties can be calculated using the two-domain model [18] for frequencies $\omega > \gamma (H_r + 4\pi M_S)$:

\[
\mu_{\text{dem}} = \frac{1}{3} + \frac{2}{3} \sqrt{\frac{(\omega/\gamma)^2 - (H_r + 4\pi M_S)^2}{(\omega/\gamma)^2 - H_r^2}},
\]

where $H_r$ is the strength of field matched to the remanent magnetization. For the used ferrite brand, it is $H_r = 3500$ Oe. The dependence of the components of the permeability tensor of ferrite versus the static magnetic field strength are presented in Fig. 2 for the frequency $f = \omega/2\pi = 30$ GHz.

For a thin ferrite slab magnetized normally to its plane, the FMR frequency $\omega_0$ is defined by the well-known formula [17]:

\[
\omega_0 = \gamma |H_0 - 4\pi M_S|.
\]
Fig. 2. (Color online) (a) Theoretical dependences of the components of permeability tensor for the thin ferrite slab versus the normally applied static magnetic field at $f = 30$ GHz; (b) the same dependences detailed for small static fields by ‘non-resonant’ ferrite model.

The dependence of FMR frequency versus the static magnetic field strength is shown in Fig. 4. Note that the formula (8) is rigorous when the field strength $H_0$ is larger than $4\pi M_S$. When the field strength is less than $4\pi M_S$, the frequency of FMR may be somewhat lower due to the fact that the ferrite changes in the multidomain state and a violation of its magnetic order grows as the static field strength decreases (see the dashed line in Fig. 4). On the same reason, the FMR linewidth should grow as the field strength decreases.

As the field strength decreases below $4\pi M_S$, the domain structure appears in the ferrite and its magnetic state demonstrates a certain disorder. Note that in this case, the values of the diagonal components of the $\hat{\mu}_f$, i.e. the value $\mu$, tends to permeability of completely demagnetized ferrite $\mu_{dem}$ (7). This value is not equal to zero (Fig. 2b). The latter is reasonable, because when domains disorder, then their contribution to the integral magnetization decreases. However, the magnetization of each domain is a positive value, in spite of the external field is directed along the domain magnetic moment or against it. Contributions to the diagonal components $\mu$ from all domains are added and it tends to some constant when the field strength decreases. A quite different behavior is observed for the off-diagonal component $\beta$. As the field strength decreases, the domains, which magnetic moment is directed along the external field, and domains, which magnetic moment is directed opposite to the field, give a different sign for the contribution to the $\beta$ (the non-reciprocal Faraday effect). Thus, contributions of all domains to the off-diagonal components $\beta$ are subtracted and $\beta$ tends to zero as the field strength decreases. Note that when the field strength is less than $4\pi M_S$, the correct count of the magnetic disorder of domain structure in the ferrite should lead to the gradual change of the components $\mu$ and $\beta$.

The fields, intensities, and polarization characteristics of the electromagnetic waves diffracted by the array of rosette-shaped elements were calculated using the full wave method described earlier in [12]. This approach is based on the method of moments for solution of the vector integral equation for surface currents induced by the electromagnetic field on the array elements [20]. The last ones are assumed to be perfectly conducting and infinitely thin. The equation was derived with boundary conditions that demand a zero value for the tangential component of the electric field on metal strips. In our calculations, we used
the Fourier transformations of fields and surface current distributions.

3 Experiment and data analysis

The experimental setup [14] consists of the structure under study, which is placed between two matching rectangular horns (transmitting and receiving ones) fitted to the Vector Network Analyzer Agilent N5230A. Horns are situated on the axis passed normally to the plane of the structure (Fig. 3a). Using the Network Analyzer the $S$-parameters, namely $S_{21}$ - the transmission coefficient for the structure in the frequency range 22-40 GHz, can be detected and analyzed by the special computer software.

For measurements in a longitudinal static magnetic field, the structure and horns are positioned between the poles of the electromagnet to provide the orientation of the components of electromagnetic field ($E, H$) and static field ($H_0$) as it is shown in Fig. 3b. The electromagnet poles have axial holes, that allow one to place horns inside the magnetic system. The poles diameter is 120 mm and the distance between them is less than 30-90 mm. Note that due to such sufficiently large poles diameter, the inhomogeneity of the static magnetic field in the structure area does not exceed 3-5 %, which is quite enough to provide experiments with high quality. The static magnetic field strength is controlled by a computer. A more detailed technique of such a kind fully automated experiment one can find in [14].

First of all, let us mention that the experimental study of transmission of normally incident wave through two kinds of planar chiral arrays differed by sign of chirality was carried out in both cases of free standing arrays and arrays placed on ferrite substrate. It was shown that there is not any difference in the intensity of transmitted field and polarization transformations obtained for these two samples. Thus the experimental evidence of indistinguishability of these properties has been demonstrated between two enantiomorphous kinds of planar chiral samples consisted of right-handed and left-handed thin metallic rosettes in the case of normally incident wave. This property was argued theoretically before in [11,12].

Thus, at the normal incidence of the exciting wave, the complex layered structure being a thin planar chi-
eral metallic array placed on the normally magnetized fer-
riote substrate (or the isotropic dielectric substrate) does
not manifest any appearance of the property related to
3D chiral objects. It is an impressive observation because
the symmetry is broken in the direction orthogonal to the
structure plane and we deal with the object which has a
volume chiral geometry. The reason is in a very small dif-
fERENCE between the fields existed on the array interfaces
with free space and the substrate in the case, when the
considered array has a small thickness in comparison with
a wavelength. A finite thickness of metallic elements of the
array is a prerequisite to make asymmetrically coupling
fields at the air and substrate interfaces and to observe an
effect of volume chirality of such structure [10].

On the basis of the theoretical approach described above,
we have defined numerically the transmission spectrum of
the structure under study. The characteristic frequency
ranges where the transmission demonstrates a minimum
and the resonant behavior exists (the metamaterial reso-
nance dip frequency $f_r$) was determined. These resonances
are caused by metallic elements of the structure. In the
case of linearly $y$-polarized normally incident plane elec-
tromagnetic wave, the dependence of $f_r$ on the static mag-
etic field strength has been calculated for two values of the planar
chiral structure period $d$ (see Fig. 4). Besides
that, the dependence of the FMR frequency on the static
magnetic field strength for the thin ferrite slab used in ex-
periments ($f_0(H_0) = \omega_0/2\pi$) is plotted in the same figure.

One can see that: (i) the variation of the metamate-
rial resonant dip frequency $(df_r/dH_0)$ is as stronger as
the frequency of this resonance is closer to the FMR fre-
quency $f_0$. This fact is caused, obviously, that near the
FMR the value of the real part of the diagonal compo-
nents of the permeability $\mu$ considerably increases. In turn,
$\mu$ is uniquely connected with the value of the resonant fre-
quency related to array; (ii) in the range of magnetic field
strength from 12500 Oe up to 15000 Oe, two resonant dips
(i.e. two values of resonant frequency for the same value of
the magnetic field strength) are observed. Such scenario is
cau sed by the effect of resonance not only diagonal compo-
nents of the permeability but off-diagonal ones as well. In
particular, it is known [16,17], that in the vicinity of FMR
frequency, the eigenwave propagation constant of the lon-
gitudinally magnetized ferrite can acquire more than one

Fig. 4. (Color online) Theoretical dependence of the
metamaterial resonance dip frequency on the static mag-
etic field strength for two values of period of the planar
chiral structure. The solid line denotes the dependence of
FMR frequency of the ferrite on the static field according
to the expression (8). The same dependence but corrected
in the region of small field is presented by the dashed line.
value (in the given case, it is two). To be specific, let us call the area, where the resonant frequency of array and FMR frequency are close enough to each other as an ‘interaction area’; (iii) as the structure period increases, the resonant frequency of response dips decreases.

Comparison of experimental data and theoretical conclusions has been made in the field range 0-6500 Oe. In particular, the qualitative agreement between experimental and calculated data for the dependence of metamaterial resonance dip frequency $f_r$ on the magnetic field strength (for the $d = 5$ mm) is revealed (Fig. 5). When the magnetic field strength exceeds the value corresponding to the saturation magnetization field ($4\pi M_S = 4800$ Oe), the derivation $df_r/dH_0$ changes sign. It is related to the mentioned above effect, namely the presence of low-field mode (with $df_0/dH_0 < 0$) in the FMR spectrum [16], when the field strength is less than $4\pi M_S$. However, as it was expected, the slope of the experimental frequency dependence of the metamaterial resonance dip on the magnetic field strength is a bit smaller than that predicted in the theory. This difference can be explained by the fact that the magnetically disordered domains appear in the structure. The maximal value of frequency shift of the metamaterial resonance on the magnetic field strength (triangle markers in Fig. 5) is about 900 MHz. The origin of the divergence between theoretical and experimental data is non-equality of actual and theoretical values of the ferrite constitutive parameters and their frequency dispersion.

In order to verify the nonreciprocal properties of the metamaterials under study, the experimental analysis of the electromagnetic wave transmission for the case where the angle between the plane of polarization of transmitting and receiving horn is $\psi = 45$ deg. It can be seen (Fig. 6) that both character and magnitude of the shift of metamaterial resonance dip frequency depend strongly on the static magnetic field direction. Thus, the nonreciprocal properties of the investigated planar metamaterial are demonstrated. Let note, that for $\psi = 90$ deg this dependence has the symmetric form as was expected. The last observation is yet another proof of an independence of the metamaterial response on the handedness of metallic rosettes.

For a more detailed study of the polarization properties of the metamaterial under study we have performed the experimental and numerical analysis of the polarization rotation (more exactly, of the rotation of main axis of the polarization ellipse) of the wave transmitted through the structure with respect to the linearly polarized incident wave. Theoretical dependences of the angle of po-
Fig. 6. (Color online) Measured metamaterial resonance dip frequency of gyrotropic planar chiral metamaterial versus the static magnetic field strength for $d = 5$ mm and $\psi = 45$ deg.

Fig. 7. (Color online) Theoretical dependences of the polarization rotation angle of two different metamaterial resonant modes versus the static magnetic field strength for two values of the structure period $d$.

The points marked by squares correspond to the high-frequency modes (hf-modes, located to the left of dependency $f_0(H_0)$ in Fig. 4), and the points marked by circles correspond to the low-frequency modes (lf-modes, located to the right of dependency $f_0(H_0)$). It is easily seen that the structure with a smaller period rotates the plane of polarization on the greater angle than the structure with the large period. This may be caused by higher quality factor of resonant modes in the structure with the smaller period that occurs due to increase of the summary surface of metallic elements when the period decreases.

One can see while the field strength tends to zero, the rotation angle decreases to zero as well for both modes. This fully coincides with used theoretical models of ferrite permeability (Fig. 2), where it was shown that the off-diagonal component $\beta$ which is responsible for polarization rotation tends to zero as the field strength decreases.

This occurs, as mentioned above, due to the compensation of the effect of multidirectional domains orientation on the rotation angle. However, let us note, that in the 'interaction area' (where $H_0$ is from 12500 Oe up to 15000 Oe) polarization rotation angles increase drastically. It can be seen that for high-frequency modes (square markers) the maximum of $\theta$ reaches $\theta_r \approx -50$ deg. For low-frequency modes (circle markers), this dependence looks monotone (under the given field strength), and reaches the maximum values at $\theta_r \approx 50$ deg.

Such resonant-like behavior of $\theta_r$ occurs obviously in the 'interaction area' due to increasing the values of off-diagonal components of the ferrite permeability (Fig. 2a) in the vicinity of FMR.
The results of experimental verification of dependences $\theta_r(H_0)$ (Fig. 7) and $f_r(H_0)$ (Fig. 4) are summarized in Fig. 8. To provide clear demonstration of the effect of geometrical parameters of the metamaterial under study on its polarization properties, experimental data are shown for: (i) the polarization rotation angle $\theta$ of linearly polarized wave transmitting through a ferrite slab (Fig. 8a); (ii) the polarization rotation angle $\theta$ of linearly polarized wave transmitting through planar chiral structure loaded with a ferrite slab when the period is chosen to be $d = 5$ mm (Fig. 8b).

One can see that the surface plotted for the ferrite slab (Fig. 8a) is much smoother than that one for the array structure loaded with ferrite slab (Fig. 8b). The monotonic growth of $\theta$ from 0 deg to 15 deg with increasing field strength from 0 Oe to 6500 Oe for all frequencies is occurred for the ferrite slab. A presence of moderate dips is caused by the impossibility to provide the perfect matching of elements of the experimental setup. Also, for the planar chiral array loaded with ferrite slab, a monotonic growth of $\theta$ on the field strength takes a place. However, near to the frequency of the metamaterial resonance dip ($f_r = 25.5 - 26.5$ GHz (Fig. 5)), this dependence acquires a pronounced resonant character, and for $\theta \to \theta_r$ achieves significantly higher values than that one for the ferrite slab (up to $\theta_r \geq 45$ deg).

It can be seen that the value $\theta_r$ (Fig. 8b) also depends on the magnetic field strength, and the maximum of $\theta_r$ is observed at $H_0 \approx 4800$ Oe (i.e. in the transition area from saturated ferrite model to unsaturated one). In this region the real part of permeability has extreme (Fig. 2a), which explains the extreme in the dependency of $\theta_r(H_0)$.

Theoretical and experimental curves for the chiral structure loaded with the ferrite slab are similar in shape and exhibit a character extreme in the vicinity of the field strength close to the saturation magnetization, as it is expected from the general representations.

**Fig. 8.** (Color online) Experimental dependences of the polarization rotation angle $\theta$ as a function of frequency and static magnetic field strength for: (a) ferrite slab; (b) ferrite loaded by planar chiral structure with period $d = 5$ mm.
The distinct feature of the planar chiral Faraday metamaterial (i.e. the resonant planar array loaded with ferrite slab) is larger sensitivity of its polarization properties to the static magnetic field strength with that one of the same ordinary ferrite slab. This phenomenon can be explained by the fact that the resonant character of the magnetic permeability component of ferrite (or their strong frequency dispersion) is applied on the resonant character of oscillations in the planar chiral structure (strong frequency dispersion of the effective material parameters of the chiral structure), which takes a place in the 'interaction area'. Note that a similar situation, known as the amplification of the Faraday effect have been detected by the authors in the millimeter wave range before, but in more simple resonant structures (the open resonator [21], the photonic crystal [14]). However, in the case considered here, we are dealing with the structure being planar resonant metamaterial that promises the similar effect in the very thin structure. The needed resonant properties of thin metamaterial slab are imparted by complex shaped metallic rosettes. The complex shape of array particles enables us to achieve resonant response of the structure in the wavelength less than pitch of the array. The 4-fold symmetry planar chiral rosettes are chosen to clear the way to design the polarization insensitive array structure at least at normal incidence of the exciting wave. Thus we can produce sub-wavelength resonant structures suitable for such promising applications as planar metamaterial which is controllable by static magnetic field.

4 Conclusion

The transmission of electromagnetic waves of millimeter range through the layered metamaterial formed by the resonant planar chiral structure loaded with the gyrotropic medium has been studied both experimentally and theoretically. Namely: (i) the dependence of frequency of the metamaterial resonant response and the angle of polarization rotation on the longitudinal static magnetic field are detected, and a satisfactory agreement between the theory and experiment is demonstrated; (ii) the range of frequencies and magnetic field strength where the angle of polarization rotation by the metamaterial appears essentially higher than that one related to a single ferrite slab is defined; (iii) at the normal incidence of the exciting wave, the independence of this metamaterial response on handedness of its planar chiral thin metallic elements has been verified; (iv) the usage of arrays with high structural symmetry based on planar chiral particles enables additional means to produce sub-wavelength resonant metamaterials, which have small size of the periodic cell and controllable properties by static magnetic field.

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