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Electrically Controlled Nonreciprocity Inversion of Microwave Transmission in a Metastructure Based on Ferrite and a Varactor-Loaded Dipole

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Abstract—A possibility of electrical control of nonreciprocity inversion of microwave propagation when using a metastructure with a ferrite plate and varactor-loaded dipole is demonstrated. In contrast to conventional methods, the inversion occurs without ferrite remagnetization. It is reached by varying the constant bias voltage on varactor that enables the tuning of the resonance frequency of dipole to the frequency of ferromagnetic resonance. This effect occurs due to the fact that a magnetic field with elliptical polarization is formed near a dipole as a result of superposition of incident and scattered waves, rotating in one direction below the resonance frequency of dipole and in the opposite direction above the frequency of this resonance.

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In recent years, it has been found that the effect of nonreciprocal absorption of electromagnetic radiation in transversely magnetized ferrite has new properties in a metastructure combined with lattice of conductive or separate elements upon the excitation of ferromagnetic resonance (FMR). This effect is used in many nonreciprocal devices [1]. The appearance and amplification of the nonreciprocity for linearly polarized wave in a metastructure arranged along the axis of rectangular waveguide or in free space need to be noted [2, 3]. In the case of a free ferrite without the lattice, nonreciprocity is completely absent. It should be remembered that nonreciprocity is observed in rectangular waveguide when a ferrite plate is located in the region where the magnetic field is circularly polarized at distance $\lambda/8$ from the lateral side [1].

In the metastructure, the rotating magnetic field required is formed by the lattice of resonance elements itself. Usually, when considering the surface waves formed by the chain of dipoles, the main attention was paid to the electric field. However, after observing the nonreciprocal effects caused by the interaction of precessing spins of ferrite and the magnetic field of the surface wave, it became necessary to study the properties of the magnetic field produced by dipoles of different shape. In [2, 3], based on the example of a bianisotropic layer that models the lattice of chiral (or dipole) elements, it was theoretically shown that the magnetic field has an elliptical or circular polarization on the frequencies near the resonance of effective parameters. There are two bands of nonreciprocal transmission of microwaves at these frequencies in metastructure with ferrite. The first lies in the range of FMR, while the second is related to the resonance of dipole elements (DR). Both of these bands can be controlled by external static magnetic field H. When using the varactors in the gaps of the element, it was possible to observe both magnetically and electrically controlled frequency bands of nonreciprocal transmission [4].

Such metastructures as magnetoelectric crystals have magnetoelectric properties in the microwave region that are observed in the form of the dependence of magnetic properties (nonreciprocal characteristics of microwave propagation) on the static electric field and in the form of the dependence of the electric properties (resonance characteristics of dipoles) on the magnetic field. It is known that magnetoelectric properties are manifested in multiferroics and heterostructures based on ferroelectric and ferromagnetic layers [5]. These structures have been attracting increased attraction recently. This is partly due to the possibility of electric (more rapid) control of the FMR characteristics as compared with control using a magnetic field, the rapidity parameters of which restrict the complex processes of magnetization and remagnetization. The electric control is performed via variation of the dielectric permittivity of ferroelectric when applying the electric field [6].

It is worth noting that publications have recently appeared in which it was proposed to create metamaterials with nonreciprocity effect using an artificial Faraday effect [7, 8] without application of an external magnetic field. In [9], it is proposed an artificial Faraday effect for printing technology, based on the results of measurements of S parameters on the level of 50–70 dB.

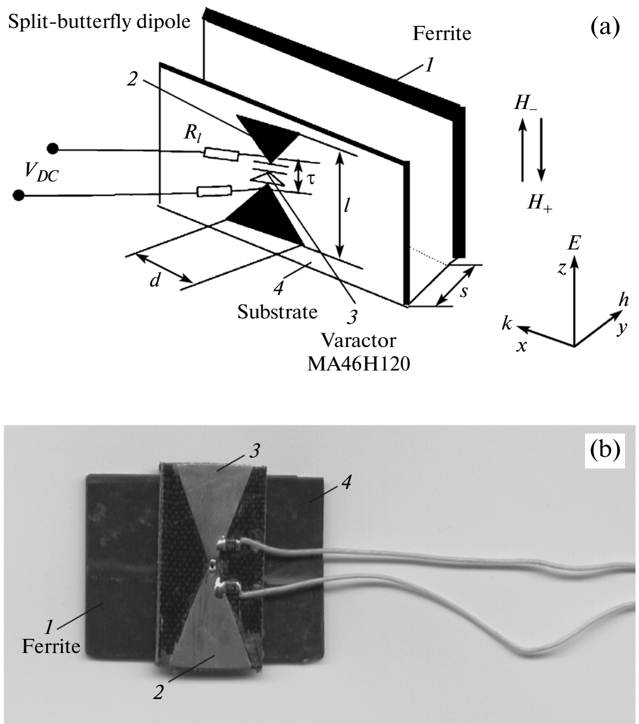

Fig. 1. (a) A scheme and (b) a photo of a microstructure containing ferrite plate *1* (30 × 20 × 1.4 mm) and disconnected "butterfly" dipole *2* loaded by MA46H120 varactor *3*. Substrate *4* is made of getinaks, $R_L = 120$ kΩ, $\tau = 0.5$ mm, $d = 10$ mm, and $s = 6.5$ mm.

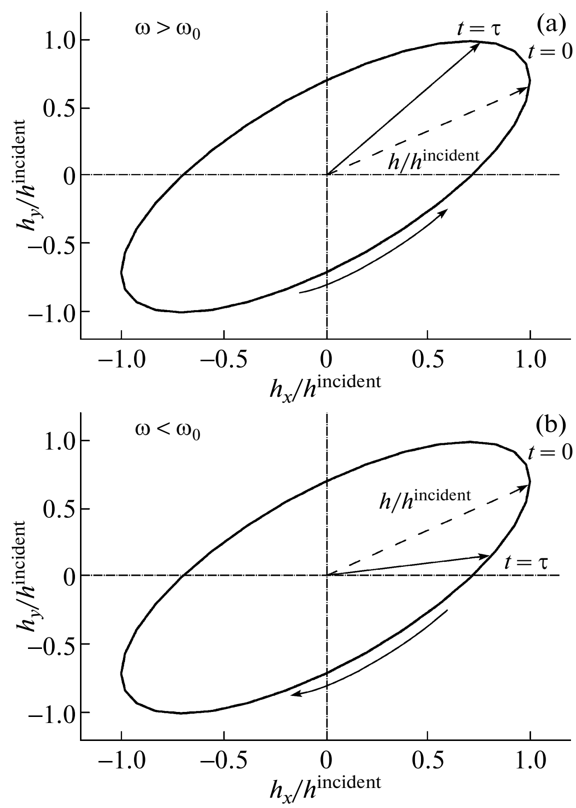

Fig. 2. Elliptical trajectories of the magnetic field of the wave near a dipole at some point $\mathcal{M}$. Dashed arrows indicate the field at the instant $t = 0$; solid lines correspond to $t < \pi/2\omega$. (a) $\omega > \omega_0$, (b) $\omega < \omega_0$, ω_0 is the frequency of DR. The trajectories of movement of the end of the magnetic field vector are shown by ellipses.

This work is devoted to FMR-based nonreciprocity in a metastructure consisting of ferrite and varactor-loaded dipole under conditions of coexistence and influence of FMR and DR. A method for electrical control of the sign of nonreciprocity for propagating microwaves is proposed and implemented. The method is based on the theoretical analysis of the field near a dipole, the dependence of the nonreciprocity sign from relative arrangement of FMR and DR, and the possibility to change this arrangement by tuning the frequency of DR when changing constant electric bias V_{DC} on the varactor. This effect observed for various dipoles, namely in the form of "butterfly," "snake," "ring," and disconnected double chiral rings. The choice of varactor is an important point. An MA46H120 varactor proves to be preferable to SMV and BB857 varactors. For approbation, we used a P2-58 panoramic sensor of standing wave ratio and a single-channel measurement method in the case in which metastructure is placed along the waveguide axis (Fig. 1) (48 × 24 mm).

It was theoretically shown that, even near a single dipole excited by a plane wave, an elliptically polarized variable magnetic field is formed on the frequencies near DR as a result of superposition of the incident field and the field scattered by the dipole. In this case, the magnetic field vector rotates in one direction below the frequency of DR and in the opposite direction above the frequency of DR. The superposition of fields was not considered previously, and only the effect of scattering of linearly polarized electric field was studied in these works.

This was probably caused by the primary application of dipoles as the emitting antennas, which cause all attention to be directed to their radiative properties.

When modeling the dipole as an equivalent oscillator with inductance, resistance and variable capacitance, one can show that mutually perpendicular projections of complex amplitudes of the total microwave magnetic field have different value and phase. Due to this, the end of the vector of resultant magnetic field moves along elliptical trajectories, with the direction of its rotation depending on the relation between the phases of corresponding projections. Figure 2 shows the behavior of the normalized magnetic field at the point $\mathcal{M}$ (on the right from dipole). The magnetic field vector rotates counterclockwise at frequencies exceeding resonance frequency ω_0 of the dipole (Fig. 2a) and clockwise below this frequency (Fig. 2b). At transition to $\mathcal{M}'$ (on the left from the dipole), the direction of the magnetic dipole rotation is changed. If the ferrite sample is placed near the dipole (near point $\mathcal{M}$, for example), an elliptically polarized magnetic field arises with variable direction of rotation caused by 1) tuning the frequency of dipole (using varactor, for example) and 2) changing mutual arrangement of the dipole and ferrite (during transition to $\mathcal{M}'$). In case of same direction of external magnetostatic field $H(\uparrow\uparrow z)$ this leads to the change in the sign of nonreciprocity of microwave transmission through this structure. We present the measurement results corresponding to the metastructure with "butterfly" dipole and an MA46H120 varactor (Fig. 1). Nonreciprocity parameter $\delta = T(H_-) - T(H_+)$ is determined as the difference of transmittances for opposite directions of magnetization when changing the direction of microwave propagation. It is determined by measuring the frequency dependencies of T.

In the absence of a static magnetic field, one observes a resonance minimum caused by the dipole resonance (DR), which may be driven by inverse bias voltage V_{DC} on the varactor (Fig. 3a). Thus, at $H = 0$ and $V_{DC} = 0$, the resonance response $DR_{0,0}$ is observed at a frequency of 3.6 GHz. With increasing voltage V_{DC}, the resonance is shifted to reach a frequency of 4.85 GHz at $V_{DC} = 20$ V.

In the presence of transverse magnetic field H, the FMR is excited and shifted to higher frequencies with increasing H. In this case, the metastructure is characterized by two resonance responses caused by DR and FMR. With the approach of FMR to DM, the mode of interrelated resonances arises and resonance responses acquire nonreciprocal properties with the opposite sign of nonreciprocity. Moreover, not only the frequency of FMR, but also the frequency of DR, is shifted when varying H. Ferromagnetic and dipole resonances are easily recognized by their response to the driving field H and voltage V_{DC}. The sign of nonreciprocity in the region of FMR depends on the relative position of DR. When varying the order of frequency of FMR and DR when DR lies at a higher frequency and vice versa, the direction of rotation of microwave magnetic field varies as, correspondingly, does the sign of nonreciprocity. Let FMR be excited when applying the magnetic field at a frequency of 4 GHz, which is higher than the frequency of $DR_{0,0}$. Moreover, the directions of spin precession and rotation of the microwave field are left-handed and coincide, while ferrite absorbs the energy of the electromagnetic field (the nonreciprocity sign upon microwave transmission is positive). In contrast to the frequency of DR, the FMR frequency varies insignificantly when varying voltage V_{DC}, and at a certain value of V_{DC} it can be lower than the frequency of DR. In this case, the direction of rotation of the microwave magnetic field changes to right-hand (at frequencies of FMR), whereas the direction of spin precession remains left-hand, while ferrite does not absorb the energy of the electromagnetic field (and the sign of nonreciprocity upon microwave transmission becomes negative).

A convincing verification of these properties is supplied by measurement of dependences of δ on the magnitude of magnetic field at a fixed frequency and various bias voltages (Fig. 3b). Figure 3b shows measurement results obtained at a frequency of 4 GHz. One can see that, at certain magnitudes of the magnetic field—namely, H = 850–1000 Oe—positive parameter δ (at $V_{DC} = 0$ V) becomes negative at $V_{DC} = 10$ V.

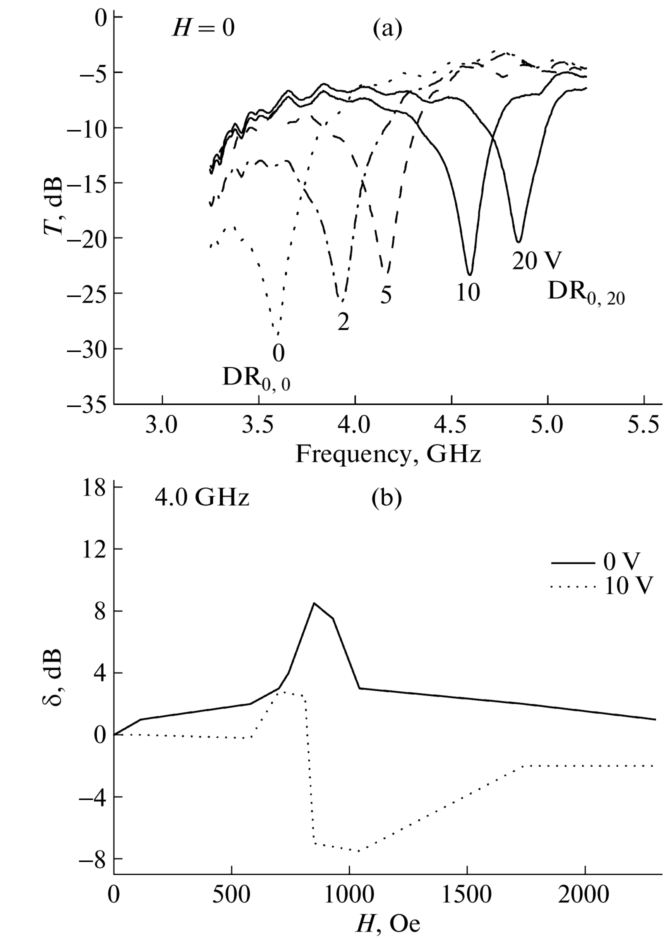

Fig. 3. (a) Frequency dependence of transmittance T in a rectangular waveguide with metastructure in the region of resonance of the dipole DR at $H = 0$ at various bias voltage V_{DC}. $DR_{0,0}$ corresponds to $H = 0$ and $V_{DC} = 0$, $DR_{0,20}$ corresponds to $H = 0$ and $V_{DC} = 20$ V. (b) Nonreciprocity parameter $\delta = T(H_-) - T(H_+)$ measured at frequency f = 4 GHz depending on magnetic field H at $V_{DC} = 0$ (solid line) and $V_{DC} = 10$ V (dotted line).

Therefore, by using the simplest metastructure containing a ferrite plate and single varactor-loaded dipole, we have demonstrated the possibility of electrical nonreciprocity switching of microwave transmission driven by constant voltage on a varactor. As a result, the rotation direction of elliptically polarized microwave magnetic field is changed. Typically, nonreciprocal inversion of propagation was carried out by switching the direction of the external magnetic field, causing changes in the direction of spin precession in ferrite. The possibility of carrying out nonreciprocity sign inversion control electrically without changing the magnetization direction may increase the rapidity of control by several orders of magnitude as compared to control using the magnetic field. In addition to this, when exciting FMR, the electromagnet can be replaced by a permanent magnet. This reduces the cost of energy consumption for maintaining constant electric current and facilitates the transition to higher frequencies. Moreover, the difficulties related with obtaining high constant magnetic fields for short-wave range FMR excitation can be overcome using hexaferrites with large internal fields of anisotropy.

The proposed metastructures and methods of control can be used in information and energy-saving technologies for the development of nonreciprocal quickly controlled systems.

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