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Electrically Controlled Frequency Bands of Nonreciprocal Passage of Microwaves in Metastructures

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Abstract—Measurements of the transmission coefficients of linearly polarized waves in a rectangular waveguide along a metastructure formed by a transversely magnetized ferrite plate and double-split rings with varactors indicated the presence—in addition to the ferromagnetic resonance—of a resonance region of nonreciprocal passage, which is controlled, in contrast to the ferromagnetic resonance, by the electric field. This effect manifests itself in magnetic fields substantially lower than the field exciting the ferromagnetic resonance at these frequencies. Electrically controlled nonreciprocal passage of microwaves cannot be achieved by means of known natural materials or traditional ferromagnets.

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At the present time, interest in metamaterials is persisting due to new approaches to creation of metastructures possessing properties nonexistent in nature. Earlier, wide response was gained by metamaterials containing conducting nonmagnetic resonant elements, which, nevertheless, possess artificial magnetism and negative refraction in microwave and optical bands. Recently, special interest has been attracted to metamaterials containing various combinations of inclusions and possessing properties not resulting from simple superposition of the properties of these inclusions. In particular, nonadditive nonreciprocal effects were observed in metastructures consisting of a transversely magnetized ferrite plate and an array of resonant elements. Nonreciprocal passage of microwaves at the ferromagnetic resonance (FMR) frequency is observed if the metastructure is arranged along the waveguide axis or in free space, whereas it is absent in the case of free ferrite [1]. In [2], nonreciprocal splitting of the resonance into a multitude of peaks was observed at the grating frequency [2]. In [3], it was shown that the use of helices with an inserted nonlinear element (varactor) results in nonlinear optical activity. In [4], nonlinear magnetoelectric coupling at microwaves was demonstrated. In this case, the metamaterial acquires new properties, which are absent in natural materials.

In this letter, we propose a metastructure making it possible to achieve nonreciprocal passage of microwaves that can be controlled not only by a magnetic field, but by a constant electric field as well. Hitherto, the means of control of nonreciprocity in known materials, including metamaterials, were restricted to the magnetic field. On the other hand, recently, the electric control of the resonance response by means of varactors inserted into the gaps of resonant elements, which was proposed in [5] for a double-split ring, has been being successfully developed. The capacitance of the varactors and, therefore, the frequency of the resonance response can be varied by varying the constant back bias voltage supplied to the varactor's contacts.

The metastructure under study is shown in Fig. 1. It involves a 30 × 20 × 1.4-mm plate of iron–yttrium garnet $3Y_2O_3 \cdot 5Fe_2O_3$ near which a double split ring made of polyamide film on copper foil is placed on a 0.5-mm-thick hardened paper substrate at distance s. Two BB857 varactors with a capacitance variable from 6.5 to 0.65 pF by supplying back bias voltage V_{DC} from 0 to 30 V are symmetrically welded face-to-face into the gaps in the rings with width τ. The sizes of the ring are chosen so that the resonance response in the absence of a magnetic field will be observed in the given range 3–6 GHz of the voltage standing wave ratio (VSWR) panoramic measurer. Resistors with $R_L = 100$ kΩ are connected to the wires from the feed source in order to reduce microwave pickups and eliminate possible excitation of parasitic resonances. The metastructure is placed into a 48 × 24-mm rectangular waveguide in parallel with the side wall so that the ferrite plate is directed along the waveguide axis. Field E is parallel to the line connecting the gap edges in the ring. The frequency dependences of transmission coefficients T are measured at different values of the transverse magnetic field parallel to the ferrite plate; H_+ and H_- correspond to different directions of magnetization. The evolution of T with variation in the constant back bias voltage V_{DC} is studied.

Figures 2a and 2b show the frequency dependences of T with the metastructure for $s = 3$ mm and

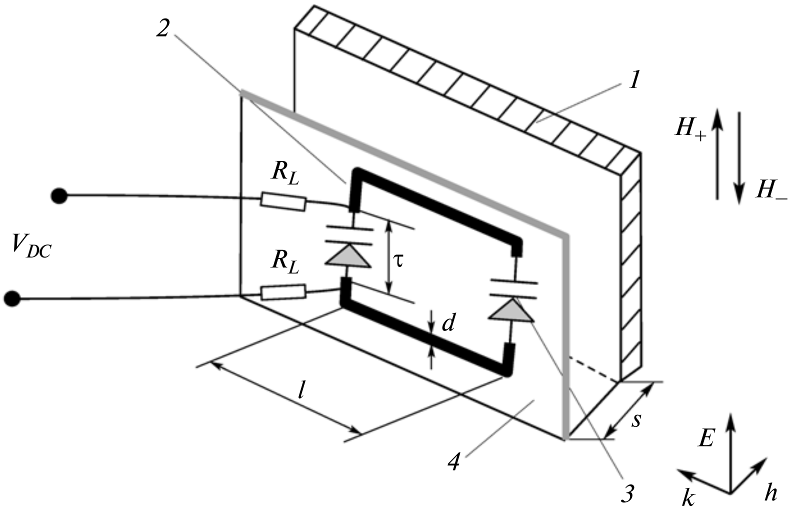

Fig. 1. Planar metastructure "ferrite plate *1*—double-split ring *2* loaded by two BB857 varactors," hardened paper substrate *4*, resistors $R_L = 100$ kΩ, $l = 18$ mm, $\tau = 1.5$ mm, and $d = 3$ mm.

$H =$ (a) 500 and (b) 900 Oe. It is evident from Fig. 2a that, in the absence of the magnetic field ($H = 0$) and in the absence of back bias voltage ($V_{DC} = 0$), a resonant minimum $I_{0,\,0\mathrm{V}}$, depending on the geometry of the ring, is observed at the frequency of 4.2 GHz. The curve $I_{0,\,0\mathrm{V}}$ can be effectively moved to the position of $I_{H,\,DC}$ in a limited frequency interval by imposing a field H and (or) supplying a voltage V_{DC} onto it. For example, after imposing a field $H = 500$ Oe (Fig. 2a), the resonance minimum T (curve $I_{H,\,DC}$) is observed at the frequency of 4.6 GHz and the displacement of the resonance minimum T from the initial position $I_{0,\,0\mathrm{V}}$ is $\Delta f_H = f(I_{H,\,0\mathrm{V}}) - f(I_{0,\,0\mathrm{V}}) = 0.4$ GHz. In this case, the passage of microwaves in the region of the resonance $I_{H,\,0\mathrm{V}}$ becomes nonmutial. In the region of $I_{H,\,0\mathrm{V}}$, nonreciprocity parameter $\delta = T_{H^+} - T_{H_-}$, defined as the difference between the passages for different directions of magnetization or different directions of microwave propagation, attains 15.5 dB. After supplying the back bias voltage, the region of nonreciprocal passage is displaced; for $V_{DC} = 20$ V, the resonant minimum $T(I_{H,\,20\mathrm{V}})$ is observed at the frequency of 5.25 GHz, the displacement is $\Delta f_{DC} = f(I_{H,\,20\mathrm{V}}) - f(I_{\mathrm{H},\,0\mathrm{V}}) =$ 0.65 GHz, and parameter δ is practically the same ($\delta_{DC} =$ 12.8 dB). In this case, nonreciprocal resonant response $I_{H,\,DC}$ is observed in a magnetic field substantially lower than in the case of FMR excitation at this frequency. In addition, the response $I_{H,\,DC}$ is controlled in a bounded frequency range, which makes it easily detectable and distinguishable from the FMR response. For $H = 500$ Oe, the FMR is excited at lower frequencies (near 3 GHz) and, in contrast to free ferrite, in the region of the FMR, at certain frequencies, dependence on the direction of field H is observed.

With an increase in field H, the FMR moves toward higher frequencies, approaching the region of the resonance $I_{H,\,DC}$. In this case, a bifurcation effect takes place: in addition to the resonance $I_{H,\,DC}$, the resonance $I'_{H,\,DC}$ below the $I_{0,\,0\mathrm{V}}$ is excited. Figure 2b demonstrates the electrically controlled nonreciprocal passage in the bifurcation conditions on imposition of field $H = 900$ Oe, when the FMR reaches its original position $I_{0,\,0\mathrm{V}}$. In this case, the resonance region $I_{H,\,0\mathrm{V}}$ is found at the frequencies about 5.4 GHz, having displaced from its original position (4.2 GHz) by $\Delta f_H =$ 1.2 GHz, and the region $I'_{H,\,0\mathrm{V}}$ manifests itself with the opposite sign of the nonreciprocity δ at frequencies about 3.36 GHz. Both resonance regions $I_{H,\,0\mathrm{V}}$ and $I'_{H,\,0\mathrm{V}}$ are electrically controllable and conserve the nonreciprocity parameter, being displaced at $V_{DC} = 20$ V to the positions $I_{H,\,20\mathrm{V}}$ and $I'_{H,\,20\mathrm{V}}$, respectively, by $\Delta f_{DC} = 0.29$ GHz and $\Delta f'_{DC} = 0.27$ GHz to the frequencies of 5.69 and 3.63 GHz. In turn, the passage in the FMR region is nonreciprocal; in this case, after supplying back voltage $V_{DC} = 20$ V, the value of nonreciprocity changes and the FMR frequency band remains fixed, in contrast to regions I and I'.

By reducing distance s and, as a result, increasing the coupling between the ferrite and the ring, we can expand the range of retuning resonance I by the magnetic field. Figures 2c–2e present the results of the study in the case of $s = 0$. As is evident from Fig. 2c, after imposing field $H = 500$ Oe, resonance $I_{0,\,0\mathrm{V}}$ is displaced by $\Delta f_H = 1.1$ GHz from the original position at 4.3 GHz to the frequency of 5.4 GHz, which substantially exceeds the corresponding displacement in the case of $s = 3$ mm. In this case, we also observe an increase in the nonreciprocity parameter ($\delta = 19$ dB),

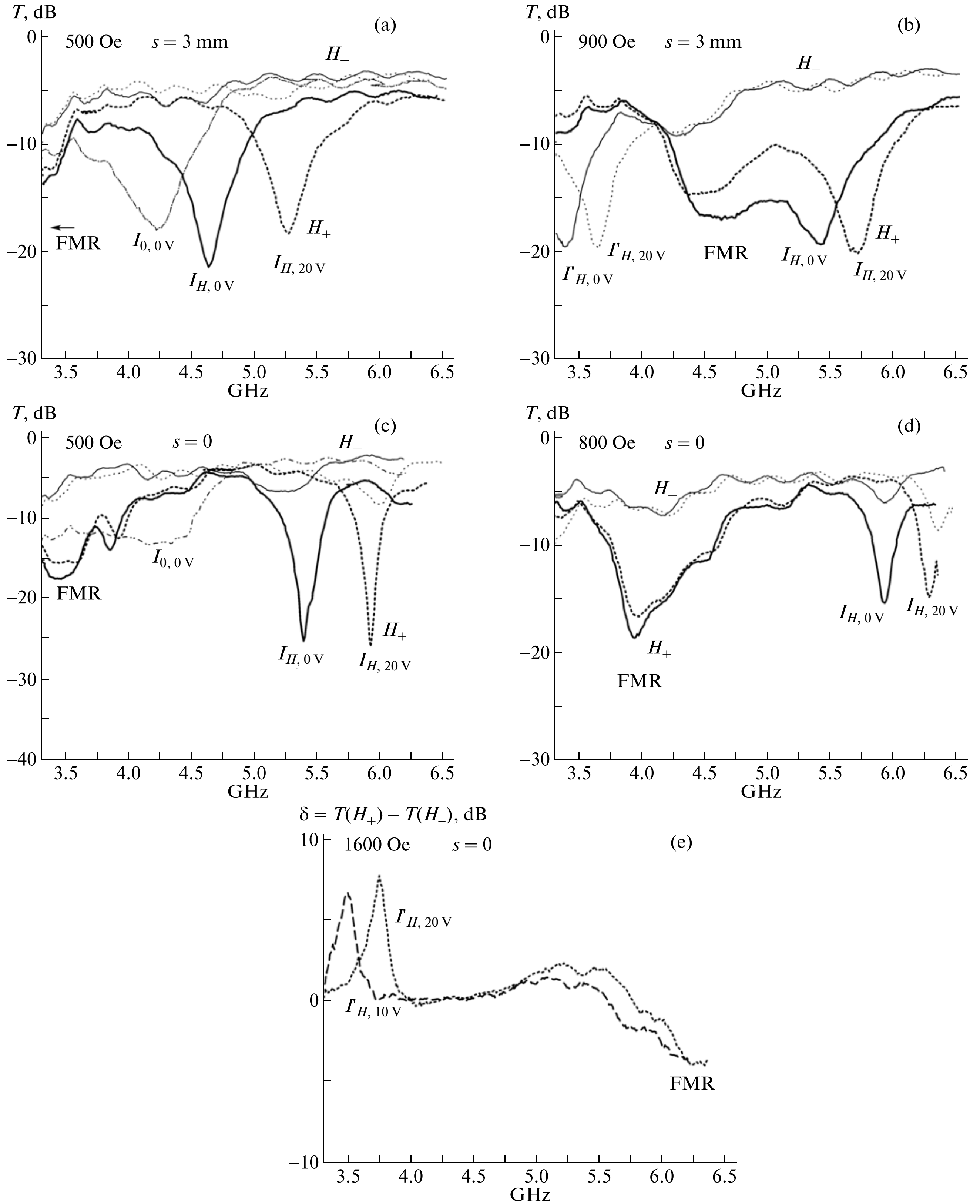

Fig. 2. Frequency dependences of the transmission coefficient T in a rectangular waveguide with a metastructure; the distance between the ferrite plate and the ring is $s =$ (a, b) 3 mm and (c, d, e) 0 and $H =$ (a, c) 500, (b) 900, (d) 800, and (e) 1600 Oe. Curves for (bold lines) H_+ and (solid lines) H_- correspond to different directions of magnetization, i.e., different spin precession directions; solid curves correspond to the absence of back bias voltage, and dashed lines correspond to $V_{DC} = 20$ V, and the dash-and-dot curve corresponds to $H = 0$ and $V_{DC} = 0$.

which is preserved as V_{DC} varies from 0 to 20 V, when nonreciprocal passage region $I_{H,\,DC}$ is additionally displaced by $\Delta f_{DC} = 0.53$ GHz. With a further increase in the magnetic field ($H = 800$ Oe, Fig. 2d) and approach to the FMR, in addition to the continuing frequency displacement, we observe weakening of the resonance minimum $I_{H,\,DC}$ of transmission coefficient T and a decrease in the nonreciprocity parameter ($\delta = 9.4$ dB). In this case, as V_{DC} varies from 0 to 20 V, nonreciprocal passage region $I_{H,\,DC}$ is displaced by $\Delta f_{DC} = 0.35$ GHz, whereas the nonreciprocal passage frequency band in the region of the FMR remains practically fixed. Here, resonance $I'_{H,\,DC}$ manifests itself at frequencies below the range of the panoramic SWR measurer. Within the measured range, we cannot directly measure the distance between peaks I and I', because, with an increase in field H and manifestation of resonance I' in the given range resonance I becomes unobservable, being displaced toward high frequencies beyond the measured range. Thus, in the case of $s = 0$, the distance $\Delta f_{II'}$ between the peaks $I_{H,\,DC}$ and $I'_{H,\,DC}$ exceeds the range of measurements (3–6 GHz) and substantially exceeds $\Delta f_{II'} = 2$ GHz for $s = 3$ mm (Fig. 2b). With a further increase in the field, the FMR approaches resonance $I_{H,\,DC}$ and, having merged with it, moves toward higher frequencies. Resonance $I'_{H,\,DC}$ approaches the original position, and the nonreciprocity of microwave passage in region $I'_{H,\,DC}$ decreases (Fig. 2e). In strong magnetic fields, when the FMR is far from resonance $I'_{H,\,DC}$, the properties of the FMR tend to the properties of the FMR of free ferrite and the properties of the resonance $I'_{H,\,DC}$ tend to the properties of a free ring for which the ferrite plate plays the role of a dielectric substrate. In this case, the nonreciprocity of passage of microwaves both in the FMR region and in the vicinity of resonance $I'_{H,\,DC}$ totally disappears.

Thus, it has been found that resonant response I connected with the ring in the presence of magnetic field H is nonreciprocal and its frequency and intensity vary with the magnitude of H. This fact is caused by the interaction of the precessing spin of ferrite with the magnetic field of the surface wave formed by the ring. It has also been found that, as voltage V_{DC} across the varactor varies from 0 to 20 V, along with retuning of frequency I, the nonreciprocal passage band is also retuned. The retuning with preservation of the nonreciprocity parameter, which equals 19 dB, attains 10%.

The studied metastructures are of undoubted interest for development of rapidly controlled nonreciprocal devices.

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