Metasandwich Ferrite Plate/Wire Grating/Longitudinal Copper Strip with Varactor to Achieving Controlled Microwave Nonreciprocal Absorption

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Abstract— ThreeClayer metasandwich ferrite plate/periodical wire grating/varactorloaded orthogonal asymmetrical strip is proposed, realized and investigated experimentally in rectangular waveguide at microwaves. It has been shown that metasandwich possesses electrically/magnetically controlled nonreciprocal microwave resonance absorbing of linearly polarized magnetic field of incident wave and not strong forward losses under multi-coupled resonances.

1. INTRODUCTION

As is well known nonreciprocal effects at microwaves are based on ferromagnetic resonance (FMR) [1] and Faraday rotation. At present there are ideas about artificial Faraday rotation in magnetless metamaterials without gyrotropic component [2].

In this paper nonreciprocal effect is due to the FMR in ferrite. The effect is related to the fact that the power of wave is absorbed by ferrite when a static magnetic field H_0 corresponding to the FMR is applied and senses of spins precession and rotating microwave magnetic field h are the same while absorption is practically absent when these senses of precession and rotating h-field are opposite. Nonreciprocal microwave devices require circular or elliptical polarization of microwave magnetic field. Waveguide nonreciprocal devices contain transversely magnetized ferrite plate at distance of $\pm\lambda/8$ from the side wall in a rectangular waveguide, where polarization of microwave magnetic field is circular [1]. Interesting effects have been noticed by using combination of ferrite with wires [3–6]. It has been found nonreciprocity of waveguide characteristics of electromagnetic waves in ferrite slab periodically loaded with metal strip [3, 4]. Periodic strip arrays on ferrite substrate have been discussed in [5]. Surface waves and applications for antenna investigated in wire media-ferrite [6].

In metastructures which contain ferrite plate and grating of resonant conductive elements (chains or individual element) one can observe nonreciprocal effects with linearly polarized magnetic field of incident wave [7–11]. In this case grating forms elliptically polarized magnetic field of surface wave below resonance frequency and provides nonreciprocal absorption under FMR excited near grating resonance at frequency domain of surface wave existence [8]. Besides it is appeared new functional possibility as both magnetic and fast voltage control of amplitude-frequency characteristics [9–11] in contrast to traditional only magnetic control with free ferrite by magnetostatic magnetic field H. But there are problems in the case of individual elements because really they can not form polarization close to circular in every ferrite spot and nonreciprocal effects are observed against the background of losses.

This paper is aimed at overcoming difficulties above by using periodical grating composed of closely spaced finite-length parallel microwires. In this case there is possibility to achieve fast electric control with set of varactors-loaded all grating wires. But it is difficult to realize.

We propose three-layer metasandwich ferrite plate/grating composed of closely spaced finite-length parallel microwires/orthogonal longitudinal varactor-loaded copper strip arranged asymmetrically. Ferrite is necessary for FMR excitation. Wire grating is used for forming close to circular polarization of microwave magnetic field in every ferrite spot. Varactor-loaded longitudinal strip provides voltage control instead of set of varactor-loaded wires using only wire grating. Resonance effects in two-layer metasandwich wire grating/one orthogonal wire without ferrite has been investigated in [12].

Here we measure transmission coefficients in rectangular waveguide with three-layer metasandwich placed along waveguide axis by single-channel measurement method. Dependences on geometry and sizes as well on static magnetic field and voltage are investigated. Metasandwich shows nonreciprocal multi-resonance effects: ferromagnetic in ferrite excited by application of static magnetic field; resonance in wires of grating excited by microwave electric field (marked below as I);

resonance excited by antiparallel currents with microwave magnetic field in set of U-circuits formed by neighbouring wires of grating and section of longitudinal strip (marked as II); resonance excited in longitudinal strip (marked as III). Voltage control of nonreciprocal properties (both shift of non-reciprocal frequency bands and reversal of unidirectional microwave propagation) is achieved under coupled multi-resonance effects.

2. INVESTIGATED METASTRUCTURES

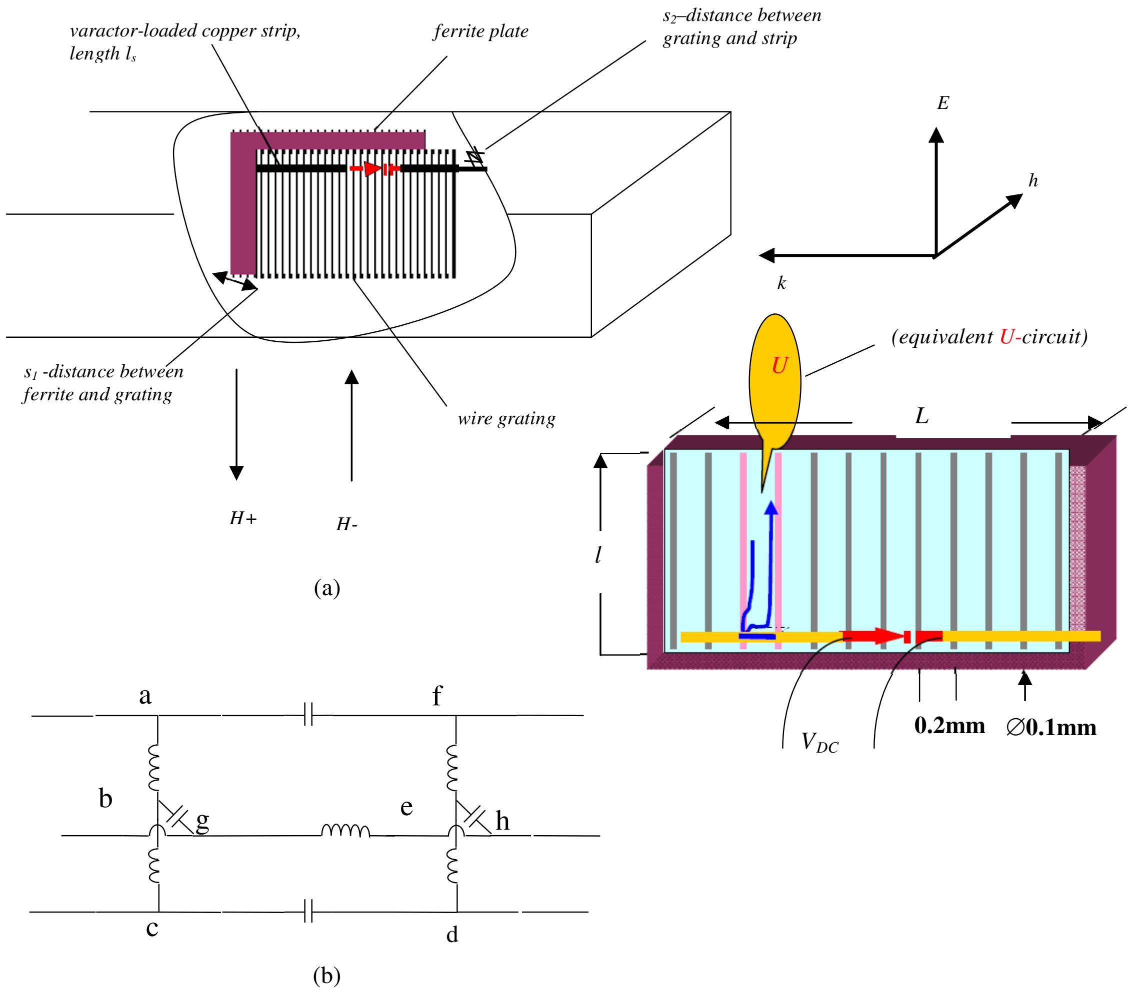


Figure 1. Tree-layer metasandwich: (a) design, (b) equivalent electric diagram of unit cell.

Tree-layer metasandwich under study and its disposition in rectangular waveguide with respect to incident wave as well equivalent electric diagram of unit cell is presented in Figs. 1(a), (b).

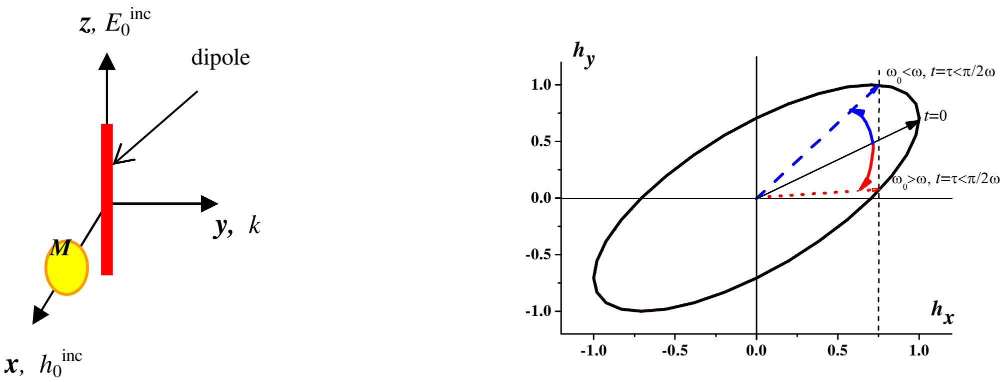
The first layer is ferrite plate. The second layer is periodical grating of closely spaced finite-length parallel microwires embedded into dielectric film. The third layer contains one varactor-loaded longitudinal strip arranged asymmetrically and orthogonally with respect to grating wires at distance s_2.

Ferrite provides the FMR excitation under applied transverse static magnetic field H. FMR is due to resonance absorbing of microwave field power in ferrite.

The grating is necessary to form close circular polarization of surface wave magnetic field in every ferrite spot and provide nonreciprocity of the FMR. Grating of wires l parallel to the E-field exhibits a resonance response (I) of the electric type and characterized by a resonance dependence of the transmission coefficient with a minimum at a certain frequency dependent on the wire length l. This grating is excited by the E-field (induction of parallel currents) and generates surface waves near resonance I (below the resonance frequency).

It has been shown theoretically [13] that the microwave magnetic field near dipole, which is excited by a plane wave, possesses elliptical polarization at frequencies around the dipole resonance

(DR) as a result of superposition of the incident and scattered fields. Total magnetic field rotates in one direction at frequencies above the DR and in the opposite direction below the DR. Besides senses of rotation are opposite on the opposite side of dipole (from the right or from the left). Fig. 2 presents calculated time-dependent rotating normalized total magnetic H-field. One can see that left-handed h-field takes place at frequencies $\omega > \omega_0$, $\omega_0 = (LC)^{-1/2}$ is the dipole resonance frequency, while right-handed H-field corresponds to $\omega < \omega_0$.



(a) (b)

Figure 2. Disposition of dipole and ferrite with respect to incident wave (a) and movement of normalized total microwave magnetic field h (b). M denotes point of location of ferrite, k, E_0^{inc}, h_0^{inc} are wave, electric and magnetic vectors of incident wave. Straight pointers depict field h in instants of time $t = 0$ (solid) and $t = \tau < p/2\omega$ (dash and dot). Curved pointers depict sense of rotation of h. Blue dash lines correspond to $\omega_0 < \omega$. Red dot lines correspond to $\omega_0 > \omega$.

Indeed, a plane electromagnetic wave

$$\vec{E}^{inc} = \vec{e}_z \frac{1}{2}\left\{E_{0z}^{inc}\exp[i(\omega t - ky)] + c.c.\right\}, \quad \vec{H}^{inc} = \vec{e}_x \frac{1}{2}\left\{H_{0x}^{inc}\exp[i(\omega t - ky)] + c.c.\right\} \tag{1}$$

falls onto a dipole that is placed as it is pictured in Fig. 3. Here $\vec{e}_j$ are the coordinate orts, wave number $k = 2\pi/\lambda$ and the dipole length l. The ratio of electric and magnetic amplitudes is equal to the vacuum wave impedance $Z_0 = E_{0z}^{inc}/H_{0x}^{inc}$.

The scattered wave is characterized by complex amplitudes of projections of its magnetic field which in spherical coordinates are

$$H_\varphi^{scat} = \frac{I_z l}{4\pi}\sin\theta\left(\frac{\exp(-ikr)}{r^2} + ik\frac{\exp(-ikr)}{r}\right), \quad H_\varphi^{scat} = H_r^{scat} = 0. \tag{2}$$

Magnetic fields of both incident and scattered waves are plane-polarized. Superposition at points $\mathcal{M}_0$ $(r,\ \theta = \pi/2,\ \varphi = 0)$ and $\mathcal{M}_\pi$ $(r,\ \theta = \pi/2,\ \varphi = \pi)$ that are placed in the entry plane $(y = 0)$ symmetrically with respect to the dipole shows that normalized total magnetic field in this points is equal to

$$\vec{h}(t) = \vec{H}/H_{x0}^{inc} = \vec{e}_x h_x(t) + \vec{e}_y h_y(t) = \vec{e}_x \cos\omega t + \vec{e}_y G\cos(\omega t + \beta). \tag{3}$$

Magnitude $G = \pm\frac{Z_0 l^2}{4\pi Z r^2}\sqrt{1 + k^2 r^2}$, "+" and "−" refer correspondingly to points $\mathcal{M}_0$ and $\mathcal{M}_\pi$. Turning the coordinate system around z-axis on the angle $\Phi = 0.5\tan^{-1}(2G\cos\beta/(1 - G^2))$ one can obtain that the magnetic field projections on new axes x', y' satisfy the canonical ellipse equation

$$h_{x'}^2 b_{x'}^{-2} + h_{y'}^2 b_{y'}^{-2} = 1. \tag{4}$$

Besides, local transverse magnetic field of surface wave inducts electromotive forces and antiparallel currents in many spatial U-circuits created from cut-wire pairs of a grating and section of longitudinal strip and like-directed currents along longitudinal strip. (Resonance response II).

In the case of asymmetrically located strip, if length l_s is resonant, the wave of current along strip l_s and the resonance response (marked as resonance III) are very strong. Its resonance frequency depends on length l_s and distance s_2.

Four resonant effects connected with ferrite (FMR), grating (I), U-circuits (II) and with longitudinal cut-strip (III) can be separately observed. The first resonance is due to the ferromagnetic resonance (FMR) excitation in ferrite. The second resonance is due to parallel currents induction in grating's wires l, the third resonance effect is due to excitation of antiparallel currents in U-circuits and the fourth resonance is due to contribute of total currents from U-circuits along longitudinal cutstrip l_s.

If resonance frequencies of the FMR, I, II and III are close, interaction between corresponding resonances are achieved. In this case resonances I, II and III acquire nonreciprocal properties and varactor-loaded strip can control both resonance III of strip and I of grating and II of U-circuits.

3. MEASUREMENTS METHODS

It is known that when required for the FMR excitation field H is applied and senses of the spins precession around H and rotating microwave magnetic field h are the same, power of the wave is absorbed by a ferrite. In the case when senses of precession and h-field rotating are opposite, absorption is absent. Senses of the H-field rotating are opposite for forward and counter-propagating waves. Senses of the spins precession are opposite for opposite direction of magnetization. The nonreciprocity δT (dB) of microwave propagation is characterized as a difference between transmission coefficients T (dB) for two situations. In the first situation senses of spin precession and rotating h-field are the same. In the second situation senses of spin precession and rotating h-field are opposite. We use single-channel measurements. In this case, the nonreciprocity δT can be defined not by reversal of the propagation direction as usual but as the difference between T corresponding to the opposite directions of magnetization, when senses of h-field rotation are the same but senses of spin precession are opposite.

$$\delta T(\text{dB}) = T(H-) - T(H+). \tag{5}$$

$H-$ and $H+$ correspond to opposite directions of the external transverse field H (magnitudes of H-field are the same). In this case senses of h-field rotation are the same but senses of spins precession are opposite.

We measure frequency dependences of transmission coefficients T in rectangular waveguide with metasandwiches placed along waveguide axis and analyze nonreciprocal properties δT in dependence on metasandwich geometry, applied magnetic field $H-$ and $H+$ as well on voltage V_{DC}.

4. EXPERIMENTAL RESULTS

Here we present experimental results for following configuration of metasandwich.

The first layer is ferrite plate of polycrystalline iron-yttrium garnet ($21 \times 14 \times 2$ mm) placed along waveguide (48×24 mm) axis. The second layer contains varactor-loaded longitudinal strip of length $ls = 27$ mm placed on a 2-mm-thick textolite substrate arranged asymmetrically and orthogonally with respect to grating wires at distance 1.5 mm from ferrite. The third layer is periodical grating of closely spaced finite-length parallel microwires (wire length $l = 22$ mm), which is placed close to substrate. Varactor MA46H120 (MACOM), with capacitance varying from 1 to o.15 pF by supplying back bias voltage VDC from 0 to 30 V, is welded into the gap of strip.

The sizes of wires are chosen so that the resonances I, II and III will be observed in the given range 3–6 GHz of the voltage standing wave ratio (VSWR) panoramic measurer.

Figures 3 and 4 show measured frequency dependences of transmission coefficients T and nonreciprocity δT in rectangular waveguide with metasandwich. We see nonreciprocal frequency bands and their evolution by voltage variation under FMR excitation near resonances of wire grating and strip with different magnitudes of static magnetic field H. The $H-$ (bold) curves and $H+$ (thin) curves correspond to the opposite directions of magnetization, i.e., to opposite rotational sense of the spins precession.

Figure 3 corresponds to $H = 230$ Oe, in this case the nonreciprocal FMR is excited lower then resonance III (in strip), II and I (in U-circuits and wire grating). The FMR is observed about 3.5 GHz and not shifted by bias voltage. We see retuned voltage nonreciprocal bands III connected with varactor-loaded strip.

Figures 4(a), (b), (c) correspond to the FMR excitation at about 4.7 GHz under $H = 1000$ Oe. When electrically retuned resonance III approaches to the FMR, regime of coupled resonances is achieved. When resonance III passes through frequency of the FMR, one can observe inversion of δT sign by VDC variation at the same frequency band (static magnetic H-field is invariable) as Figures 4(b) and 4(c) demonstrate. Inversion of the sign of δT means switching direction of nonreciprocal propagation.

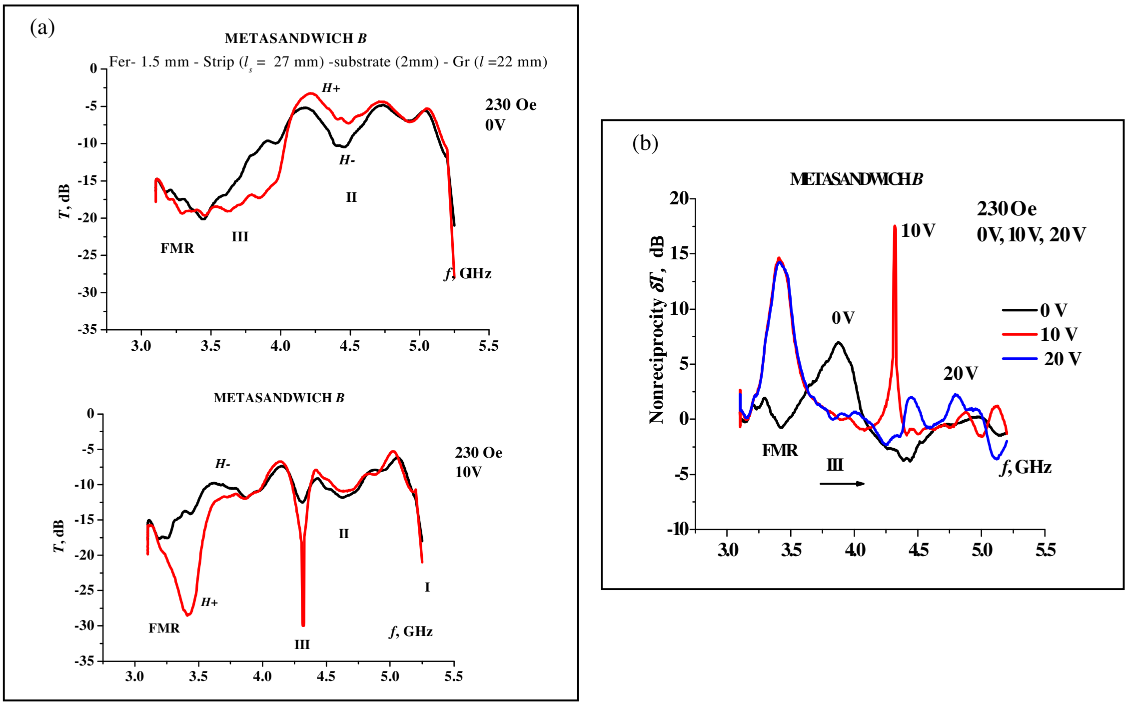


Figure 3. Measured T and δT with voltage V_{DC} variations at $H = 230\,\text{Oe}$: (a) frequency dependences of T, (b) frequency dependences of δT.

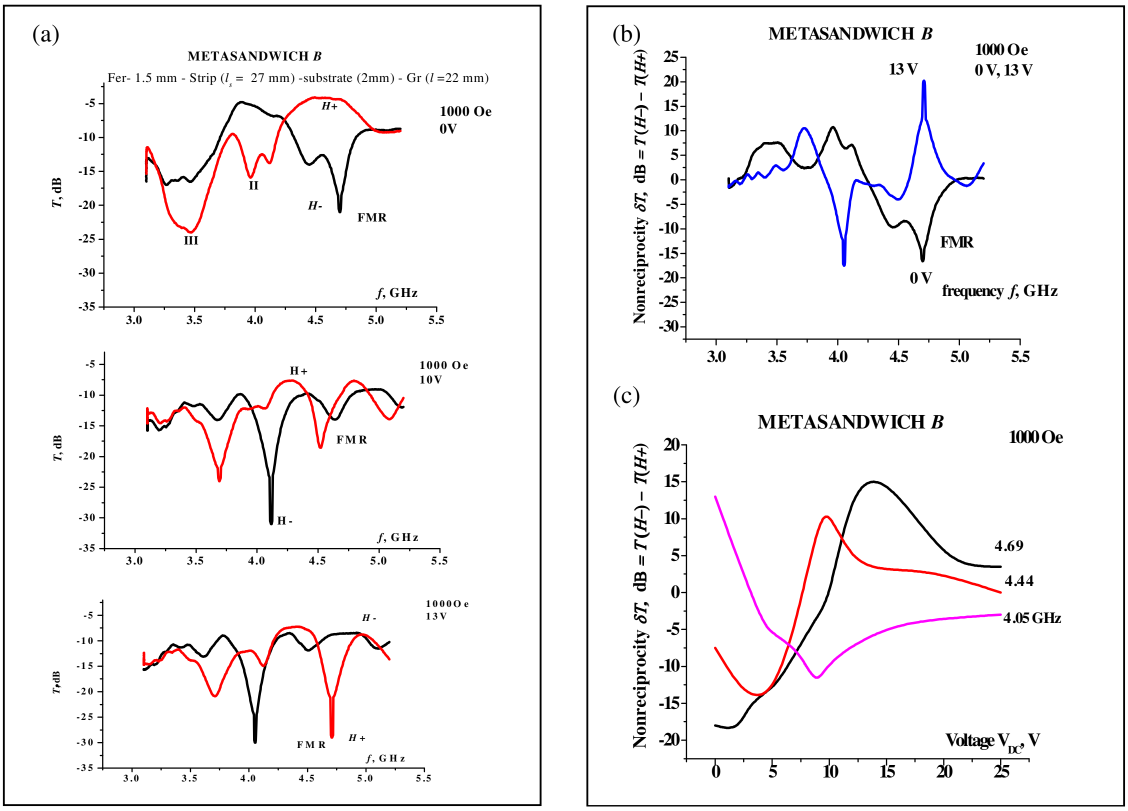


Figure 4. Measured T and δT with voltage V_{DC} variations at $H = 1000\,\text{Oe}$: (a) frequency dependences of T, (b) frequency dependences of δT, (c) dependences of δT on V_{DC} at fixed frequencies.

5. CONCLUSIONS

Metasandwich that consisted of ferrite plate and combination of cut-wire grating with varactor-loaded longitudinal strip (or longitudinal cut-wire) can possess electric controllability of nonreciprocal absorbing in the form of retuning nonreciprocal frequency bands as well of inversion of the sign of nonreciprocity δT at the same frequency of certain domains by voltage variation. Inversion of the sign of δT means switching direction of nonreciprocal propagation.

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