Reversal of Microwave Propagation Nonreciprocity in Metastructures by Voltage Application under Ferromagnetic Resonance Excitation near Resonance of Dipole or Chiral Elements

G. A. Kraftmakher, V. S. Butylkin, and Yu. N. Kazantsev
Kotelnikov Institute of Radioengineering & Electronics, RAS, Russia

Abstract— Ferrite plate/varactor-loaded conductive resonance elements (chains or single element) metastructures are investigated experimentally in waveguide to achieving voltage controlled inversion of sign of the nonreciprocity δ of microwave propagation. Dipoles of various shapes (butterfly, loop, snake, double split rings) with different type-varactors have been investigated. The metastructures show unique magnetically and electrically controlled nonreciprocal effects under coupled ferromagnetic resonance (FMR) in ferrite and resonance in dipoles (DR). Inversion of sign of δ occurs by the application of a bias voltage to a varactor when resonance frequency of DR passes through the FMR frequency as a result of which reversal of sense of rotating elliptically polarized h-field takes place. Usually inversion of nonreciprocal propagation of microwaves in ferrite is implemented by reversal of magnetization direction as a result of which reversal of sense of spins precession occurs.

1. INTRODUCTION

In recent years, there has been increasing interest in the study of resonance metamaterials on basis of resonant conductive elements [1, 2] as well nonreciprocal metamaterials, containing combination of ferrite and resonance elements, with tunable or switchable characteristics for development of microwave devices such as filters, nonreciprocal isolators and circulators. The emphasis is novel functionality as the fast electric control of amplitude-frequency characteristics in comparison with traditional [3] magnetic control of ferrite by external static magnetic field. In the case of magnetic control time switching is not so fast because one depends on not fast enough complex processes of magnetization and remagnetization. At the present time varactor-loaded split ring are used for electrically tunable filters at microwave frequencies [4] and for tunable nonlinear phenomena [5]. Besides, electric field tunable ferromagnetic resonance (FMR) response is investigated in ferromagnetic-ferroelectric heterostructures through the voltage controlled dielectric permittivity of the ferroelectric layer [6, 7]. Many publications are devoted to fundamental science of multiferroics, materials that simultaneously show ferromagnetism and ferroelectricity and can be controlled by both magnetic and electric field [8]. Nonreciprocity in periodic strip arrays on ferrite-dielectric substrate is discussed and calculated in [9]. At present there are ideas about artificial Faraday rotation in magnetless metamaterials without gyrotropic component [10], but strong losses complicate verification and real application.

We suggest another way by using metastructures containing ferrite plate and grating or chains of conductive resonant elements. The metastructures can show unique resonant nonreciprocal effects in the case when the FMR in ferrite is excited in the neighborhood of resonance of conductive elements [11–15]. It has been observed appearance of nonreciprocity and giant nonreciprocal FMR while there is not nonreciprocity when ferrite is placed without grating.

Recently, it has been observed that planar metastructure, formed by a transversely magnetized ferrite plate and conductive twice-split ring loaded with two varactors, can provide electrically tunable frequency bands of nonreciprocal resonant response and wide tuning range by the application of a bias voltage V_{DC} to a varactor [16, 17]. Dipoles of various shapes (butterfly, loop, snake) with different type-varactors have been investigated; the best frequency change has been reached with butterfly shape and varactor MA46H120 [18].

2. MEASUREMENTS METHODS, EXPERIMENTAL RESULTS

In this paper we demonstrate a way to achieving voltage controlled sign reversal of the nonreciprocity δ in the presence of a static magnetic field H without reversal of the magnetization direction in contrast to traditional magnetic switching magnetization direction.

A governing phenomenon of nonreciprocal microwave devices under consideration is ferromagnetic resonance. In this case circular or elliptical polarization of microwave magnetic field is necessary. 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. In the case of metastructures necessary h-field is formed by the grating of resonant elements.

When a static magnetic field H, required for the FMR excitation, 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 rotation 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 directions of magnetization.

The nonreciprocity δ(dB) of microwave propagation is characterized as difference between transmission coefficients 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. The nonreciprocity δ of microwave propagation can be defined as difference between transmission coefficients for propagating modes in the opposite directions without reversal of magnetization direction, when senses of h-field rotation are opposite but senses of spin precession are the same, nonreciprocity $\delta(\mathrm{dB}) = |S_{21}|^2 - |S_{12}|^2$. The nonreciprocity δ can be also defined without reversal of the propagation direction (single-channel measurements). In this case nonreciprocity δ (dB) is defined as the difference between transmission coefficients $T = |S_{21}|^2$ corresponding to the opposite direction of magnetization, when senses of h-field rotation are the same but senses of spin precession are opposite, $\delta(\mathrm{dB}) = T(H_-) - T(H_+)$. $\mathbf{H}_+$ and $\mathbf{H}_-$ correspond to opposite directions of the external transverse static magnetic field H and provide opposite senses of spins precession.

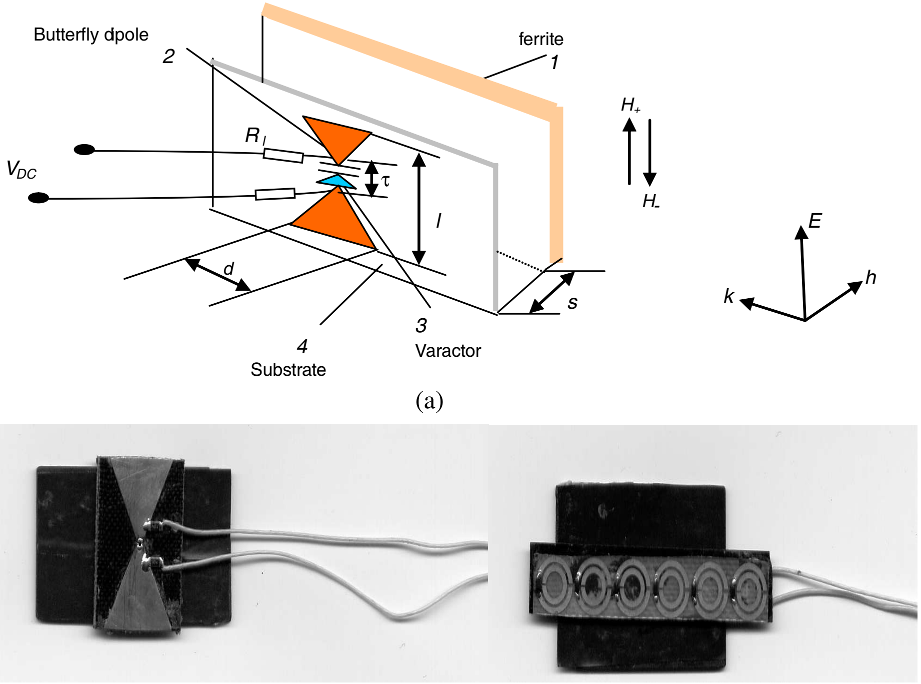
Below the suggested method for reversing the sign of the nonreciprocity is confirmed by direct experimental proofs on a ferrite plate/varactor-loaded split Butterfly dipole metastructure placed along 48 × 24-mm rectangular waveguide axis. The metastructure under study is shown in Fig. 1. It involves a plate of iron-yttrium garnet $3\mathrm{Y_2O_3}\cdot 5\mathrm{Fe_2O_3}$, near which a split Butterfly dipole, made of copper foil on polyimide film, is placed on 0.5-mm-thick hardened paper substrate at distance s. One MA46H120 (MAKOM) varactor, with a capacitance variable from 1 to 0.15 pF by supplying back bias voltage V_{DC} from 0 to 30 V, is welded into the gap in the dipole with width τ. The sizes of the dipole are chosen so that the resonance response will be observed in the given range 3–6 GHz of the voltage standing wave ratio (VSWR) panoramic measurer. Resistors with $R_L = 100\,\mathrm{k\Omega}$ are connected to the wires from the feed source in order to eliminate possible excitation of parasitic resonances. We use single-channel method.

The metastructure shows two resonance minima of T. The first resonance minimum is due to the dipole resonance (DR). The DR is excited by microwave electric field without static magnetic field and can be tuned by application of a bias voltage V_{DC} to a varactor. In Fig. 2(a) we see that under $V_{DC} = 0\,\mathrm{V}$ and $H = 0$ resonance response of metastructure ($\mathrm{DR}_{0,0}$) is observed at 3.6 GHz and shifts to 4.85 GHz with V_{DC} increase to 20 V ($\mathrm{DR}_{0,20}$). The second resonance effect is due to the FMR in ferrite, it is excited in the presence of H-field and controlled by the H-field magnitude. In the case when the FMR approaches to the DR, metastructure acquires nonreciprocal properties which can be controlled by both bias voltage V_{DC} and static magnetic field H in dependence on distance between ferrite plate and dipole. At the same time, it is observed dependence of nonreciprocity sign on the FMR-position relatively to the DR frequency. When position "FMR below DR" changes to "FMR above DR", reversal of sense of rotation of elliptically polarized h-field occurs and sign reversal of the nonreciprocity is observed. One can reverse the nonreciprocity sign by the FMR or DR positional control. To observe this effect in the given frequency range 3–6 GHz of panoramic measurer we correlate the DR frequency by application of a bias voltage V_{DC} to a varactor, the FMR frequency is correlated by application of necessary static magnetic field H (Figs. 2(b), 2(c)). Figs. 2(b), 2(c) shows measured transmission coefficients T in metastructure under different position of the FMR relatively to the DR. Dot curves correspond to the DR in the H-field absence.

Figure 2(b) shows frequency dependences of $T(H_-)$ and $T(H_+)$ at $V_{DC} = 0\,\mathrm{V}$. In this case at $H = 0\,\mathrm{Oe}$, we see only the $\mathrm{DR}_{0,0}$ (dot curve) at 3.6 GHz. With application of static magnetic field $H = 850\,\mathrm{Oe}$, the FMR is excited at about 4.25 GHz and the $\mathrm{DR}_{0,0}$ shifts towards 3.2 GHz. Both the FMR and the DR frequency domains possess nonreciprocal properties with opposite signs of the nonreciprocity: transmission coefficients $T(H_-)$ and $T(H_+)$ are not the same. One can see that in the FMR frequency domain, the sign of δ is positive. In this case the FMR is excited above the

DR.

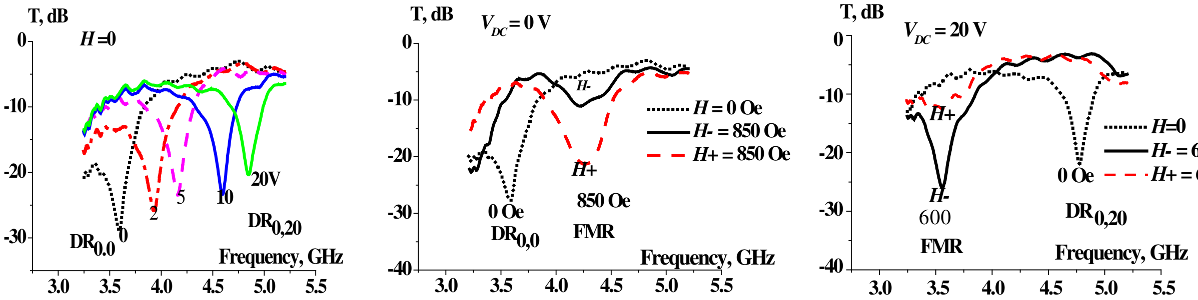
Figure 2(c) shows frequency dependences of $T(H_-)$ and $T(H_+)$ at $V_{DC} = 20\,\text{V}$. In this case the $\text{DR}_{0,20}$ is observed at 4.77 GHz. With application of field $H = 600\,\text{Oe}$ the FMR is excited below the DR at about 3.55 GHz. The sign of δ is getting negative in contrast to Fig. 2(b) ("FMR above DR"). So, nonreciprocity sign depends on the FMR position relatively to the DR.



(a)

(b)

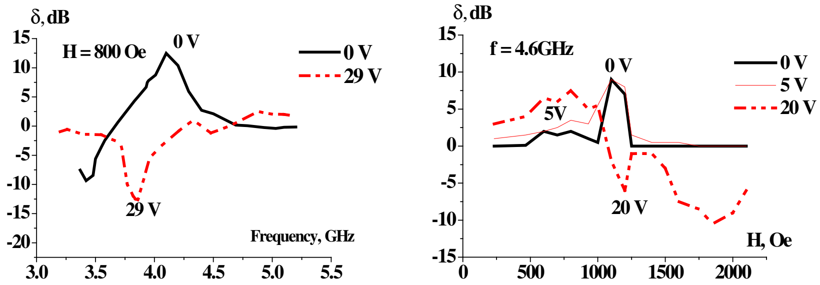
Figure 1: (a) Planar metastructure containing ferrite plate 1 ($30 \times 20 \times 1.9\,\text{mm}$) of iron-yttrium garnet $3\text{Y}_2\text{O}_3{\cdot}5\text{Fe}_2\text{O}_3$ and varactor 3-loaded copper split Butterfly dipole 2; hardened paper substrate 4, resistors $\mathbf{R}_L = 100\,\text{k}\Omega$, $\mathbf{l} = 22\,\text{mm}$, $\boldsymbol{\tau} = 1.5\,\text{mm}$, $\mathbf{d} = 10\,\text{mm}$. $\mathbf{s} = 6.5\,\text{mm}$. Area between ferrite 1 and substrate 4 has been filled with foam and (b) Photos of ferrite plate/varactor loaded split Butterfly dipole and ferrite plate/varactor loaded double split rings metastructures.



(a) (b) (c)

Figure 2: Measured frequency dependences of transmission coefficients T in metastructure; (a) dipole resonance (DR_0) excited by microwave electric field in the absence of external static magnetic field H at different bias voltages V_{DC}; (b) DR below the FMR at $V_{DC} = 0$ and $H = 850\,\text{Oe}$; (c) DR above the FMR at $V_{DC} = 20$, and $H = 600\,\text{Oe}$;.

One can observe sign reversal of δ by only electrical tuning the DR position, if the resonance frequency of a dipole passes through the FMR frequency, as shown in Figs. 3(a), 3(b). Fig. 3(a) presents the frequency dependences of nonreciprocity δ in metastructure ferrite plate/varactor loaded split Butterfly dipole under $H = 800\,\text{Oe}$. In this case the FMR is excited slightly above the DR at the bias voltage $V_{DC} = 0$ and δ sign is positive at frequency domain around 4 GHz. With applying $V_{DC} = 29\,\text{V}$, when the DR passes through the FMR to position "the FMR below the DR", sign of δ is getting negative. At that the FMR position remains practically unchanged.



(a) (b)

Figure 3: (a) Dependences of nonreciprocity δ, dB $= T(H_-) - T(H_+)$ on frequency in metastructure ferrite plate/varactor loaded split Butterfly dipole under $H = 800$ Oe at bias voltage $V_{DC} = 0$ (sign of δ is positive) and $V_{DC} = 29$ V (sign of δ is negative). (b) Dependences of δ on H-field value in metastructure ferrite plate/chains of varactor loaded double split rings under $f = 4.6$ GHz at bias voltage $V_{DC} = 0$, 5, 20 V.

Fig. 3(b) demonstrates sign reversal of δ in dependence on H-field value in ferrite plate/varactor loaded double split rings metastructure under fixed frequency 4.6 GHz at different bias voltages V_{DC}. One can see that at certain values of H-field positive δ at $V_{DC} = 0$ is getting negative at $V_{DC} = 20$ V.

3. CONCLUSION

Observed nonreciprocal effects are due to the FMR, to influence of the DR as well to features of microwave magnetic field h in metastructure. Reversing the sign of the nonreciprocity δ occurs by the application of a bias voltage to a varactor when frequency of the DR passes through the FMR frequency. In this case position "DR below FMR" changes to "DR above FMR" and at the FMR-domain left-handed h-field is transformed into right-handed but sense of spin precession is not changed because direction of H-field is not reversed. Usually reversing sign of the nonreciprocity in ferrite is achieved by not so fast reversal of magnetization direction, as a result of which reversal of sense of spins precession occurs.

Thus, the metastructures ferrite plate/varactor-loaded resonant elements provide fast electrically controlled reversing sign of the nonreciprocity of microwave propagation and open up wide prospects for applications in the field of fast switchable nonreciprocal devices.

REFERENCES

1. Zheludev, N. I. and Yu. S. Kivshar, "From metamaterials to mtadevices," *Nature materials*, Vol. 11, No. 11, 917–924, 2012.
2. Thomas, H. H. and S. A. Cummer, "Controllable magnetic metamaterial using digitally addressable split-ring resonators," *IEEE Antennas and Wireless Propagation Lett.*, Vol. 8, 262–265, 2009.
3. Lax, B. and K. J. Button, *Microwave Ferrites and Ferromagnetics*, McGraw-Hill, New York, 1962.
4. Gil, I., J. Garcia-Garcia, J. Bonache, F. Martin, M. Sorolla, and R. Marques, "Varactor-loaded split ring resonators for tunable notch filters at microwave frequencies," *Electronics Letters*, Vol. 40, No. 21, 1347–1348, 2004.
5. Kapitanova, P. V., A. P. Slobozhnanyuk, I. V. Shadrivov, P. A. Belov, and Y. S. Kivshar, "Competing nonlinerities with metamaterials," *Appl. Phys. Letters*, Vol. 101, No. 23, 231904, 2012.
6. Ustinov, A. B. and G. Srinivasan, "Subterahertz excitations and magnetoelectric effects in hexaferrite-piezoelectric bilayers," *Appl. Phys. Letters*, Vol. 93, No. 14, 142503, 2008.
7. Song, Y.-Y., J. Das, P. Krivosik, N. Mo, and C. E. Patton, "Electric field tunable 60 GHz ferromagnetic resonance response in barium ferrite-barium strontium titanate multiferroic heterostructures," *Appl. Phys. Letters*, Vol. 94, No. 18, 182505, 2009.
8. Pyatakov, A. P. and A. K. Zvezdin, "Magnetoelectric and multiferroic media," *Physics ± Uspekhi*, Vol. 55, No. 6, 557–581, 2012.
9. Cochet, G., A. Vallecchi, A. G. Schuchinsky, and P. Queffelec, "Entwined spiralarrays on ferrite substrate," *6 Int. Congress on Advanced Electromagnetic Materials in Microwaves and Optics*, 215–217, Sankt-Peterburg, Russia, Sept. 17–20, 2012.

10. Kodera, T., D. L. Sounas, and C. Caloz, "Artificial Faraday rotation using a ring metamaterial structure without static magnetic field," *Appl. Phys. Letters*, Vol. 99, No. 3, 031114, 2011.
11. Butylkin, V. S. and G. A. Kraftmakher, "Giant nonreciprocal effect under conditions of mutual influence of ferromagnetic and chiral resonance," *Tech. Phys. Letters.*, Vol. 32, No. 9, 775–778, 2006.
12. Butylkin, V. S. and G. A. Kraftmakher, "Nonreciprocal microwave transmission in metastructures with transversely magnetized ferrite plate and a grating of resonant elements," *Tech. Phys. Letters.*, Vol. 33, No. 10, 856–860, 2007.
13. Butylkin, V. S. and G. A. Kraftmakher, "Nonreciprocal transmission spectrum of a ferrite plate — Resonant element grating metasandwich with split resonance," *Tech. Phys. Letters*, Vol. 35, No. 5, 397–400, 2009.
14. Kraftmakher, G. A. and V. S. Butylkin, "Nonreciprocal amplitude-frequency resonant response of metasandwiches 'ferrite plate-grating of resonant elements'," *Eur. Phys. J. Appl. Phys.* Vol. 49, 33004, 2010.
15. Butylkin, V. S., G. A. Kraftmakher, and V. P. Mal'tsev, "The nonreciprocity of microwave transmission along a bianisotropic-ferrite metastructure," *J. Commun. Technol. Electron.*, Vol. 58, No. 6, 543–550, 2013.
16. Kraftmakher, G. A., V. S. Butylkin, and Yu. N. Kazantsev, "Electrically controlled frequency bands of nonreciprocal passage of microwaves in metastructures," *Tech. Phys. Letters*, Vol. 39, No. 6, 505–508, 2013.
17. Kraftmakher, G. A., V. S. Butylkin, and Yu. N. Kazantsev, "Electrically tunable nonreciprocity of microwave transmission through 'ferrite-varactor loaded resonant element' planar metastructure," *Phys. Status Solidi C*, Vol. 11, Nos. 5–6, 1033–1038, 2014.
18. Kazantsev, Yu. N., G. A. Kraftmakher, and V. P. Mal'tsev, "Methods for resonance frequency tuning ranges of frequency-selective surfaces using varactors," *J. Commun. Technol. Electron.*, Vol. 58, No. 9, 933–939, 2013.