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Sign reversal of the nonreciprocity of microwave propagation in a "ferrite + varactor-loaded dipole" metastructure without reversal of the magnetization direction

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Abstract **–A method for reversing the sign of the nonreciprocity of microwave propagation without reversal of the magnetization direction is proposed and implemented on a "ferrite plate + varactor-loaded split Butterfly dipole" metastructure placed along waveguide axis. The sign of the nonreciprocity is changed when the resonance frequency of a dipole passes through the ferromagnetic resonance frequency due to the application of a bias voltage to a varactor. The metastructures can be useful for fast channel switching in microwave communication systems.**

I. INTRODUCTION

Recently, there has been some interest in the study of resonance and nonreciprocal metamaterials with tunable and switchable characteristics and novel functionalities as the electric control of the nonreciprocity of microwave propagation. Electric tuning of the ferromagnetic resonance (**FMR**) frequency, when nonreciprocity is absent, was observed in ferrite-piezoelectric or ferrite-ferroelectric layered structures through the variation in the permittivity of piezoelectric or ferroelectric layer [1, 2]. In [3 - 6] it has been shown that planar metastructure "ferrite plate + varactor-loaded conductive resonant element" can provide nonreciprocal resonant response of conductive element and wide tuning range due to the application of a bias voltage to a varactor. Electric control of nonreciprocal transmission cannot be achieved with natural materials or traditional ferromagnetic. In this paper for the first time sign reversal of the nonreciprocity is implemented without reversal of the magnetization direction in contrast to traditional magnetic switching by magnetization direction reversal.

II. MAIN RESULTS

Investigated metastructure "ferrite plate + varactor-loaded split Butterfly dipole" is shown in **Fig. 1**. The metastructure is placed in waveguide along waveguide axis. Frequency dependences of transmission coefficients T and the nonreciprocity parameter δ are measured under different bias conditions. Parameter $\delta = T(H_+) - T(H_-)$ is defined as the difference between transmission coefficients T under opposite direction of magnetization (opposite senses of spin precession), that corresponds to the difference between coefficients T for propagation modes in the opposite directions. Our prior experiments have shown intensification of nonreciprocity at the **FMR-**frequency excited nearby the dipole resonance (**DR**) [3, 4] and dependence of nonreciprocity sign on **FMR**-position [5]. When position "**FMR** lower **DR**" changes to "**FMR** higher **DR"** sign reversal of the nonreciprocity is observed. One can reverse the nonreciprocity sign by the **FMR** or **DR** positional control. The **FMR**-position can be tuned by external magnetic field H under practical conservation of **DR-**position (**Fig. 2** shows theoretical calculation for bianisotropic-ferrite metastructure). The **DR**-position can be tuned through change of the varactor's capacitance by varying bias voltage V_{DC} supplied to the varactor's contacts.

Fig. 3 shows the way to achieve sign reversal of the nonreciprocity by the **DR** positional control under necessary conditions of the **FMR**-excitation. In **Fig. 3a** we see that under $H = 0$ and $V_{DC} = 0$ resonance response of metastructure is observed at 3.6 GHz (solid). This response is due to the **DR** which shifts to 4.66 GHz with increase of V_{DC} to 29 V (dot).

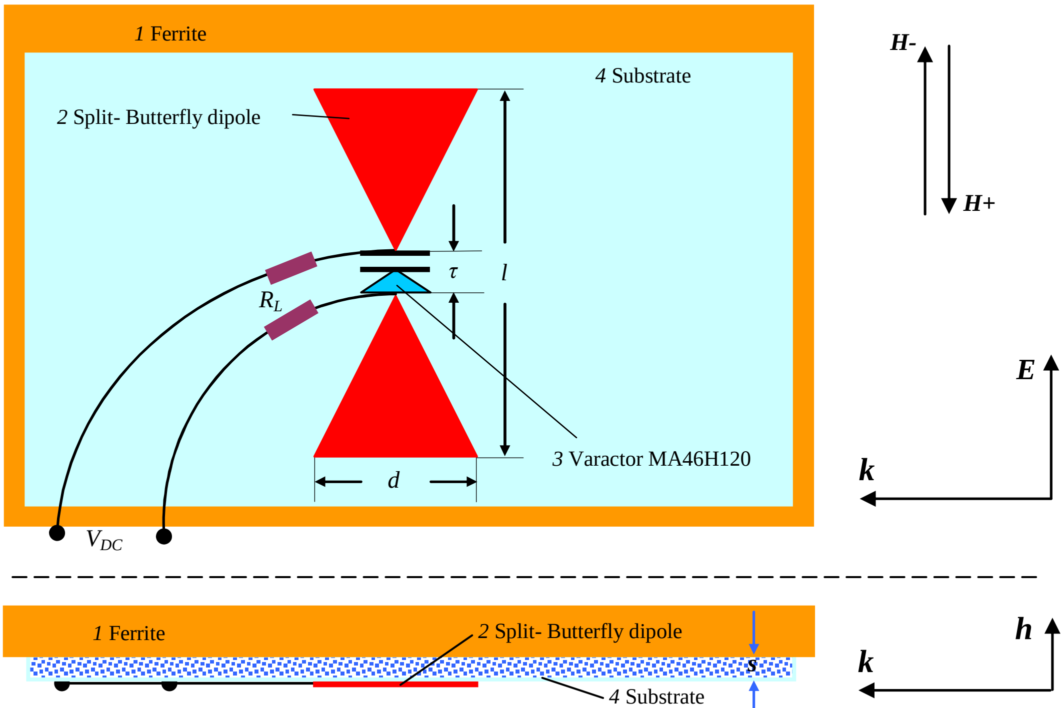

Fig. 1. Planar metastructure containing ferrite plate *1* (30 x 20 x 1.9 mm) of iron-yttrium garnet $3Y_2O_3$ $5Fe_2O_3$ and *3* varactor - loaded copper split Butterfly dipole *2*: textolite substrate *4*, resistors $\boldsymbol{R_L}$ = 100 kΩ, ***l***=22 mm, $\boldsymbol{\tau}$ = 1 mm, ***d*** = 10 mm. ***s*** = 6.5 mm. Area between ferrite *1* and substrate *4* has been filled with foam. $\boldsymbol{H_+}$ and $\boldsymbol{H_-}$ correspond to opposite directions of the external applied field ***H***.

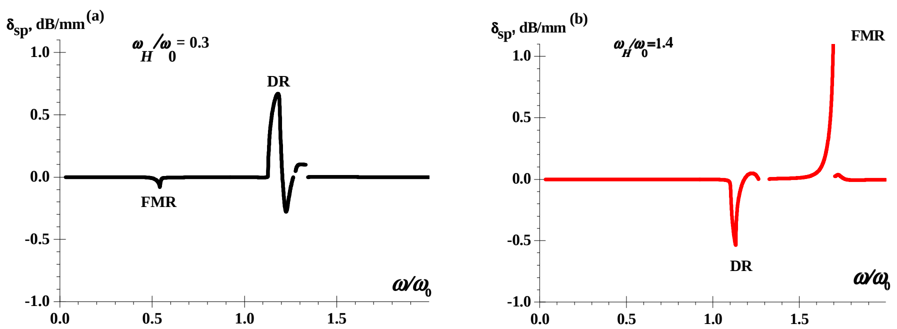

Fig. 2. Calculated specific transmission nonreciprocity parameter δ_{sp} per unit length of a bianisotropic-ferrite metastructure in dependence on relative frequency ω/ω_0 (ω_0 – intrinsic frequency of bianisotropic material dipole elements, ω_H – **FMR** frequency): (a) ω_H/ω_0 =0.3 (**FMR** is excited lower then the dipole resonance **DR**); (b) ω_H/ω_0 =1.4 (**FMR** is excited higher then the **DR).**

Fig. 3b shows resonance response of free ferrite due to the **FMR** excitation near the **DR** in position "**FMR** higher **DR**" (H_1 = 850 Oe, resonance frequency 4.1 GHz, H_2 = 950 Oe, resonance frequency 4.7 GHz)**.**

Fig. 4a shows frequency dependences of the nonreciprocity δ in metastructure under H = 850 Oe at different bias conditions. Nonreciprocity sign is positive at V_{DC} = 0 when the **FMR** is excited higher then the **DR** (solid curve). With applying V_{DC} = 29 V the nonreciprocity sign is getting negative (dot curve), in this case the **DR** passes through the **FMR** to position "**FMR** lower **DR**". At that **FMR** position remains practically unchanged.

Fig. 4b demonstrates sign reversal of the nonreciprocity in dependence on different bias voltages V_{DC} under field H = 850 Oe at fixed frequencies of the **FMR** domain.

Sign reversal of the nonreciprocity can be explained by the interaction between precessing spins of ferrite and microwave magnetic h-field which is superposition of the fields incident and scattered by dipole: the total h-field is elliptically polarized and rotates in one direction at frequencies below and in the opposite direction above the dipole resonance (**DR**).

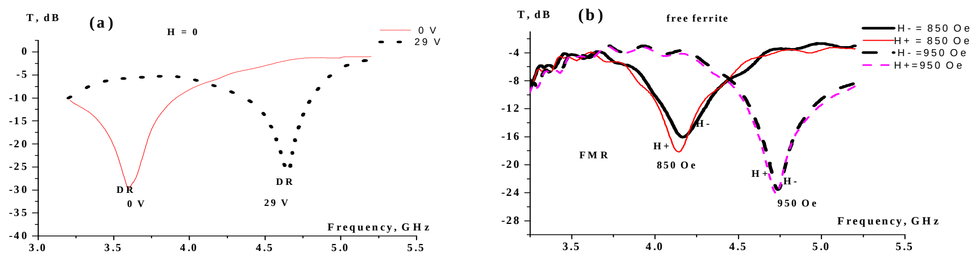

Fig. 3. Measured frequency dependences of transmission coefficients *T*: (a) in metastructure under *H*=0 at different bias conditions, (b) in free ferrite at different values of *H*-field.

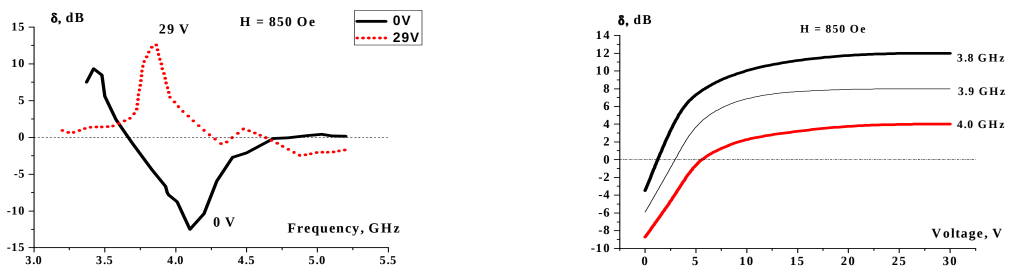

Fig 4. Measured nonreciprocity $\delta = T(H_+) - T(H_-)$ in metastructure, *H*=850 Oe: (a) dependences on frequency at different bias conditions, (b) dependences on V_{DC} at fixed frequencies 4.0, 3.9, 3.8 GHz of the **FMR** domain.

II. Conclusion

It has been shown that metastructure "ferrite plate + varactor - loaded split Butterfly dipole", placed along waveguide axis, can provide sign reversal of the nonreciprocity of microwave propagation at the **FMR** domain, when the resonance frequency of a dipole passes through the **FMR,** due to the application of a bias voltage to a varactor, as a result of which reversal of sense of rotation of elliptically polarized h-field occurs. Presented metastructures are useful for fast channel switching in microwave communication systems.

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