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Voltage tunable nonreciprocity of microwaves transmission with varactor-loaded planar meta-structures

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Abstract **– We suggest new planar meta-structures "ferrite plate – varactor-loaded resonant element" that provide voltage tunable nonreciprocity of microwaves transmission in contrast to traditional magnetic control. The effect is observed by tuning varactor capacitance with changing reverse-bias voltages under the ferromagnetic resonance excitation near the varactor-loaded element resonance frequency. Wide tuning range has been obtained with nonreciprocity 19 dB between 5.4 and 5.9 GHz. Presented meta-structures are useful for development of quick-tunable nonreciprocal systems.**

I. INTRODUCTION

Last time of special interest is the study of voltage tunable varactor-loaded metamaterials. Many publications along with [1] are devoted to voltage tuning through the voltage controlled varactor capacitance. Besides, unique effects are observed, for example, nonlinear magnetoelectric coupling [2] and nonlinear optical activity [3]; there are no natural materials with such properties. In this presentation for the first time we demonstrate voltage tunable nonreciprocal resonance response at microwaves in contrast to traditional control methods by magnetic field. Previously we investigated nonreciprocal microwave resonance response and non-additive properties with complex planar meta-structures containing ferrite plate and grating of resonant elements forming surface plasmon-polaritons. In papers [4] and [5] it was shown that such planar meta-structures exhibit giant nonreciprocity in the transmission at the ferromagnetic resonance (**FMR**) frequencies at certain values of the static magnetic field ***H*** under conditions of a mutual influence between the **FMR** and grating resonance while nonreciprocal resonance effects are absent with free ferrite. The nonreciprocal **FMR** is due to the interaction between precessing spins in ferrite and a local magnetic field ***h*** of the surface wave with elliptic (circular) polarization formed by a grating (chains or single resonant element). The nonreciprocity $\boldsymbol{\delta}$ is the difference between transmission coefficients ***T*** corresponding to the opposite directions of magnetization ***H+*** and ***H-*** (opposite senses of spin precession) or is the difference between transmission coefficients ***T*** for propagating modes in the opposite directions.

Here we demonstrate in a rectangular waveguide magnetic and electric control of transmission nonreciprocity by both field ***H*** and small direct-current voltages $\boldsymbol{V_{DC}}$ with "ferrite plate - varactor loaded split-ring" meta-structure. Wide tuning range has been obtained also with varactor-loaded split-butterfly dipole.

II. INVESTIGATED META-STRUCTURES.
EVOLUTION OF RESONANCE RESPONSE WITH STATIC MAGNETIC AND ELECTRIC FIELDS

Investigated meta-structure contains a plate of isotropic yttrium-iron garnet $3Y_2O_3$ $5Fe_2O_3$ (30 x 20 x 1.4 mm) and copper twice split ring loaded with voltage dependent nonlinear capacitance as varactor BB857 (Fig. 1). The varactor capacitance can be tuned between 6.5pF and 0.65 pF by changing reverse-bias voltages $\boldsymbol{V_{DC}}$ from 1 V to 30 V. Meta-structure is arranged along the rectangular waveguide axis in a transverse external static magnetic field ***H*** and oriented parallel to the narrow side wall. Evolution of amplitude-frequency resonance response (transmission coefficient ***T***) is investigated in dependence on the magnitude of applied field ***H*** under the magnetization reversal and in dependence on reverse-bias voltages $\boldsymbol{V_{DC}}$.

Applying ***H*** field the **FMR** is excited and shifts to higher frequencies with ***H*** field increase.

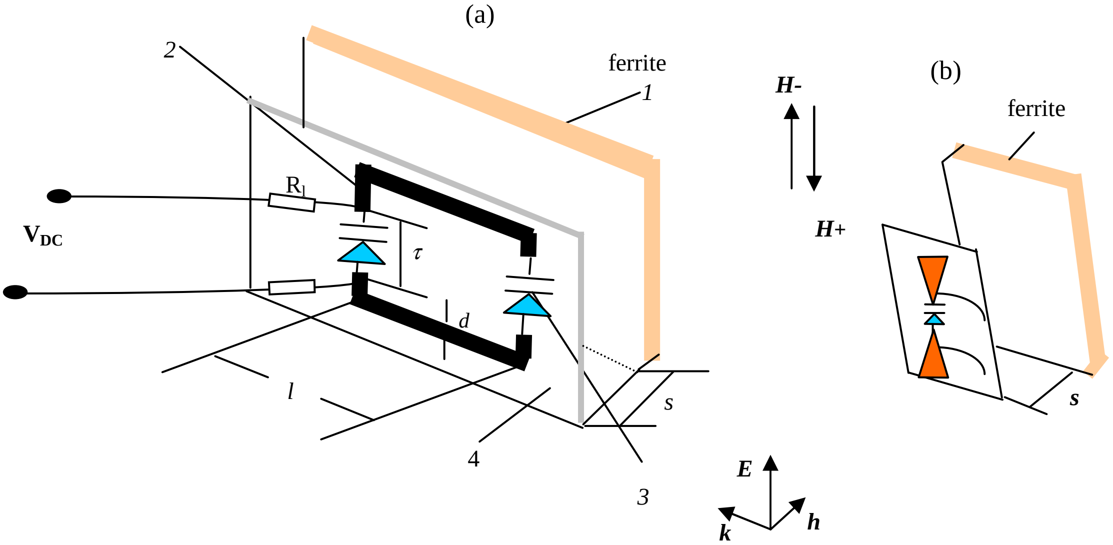

Fig. 1. Meta-structures: (a) “ferrite plate 1– varactors 3-loaded twice split-ring 2”, substrate 4, $\mathbf{R_L}$ = 100 kΩ, ***l***=18 mm, ***τ***= 1.5 mm, , ***d*** = 3 mm; (b) “ferrite plate – varactor-loaded split-dipole butterfly”.

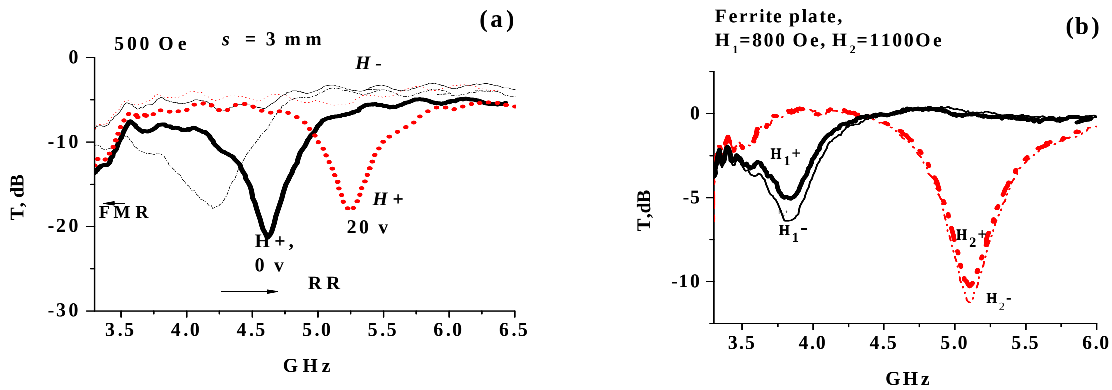

Fig.2. Frequency dependences of the transmission coefficient ***T*** in a rectangular waveguide, curves for ***H+*** (bold) and ***H-*** (thin) correspond to different directions of magnetization:
(a) metastructure (***s*** = 3mm), ***H***=0, V_{DC} = 0 (dash-dot); ***H*** = 500 Oe, V_{DC} = 0 (solid), ***H*** = 500 Oe, V_{DC} = 20 V (dot);
(b) ferrite without ring, nonreciprocity is absent.

In Figure 2 we see evolution of resonance response with meta-structure (distance ***s*** = 3mm) applying a static magnetic field ***H*** = 500 Oe and voltage V_{DC} =20 V. When ***H*** = 0, V_{DC}.= 0 the **FMR** is not excited but we see resonance response at 4.2 GHz (dash-dot curve) due to varactor-loaded split-ring resonance (**RR)**. Under ***H*** = 500 Oe, when the **FMR** is excited at about 3 GHz, the **RR** is observed at 4.6 GHz, the **RR** frequency shift is Δf_H = 0.4 GHz with changing value of the ***H*** field from 0 to 500 Oe. Besides, nonreciprocity appears at the **RR** frequencies, level of resonant curve under the ***H-*** (thin curve) and under ***H+*** field (bold curve) is not the same, nonreciprocity $\delta = T(H+) - T(H-)$ is 15 dB. Nonreciprocal **RR** can be tuned by changing the biasing voltage V_{DC}. Changing the V_{DC} from 0 to 20 V the **RR** frequency shifts to 5.25 GHz (dot curve) and the **RR** frequency shift Δf_{DC} = 0.65 GHz. The field ***H*** is much less then the field (1150 Oe) necessary to the **FMR** excitation at **RR** frequency.

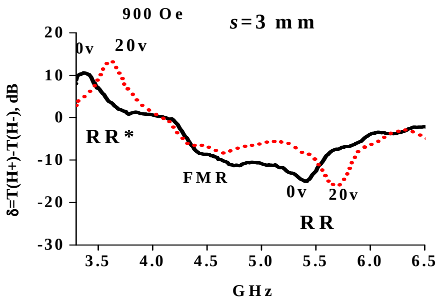

Fig. 3. Bifurcation. Evolution of frequency dependence of the nonreciprocity δ with changing V_{DC} under s = 3 mm: V_{DC}=0 V (bold); V_{DC}=20 V (dot)

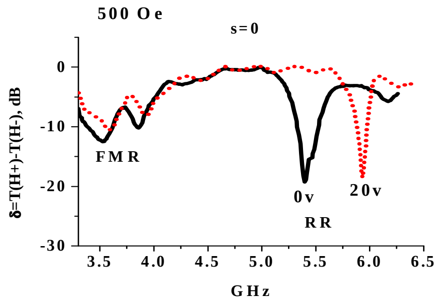

Fig. 4. Evolution of frequency dependence of the nonreciprocity δ with changing V_{DC} under s=0: V_{DC}=0 V (bold); V_{DC}=20 V (dot)

With further increase of the field ***H*** when moving **FMR** approaches the **RR** first position one can observe bifurcation effect. In this case the second ring resonance (**RR***) is excited lower than the first position and we observe two separate nonreciprocal resonances (**RR**$_B$ and **RR***$_B$) with opposite signs of the nonreciprocity δ at different frequencies. In Fig. 3 we see nonreciprocity δ corresponding to bifurcation situation under the field ***H*** = 900 Oe. In this case the **RR**$_B$ is excited at 5.4 GHz and **RR***$_B$ is excited at 3.4 GHz. Two resonances can be tuned simultaneously by changing varactor biasing voltage. By changing the V_{DC} from 0 to 20 V the shift Δf_{DC} (**RR**$_B$) = 0.29 GHz and the shift Δf^*_{DC} (**RR***$_B$) = 0.27 GHz. In this time transmission at the **FMR** domain (around 4.5 GHz) is nonreciprocal but the **FMR** frequency is not practically tuned by changing voltages V_{DC}

With decreasing the distance s coupling between ferrite and ring increases and the shift Δf_H increases. In this case the nonreciprocity δ also increases. Fig.4 corresponds to s = 0. The shift Δf_H = 1.1 GHz with changing ***H*** from 0 to 500 Oe; the nonreciprocity δ = 19 dB and the shift Δf_{DC} = 0.53 GHz by changing V_{DC} from 0 to 20 V.

III. Conclusion

So, the electrical tunability of nonreciprocity of microwaves transmission by tuning varactor capacitance has been demonstrated in waveguide with meta-structure containing a transversely magnetized ferrite and a varactor-loaded split-ring under interaction between precessing ferrite's spins and a magnetic field of the wave formed by the ring. Wide tuning range has been obtained also with varactor-loaded split-butterfly dipole.

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