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Phase-constant-nonreciprocal composite right/left-handed metamaterials based on coplanar waveguides

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The purely phase-constant-nonreciprocal composite right-left handed metamaterial structure is proposed based on coplanar waveguides loaded with a ferrite layer. The structure exhibits considerably large nonreciprocity in phase constant which depends on the effective magnetization and whose magnitude can remain in leaky wave region of wavenumbers or can overcome a boundary to slow wave region. The nonreciprocity in amplitude of transmission coefficients, on the other hand, is effectively reduced by using a cavity-backed design to prevent undesired nonreciprocal radiation loss. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4865775>]

I. INTRODUCTION

Composite right-left handed (CRLH) metamaterials¹ demonstrate positive or negative refraction depending on the frequency band and became an object of strong interest in the past decade. Since propagation of fast waves is supported with magnitude of refraction index less than unity, the popular area of application is leaky wave antenna design. The dispersion-based electronic beam steering is possible in metamaterial antennas by varying the operational frequency.² On the other hand, zeroth-order resonance in CRLH metamaterial³ allows for high efficient and very directive radiation from the antenna.

The implementation of nonreciprocity in phase constant using ferrites is a new approach to metamaterials. It can be explained by shift of dispersion curves of CRLH metamaterial along phase constant β axis by a value $\Delta\beta$.⁴ This means that the propagating wave can have opposite wave numbers and refraction indices in opposite propagation directions in certain frequency band. The phase-constant nonreciprocity $\Delta\beta$ depends on effective magnetization in ferrite, and the metamaterial still can behave as reciprocal media when magnetization is zero. The advantage of nonreciprocal metamaterials is in possibility to create a variety of new nonreciprocal devices, including nonreciprocal CRLH delay lines, pseudo travelling wave resonators, and beam steering antennas. The pseudo-traveling wave resonance described in Ref. 5, is a case of zeroth-order resonance, but with a significant phase gradient along the resonator, which is a direct result of nonreciprocity and related to $\Delta\beta$. The effect found its application in high-efficient leaky wave antenna, allowing for beam steering without varying the operational frequency.⁶ The radiation angle θ of resonant type antennas is approximately defined by $\sin \theta = \Delta\beta/\beta_0$, where β_0 is the phase constant in free space.

In the previous work, the nonreciprocal metamaterial was based on ferrite-embedded microstrip line structures

where nonreciprocal effect was related to asymmetry of the circuit.⁷ However, relatively low values of the achieved phase-constant nonreciprocity limited the performance in the applications.

In this work, we propose coplanar waveguide (CPW)-based CRLH metamaterial structure on dielectric substrate loaded with transversely magnetized cavity-backed ferrite slab on the other side, as shown in Fig. 1. The back cavity helps to avoid excessive nonreciprocal radiation from ferrite layer, limiting the structure to radiate uniformly from dielectric layer side. The coplanar configuration asymmetrically loaded with ferrite layer allows for greater effect of nonreciprocity, which means larger beam scanning angles for leaky wave antenna applications.

With stronger nonreciprocity, $\Delta\beta$ can exceed β_0 , moving from leaky wave region to slow wave region. This allows for switching between radiating and non-radiating regimes of the metamaterial purely by the means of external DC magnetic field.

Although similar CRLH coplanar waveguides without cavity-back structure were proposed earlier,⁸ the effect of nonreciprocity in phase constant was not investigated.

II. DESIGN OF METAMATERIAL WITH ENHANCED PHASE NONRECIPROCITY

In the CRLH metamaterial design, we use the basic concept of lumped series capacitors and shunt inductors complementing inductance and capacitance of the coplanar transmission line to provide negative effective μ and ε in the same band, as described in Ref. 1. The lumped elements are designed to minimize the band-gap near the operational frequency f_0 . The coplanar structure is created on low dielectric constant substrate of thickness h_d , which is a top layer in Fig. 1(a) and serves as a broadside apertures for leaky wave antenna.

The nonreciprocity in phase constant in the proposed structure can be explained by a combination of broken time reversal symmetry owing to gyromagnetic properties of

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FIG. 1. Metamaterial structure: (a) schematic cross-section, (b) simulation model with CPW topology. The first interdigital capacitor is of double value for port matching purpose.

ferrite and broken spatial inversion symmetry originating from the asymmetric waveguide structure with respect to a plane made by the magnetization and longitudinal direction. In the previous work,^{5,6} asymmetric insertion of shunt stubs in ferrite-embedded microstrip line was used for this purpose. In the present approach, we utilize coplanar transmission line asymmetrically loaded by ferrite layer as in Fig. 1, to achieve the same effect with a greater magnitude. The ferrite is magnetized by an external DC magnetic field H directed in plane of the structure transversely to the coplanar line. The magnitude of nonreciprocity $\Delta\beta$ increases with ferrite layer thickness h_f that is equivalent to increasing the asymmetry. The nonreciprocity can be tuned by changing ferrite magnetization M in a range from saturation magnetization M_S to its opposite value $-M_S$ with the external DC magnetic field.

It is well-known that in a coplanar line the electromagnetic field is generally concentrated in the layer with high dielectric constant, which is represented by ferrite in the present structure. The gyromagnetic effect in the magnetized ferrite changes the field distribution asymmetrically relatively to the plane of magnetization and the wave vector. In tangentially magnetized slab in Fig. 1, the field is concentrated on one of its surfaces determined by relation between $\vec{M}$ and $\vec{\beta}$, either in the vicinity of the coplanar line's metal layer, or on the opposite side for opposite propagation direction. Therefore, the coplanar structure without ground plane on ferrite layer side can exhibit significant parasitic radiation that is nonreciprocal and can downgrade the performance of metamaterial antennas.

To prevent parasitic radiation, we propose screening of ferrite layer as in Fig. 1. It is noted that an air gap h_a is inserted in this cavity to prevent domination of rectangular waveguide modes that could appear in the structure with sole screened ferrite slab at the back side. Therefore, h_a should be considerable, supposedly of the same order as h_f .

III. NUMERICAL SIMULATION

The simulations were performed using practical values for parameters of materials and coplanar structures. The magnetization is assumed as $4\pi M = 1450$ G, which is common when using garnet ferrites. The ferrite dielectric constant is $\epsilon_f = 15$, dissipation factor is $\Delta H = 40$ Oe, and the thickness of the slab is $h_f = 2.5$ mm. The air cavity backing

the ferrite has the same depth $h_a = 2.5$ mm. The top dielectric layer has thickness $h_d = 0.8$ mm and a dielectric constant $\epsilon_d = 2.6$. The conducting side-walls of the structure covering the cavity are connected to ground planes of the coplanar line. The parameters g , g_L , w_L , and g_C of the coplanar line in Fig. 1 are set to 0.15 mm, $w = 1.05$ mm. The period $p = 3.3$ mm defines the metamaterial unit cell size. The parameters $l_L = 1.7$ mm and $l_C = 0.7$ mm, lengths of shunt inductances and interdigital capacitor fingers, allow for effective reduction of CRLH metamaterial band-gap. The proposed design is intended for simple production. The ferrite slab is installed inside channel section from nonmagnetic metal and covered by the CPW structure on dielectric, as shown in Fig. 1(a). The assembly is put between poles of biasing magnetic system.

The numerical simulation results for 4 unit cells are obtained using finite element method solver in ANSYS HFSSTM ver.13. On the dispersion diagram in Fig. 2 acquired from complex S -parameters, dispersion curves for positive and negative power transmission along the waveguide are shown with red and blue solid lines, respectively. The operational frequency corresponds to the condition of phase constants equal by magnitude for opposite power transmission. As it follows from Fig. 2, there are two frequencies satisfying this condition, from which we choose lower one $f_o = 6.9$ GHz, with higher $\Delta\beta$. A small band-gap in the frequency response is related to the difficulty in designing lumped elements in the metamaterial and particularly caused by imperfect asymmetric design of 4-finger interdigital capacitors.

The nonreciprocity in phase constant $\Delta\beta$ is shown with green dotted-line and it makes up formidable values larger than 1.26 rad/cm at f_o , which is the main achievement of this work. It is more than 2.2 times larger than typical cases of microstrip line-based nonreciprocal metamaterials.^{6,7} It should be emphasized that the nonreciprocal effect is achieved purely in phase constant β , while the nonreciprocity in magnitude of the transmission coefficients, between S_{21} and S_{12} in Fig. 3 is less than 0.12 dB per unit cell, and looks insignificant.

For comparison, further simulations for the case without the conductor plate for screening of the ferrite layer separately demonstrated the nonreciprocity in magnitude of the transmission coefficients about 0.4 dB per unit cell at 6.9 GHz, and it was much more significant at lower frequencies. As we mentioned, this is due to nonreciprocal parasitic radiation from the

FIG. 2. Dispersion diagrams of the proposed nonreciprocal CRLH metamaterial (solid lines). Magnitude of nonreciprocity $\Delta\beta$ (dotted-line). Phase constant in free space β_0 (dashed-dotted line).

FIG. 3. Frequency response of the proposed phase-nonreciprocal CRLH metamaterial structure.

FIG. 4. Dispersion diagrams of the nonreciprocal metamaterial in non-radiating regime ($4\pi M_S = 1850$ G).

ferrite layer. In addition, the open-boundary structure also leads to almost 15% reduction in nonreciprocity $\Delta\beta$ due to lower field confinement in ferrite substrate. Therefore, the advantage of cavity-backed design of the nonreciprocal metamaterial was unconditionally confirmed.

Moreover, by magnetizing the ferrite to higher values of M , the magnitude of nonreciprocity $\Delta\beta$ can approach the phase constant in free space β_0 . In the leaky wave antenna, that causes back- or end-fire radiation with an angle $\theta = \pm 90^\circ$. With further increase in the magnetization, the dispersion diagram shifts to slow wave modes region, as illustrated in Fig. 4 for saturation magnetization $4\pi M_S = 1850$ G, that is available in some ferrites such as calcium vanadium garnet (CVG). Therefore, switching of dominant modes

between radiating and non-radiating regimes can be realized by the means of external DC magnetic field.

IV. CONCLUSION

In this work, we demonstrated purely phase nonreciprocal CRLH metamaterial structure based on coplanar line. The structure demonstrates considerably large magnitude of nonreciprocity in phase constant. Originally intended for directional antenna application, it allows for antenna beam steering in wider range of angles. The cavity-back design allows not only for reduction of nonreciprocity in magnitude of the transmission coefficients to negligible values but also for enhancement of nonreciprocity in phase constant owing to better field confinement in gyromagnetic substrate. In addition, new effect of switching of dominant modes between radiating and non-radiating regimes by means of external DC magnetic field was proposed in the metamaterials. The phenomenon can open up new applications state of the art antennas, delay lines, and isolators. For instance, just switching the antenna to non-radiating regime can allow for simple and precise radiated power measurement in microwave system.

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