Magnetically tunable metamaterial absorbers based on two layers ferrite-ferrite structure with different ferromagnetic resonant line widths

Yan-qing Tan *, Dong Chen, Yi-wei Peng, Xiang Ding
The Fifth Electronics Research Institute of Ministry of Industry and Information Technology,
Guangzhou, China

Jun-rong Liu
Guangzhou CEPREI Calibration and Testing Service Co., Ltd., Guangzhou, China
* Corresponding author: tanyanqing@ceprei.com

***Abstract*—Magnetically tunable metamaterial absorbers based on two layers ferrite-ferrite with different ferromagnetic resonance line widths have been proposed in this paper. The metamaterial absorber is composed of a metallic background plane, two layers ferrite-ferrite substrate and metallic SRRs. The ferromagnetic resonance generated in the metamaterial absorber under the action of a bias magnetic field, the absorption reaches the maximum at the ferromagnetic resonance frequency. The frequency increases from 2.72 GHz to 7.42 GHz with the increasing of the applied magnetic field from 1000 Oe to 2000 Oe. A good agreement between simulated results and the predicted results has been achieved. Our results pave a path towards design of tunable devices in unintended radiations suppression applications.**

Keywords- Metamaterials; Absorbers; Two layers ferrite-ferrite substrate; Ferromagnetic resonance line width

I. INTRODUCTION

Absorber materials are widely used in consumer electronic products, military stealth techniques and other applications to suppress unintended radiations. To seek high efficiency and wide frequency band of microwave absorber, numerous of absorber materials were studied, such as urethane, foams, silicone elastomers and other specific materials [1, 2]. However, the conventional absorbers thickness cannot be made thin enough because of the diffraction limit, which leads to limitation of the application of absorbers.

In recent decades, metamaterial have attracted considerable attention for its unique and exotic electromagnetic and optical properties in most fields, such as antennas, invisible cloaks, super lenses, especially in electromagnetic absorbers [3-5]. The independent tailored electric and magnetic responses to incident radiation in metamaterials results in the realization of such properties. Based on the numerous investigations, nowadays the metamaterials have been demonstrated nearly in every technologically relevant spectral range, from radio, microwave, mm-Wave, THz, MIR, NIR, to the near optical. The control of metamaterial effective permittivity and permeability can be realized by the control of lattice arrangement, unit cell geometry, and material parameters like resonance line width. To date metamaterials have been extensively studied as electromagnetic absorber, in which the perfect absorber properties can be obtained almost at any frequency by properly selecting the structure and its unit cell dimensions [6, 7].

Recent researches show that the metamaterials research hotspots focused on tunable metamaterials, including adjust its resonant frequency via tunable media like liquid crystals, varactor diodes, graphene and phase change materials. Besides these tunable media, magnetic ferrite is also an interesting branch because of its ferromagnetic resonance (FMR), which is a well-known interaction between the magnetic field and electromagnetic wave in ferrites. Because the FMR can be tuned by adjusting the applied magnetic field, ferrites can be used to realize tunable metamaterials [2, 4, 8-11]. By interacting with electromagnetic wave, ferrite based metamaterials provide negative permeability when the FMR takes place. Furthermore, as a consequence of different magnetic parameters of the layers, two layers ferrite-ferrite structure may exhibit exotic resonance properties, such as spin-wave exchange excitation originates from the pinning of spins at a ferrite layer’s boundary. Therefore, the two layers ferrite-ferrite maybe an effective attempt in tunable metamaterials [12-14].

In this work, we presented a tunable metamaterial absorber based on two layers ferrite-ferrite structures. By integrating two layers ferrite-ferrite as the substrate into a conventional metamaterial absorber, we obtained magnetic biased frequency-tunable absorption. The microwave absorption properties can be tuned by both the applied external magnetic field and the saturation magnetization $4\pi M_s$ of the substrate ferrite.

II. THEORY AND DESIGN

The unit cell of the considered metamaterial absorber is schematically shown in Figure 1. The lattice dimension of the unit cell a=4 mm, which is significantly smaller than the wavelength of the microwave. A metallic copper layer with conductivity of 5.8 ×107 S/m and thickness 0.018 mm is used as ground plane. The substrate of the metamaterial absorber is composed of two layers ferrite-ferrite, which can be characterized by its saturation magnetization $4\pi M_s$ and

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resonance line width, the saturation magnetization 4πMs of the lower ferrite layer is 400 Gauss with the resonance line width of 55 Oe, while for the upper ferrite layer it gives 2800 Gauss and 500 Oe. The thickness of both ferrite layers are 0.5 mm. On top of the substrate, split resonance ring structure with an array of metallic electric-LC is etched. The copper plane thickness is 0.018mm, the line width of the ring is 0.6 mm, the inner and outer radius of the ring are 1 mm and 1.6 mm respectively, the split gap of the ring is 0.5 mm. Therefore, we obtain a magnetic tunable metamaterial absorber with its unit cell composed of metamaterial structure and corresponding two layers ferrites substrate with different ferromagnetic resonance line width.

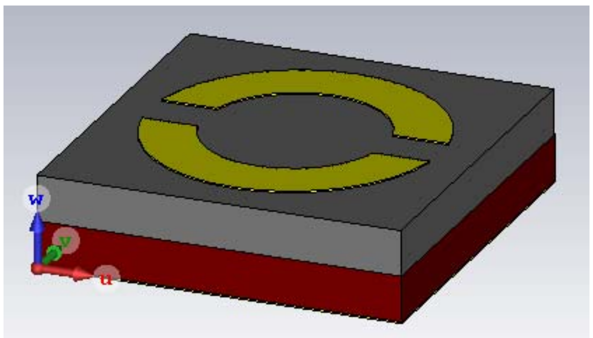

Figure1. Structure of ferrites-based metamaterials absorbers

When an external magnetic field is applied, FMR can be aroused in the metamaterials absorbers as interaction between the external magnetic field and the magnetic field of incoming electromagnetic wave. The FMR frequency can be expressed by [1, 2]

$$f_r = \gamma\sqrt{[\boldsymbol{H}_0 + (N_x - N_z)4\pi\boldsymbol{M}_s][\boldsymbol{H}_0 + (N_y - N_z)4\pi\boldsymbol{M}_s]} \tag{1}$$

Where γ is the gyromagnetic ratio; $4\pi\boldsymbol{M}_s$ is the saturation magnetization; $\boldsymbol{H}_0$ is the applied magnetic field; N_x, N_y, and N_z are the demagnetization factors for *x, y*, and *z* directions, respectively, they should fulfill the relationship described as follow:

$$N_x + N_y + N_z = 1 \tag{2}$$

Considering electromagnetic wave propagating at the interface between air and metamaterials, the effective permeability μ_{eff} of ferrite can be represented

$$\mu_{eff} = 1 - \frac{\omega_m}{\frac{\omega^2}{f_r+\omega_m} - f_r - j\alpha\omega[\frac{\omega^2}{f_r+\omega_m}+1]} \tag{3}$$

Where f_r is the ferromagnetic resonance frequency, $\boldsymbol{\omega}_m = 4\pi\boldsymbol{M}_s\gamma$ is ferrite's characteristic frequency, and $\alpha = \gamma\Delta\boldsymbol{H}/2\omega$ is the damping of the ferromagnetic precession. According to the equations mentioned above, the effective permeability and ferromagnetic resonance of the ferrites are highly related to the applied magnetic field.

The absorption efficiency was used to characterize the wave scattering properties, which can be expressed as

$$A(\omega) = 1 - R(\omega) - T(\omega) \tag{4}$$

where $R(\omega) = |S_{11}(\omega)|^2$, $T(\omega) = |S_{21}(\omega)|^2$, A, R, T represents the absorption, reflection and transmission coefficients, respectively. S11 and S21 are the scattering parameters of reflection and transmission, respectively. In this metamaterial absorber, a copper metallic ground plane has been introduced, which is thicker than the penetration depth leads to the shielding of the bottom metal plate, thus there would be no transmission though the absorber across the entire frequency range and the S21 is negligible. Therefore, the absorption can be expressed as

$$A(\omega) = 1 - R(\omega) = 1 - |S_{11}(\omega)|^2 \tag{5}$$

In order to minimize the reflectivity and enhance the absorption, the impedance of the metamaterial can be tuned to match the free space $[Z(\omega) = \sqrt{\mu(\omega)/\varepsilon(\omega)} = 1]$ at a certain frequency. At the ferromagnetic resonance frequency, the magnetic field component and electric field component couple with metamaterial structure and metallic ground plane respectively, and then the absorption maximum can be realized.

III. RESULTS AND DISCUSSION

In order to understand the electromagnetic properties of the magnetically tunable metamaterial absorbers, we modeled a unit cell as designed above and simulated the absorption spectra using the commercial high frequency electro-magnetic simulation software that is based on Finite Integration Time Domain method. The incident microwaves propagate along the z direction, while the electric field and magnetic polarization is kept along the x and y direction, respectively.

Figure 2 shows the simulated absorption of the ferrite based metamaterial absorber under different applied magnetic fields. It is obvious that an absorption maximum appears under each applied magnetic field, and all these absorption peaks exceed 80%, which demonstrates that the two layers ferrite-ferrite based metamaterial absorber interacts with the incoming electromagnetic waves. Such behavior originates from the ferromagnetic resonance takes place in the ferrite substrate, which caused by the strong coupling effect between the ferrite substrate and the incident magnetic field. In the metamaterial absorbers, the incident magnetic field drives circulation currents between the SRRs and the bottom metallic layer, then the SRRs at the front side of ferrite is primarily responsible for determining permittivity ε.

Furthermore, we can also clearly find that the absorption spectra of the metamaterials absorbers can be dynamically controlled by adjusting the external magnetic field. It is shown in Figure 2 that the absorption peaks blue-shift when the magnetic field gradually increase. Particularly, for absorbers under 1000 Oe magnetic field, an absorption peak appears at 2.73 GHz with peak absorption of 80.5%, when we gradually increase the magnetic field from 1000 Oe to 2000 Oe, the resonant frequency moves from 2.73 GHz to 5.14 GHz. Meanwhile, the absorption peaks first increases from 80.5% to 86.65%, and up to nearly 100% at 4.25 GHz, then drops down to 86.5%.

The absorption peaks under different applied magnetic field increases with the increasing of applied magnetic field, which demonstrates the magnetically tunable behavior. The results shown in Figure 2 match well with the behavior predicted in Equations mentioned above.

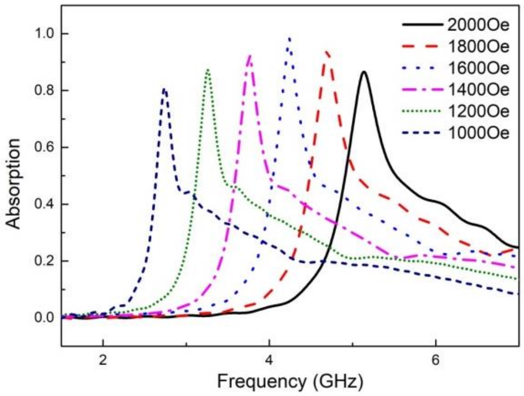

Figure 2. Adsorption Vs. frequency at different biased magnetic field

To better understand the physical properties of the designed metamaterials absorbers, the relationship between resonant frequencies and the magnetic field is shown in Figure 3. It is clearly that the resonant frequencies are linear with the applied magnetic field, this is due to the fact that the intrinsic resonance of ferrite at low magnetic field is far below X-band, and thus the effective permeability of ferrite in the X-band is almost linear to the magnetic field. It is reported that when the magnetic field increases to a certain value, the resonant frequency vs. magnetic field may demonstrate a strongly nonlinear response by the intrinsic resonance of ferrite shifts closer to X-band. The result of Figure 3 is accordance to the equation (3).

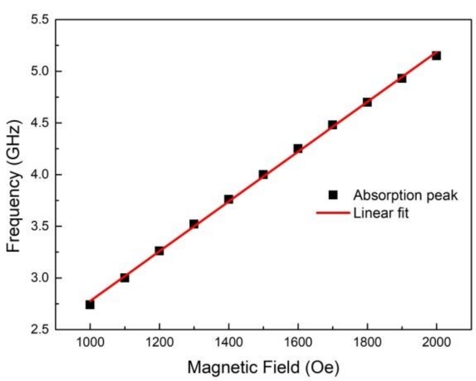

Fig.3 Relationship between absorption frequencies and magnetic fields

From the result in Figure 2 and Figure 3, we know that the resonant frequencies of metamaterials absorbers are very sensitive to the magnetic field, but unfortunately the high absorption band is reduced as well. Therefore, it is important to find an equilibrium condition between the relatively large frequency shift range and uniform absorptivity in the tuning range, which is also one of the relatively emphases in our further work.

IV. CONCLUSIONSUS

To conclude, we have proposed a magnetically tunable metamaterial absorber composed of a two layers ferrite-ferrite substrate and a periodic array of SRRs. Ferromagnetic resonance behavior takes place when a bias magnetic field applied and leads to an absorption maxima in the frequency range of 2-8 GHz. Moreover, excellent tunable performance was demonstrated by the increasing of absorption frequency with the increasing of the applied magnetic field. This work provides a way to fabricate the microwave absorbers, which has greater potential for consumer electronic products and military stealth techniques.

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