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Ferrite-based metamaterial microwave absorber with absorption frequency magnetically tunable in a wide range

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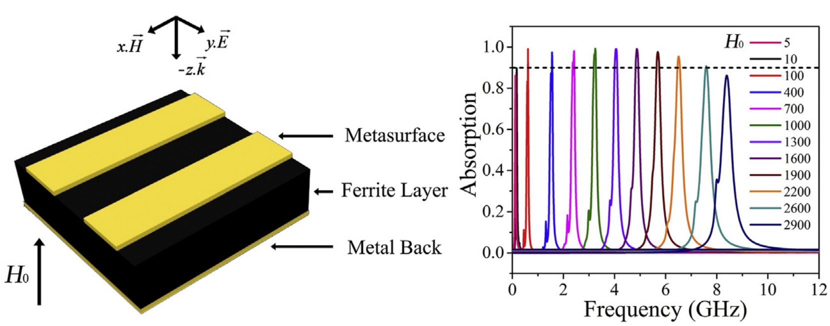
HIGHLIGHTS

- A tunable metamaterial absorber (MMA) is designed and experimentally validated by combining a ferrite and a metasurface.
- The absorption peak of the MMA is tunable magnetically in an ultra-wide frequency range from 0.2 to 7.6 GHz.
- The good tunability of the ferromagnetic resonance frequency of the ferrite endows the MMA with a wide tuning-range.
- The metasurface eliminates the polarization conversion brought by the ferrite and greatly enhances the absorption.

GRAPHICAL ABSTRACT



Unit cell of metamaterial Tunability of metamaterial

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ABSTRACT

A metamaterial absorber with a near-perfect absorption peak, which is tunable magnetically in an ultra-wide frequency range from 0.2 to 7.6 GHz, is proposed and fabricated by combining a ferrite with a metastructure. In our design strategy, the adjustable resonance frequency of the ferrite by external magnetic field provides the tunability, while the metastructure of periodic metal strips eliminates the polarization conversion brought by the ferrite and further enhances the absorption via diffraction and interference mechanisms. The measured absorption of the as-fabricated ferrite-based tunable MMA is in good accordance with the simulation results, validating the design method. Our results here illustrate that the ingenious integration of metamaterials with traditional ferrite materials promises a way to achieve a wide frequency tuning range of a strong absorption band, especially in low frequency bands.

1. Introduction

In modern information society, microwave absorbers (MAs) have vital applications in various fields, such as electromagnetic (EM) shielding, antenna, and stealth technology for military purpose [1,2]. The widespread existence of various and complicated EM wave sources requires the MAs to often work in a wide frequency range. The most direct and effective solution is to have a broadband absorption. Thus varieties of broadband MAs have been so far developed based on ferrites, magnetic metal powders, conductive polymers, carbon fibers and the composites [3–7]. Among them, those containing magnetic metal powders, especially carbonyl iron demonstrate remarkable advantages in

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thickness reduction and absorption bandwidth extension by virtue of their large magnetic permeability. However, they still show inferior absorption in the low frequency range, while their permeability is reaching a ceil set by the Snoek's limit [8]. This suggests that the above mentioned traditional microwave absorbers encounter a formidable bottleneck in broadband absorption at low frequencies, especially below 6 GHz [8,9].

Recently emerging metamaterial absorbers (MMAs) may show nearly perfect absorption at low frequencies depending on unit structures [10], and further possess advantages of thin thickness and design flexibility [11]. However, the so far developed MMAs still suffer from a small absorption bandwidth-to-thickness ratio because of resonance absorbing mechanisms [12,13], though many efforts have been devoted to improving the absorption bandwidth by using multiple unit cells [14–18], multiple-layer structures [19–21], non-planar structures [22, 23] and so on. Alternatively, tunable or adaptive MMAs are proposed to enable microwave absorbers to work in a wide low-frequency range, instead of broadband absorbers in many occasions [24,25]. This is because the working frequency of radio transmitters is narrow-band [26,27] and the requirement of broad bandwidth is generally derived from various microwave sources with different working bands.

Tunable MMAs generally consist of tuning media and metastructures. Between them, the tuning media greatly determine the tuning range, and the metastructures affect the absorption intensity and frequency. Up to now, varactor diodes [28–30], microfluidic channel [31,32] and ferrite [33–35] have been explored as the tuning media for tunable MMAs in microwave bands, while liquid crystals [36–38], graphene [39,40], phase-change materials [41] and micro-electro-mechanical systems (MEMS) [42] are frequently employed in THz tunable MMAs. However, the tuning ranges of the MMAs are all too narrow. For example, the absorption frequency of the tunable MMAs in microwave range is tunable usually within no more than 2 GHz [28,31]. Therefore, there is still a great challenge to develop tunable MMAs with a wide tuning range in microwave frequencies.

In this work, we have designed a tunable MMA with a near-perfect absorption peak shifting in a frequency range of 0.2 to 7.6 GHz by modulating external magnetic field. The as-designed tunable MMA consists of a metal-backed Garnet-type ferrite with a metal-strip-arrayed metastructure on the surface. The ferrite acts as the tuning medium, of which the resonance frequency can be modulated in a wide frequency range under external magnetic field to provide the wideband tunability, while the metal-strip-arrayed metastructure suppresses the polarization conversion brought by the ferrite and enhances the absorption. Consequently, a wide tuning-range MMA with near-perfect absorption is achieved, of which the absorption frequency is experimentally demonstrated to be magnetically tunable as expected by the simulated results. The design strategy presented here paves a way to significantly extend the working frequency range and to greatly enhance the absorption of tunable MMAs.

2. Simulation methods and experiments

2.1. Simulations

The tunable absorption properties of the as-designed MMA are demonstrated by numerical simulations using a commercial finite-element-method (FEM) based software package (CST Microwave Studio). Unit cell boundary condition is used to simulate the periodically repeated metasurface structure. To retrieve S-parameters, port boundary condition is applied on two sides of the unit cell under simulation. The magnetic properties of the ferrite is fitted to a Gyrotropic model with saturation magnetization ($4\pi M_s$) and resonance beamwidth (ΔH) of the Garnet-type ferrite set to 400 Gs and 55 Oe, respectively [43]. In this model, an external magnetic field can be applied to tune the magnetic properties of the ferrite directly. The relative permittivity of the ferrite is set to 12.8 with a loss tangent of 0.0002. In all simulations, the metals are set as copper with a conductivity of 5.96×10^7 S/m.

2.2. Fabrication

The sample that we use for experimental verification is obtained as follows. A ferrite named X4D was first purchased from Westmag Technology Co., China. X4D is a Garnet ferrite with a saturation magnetization (4πMs) of 400 Gs and a resonance beamwidth (ΔH) of 55 Oe. Its relative permittivity is 12.8 with a loss tangent of 0.0002. It is noted that the permittivity and magnetic properties are the same as those we use in simulations. The thickness and size of the ferrite are customized by the producer to be 1 mm and 80×40 mm at our request so as to facilitate the reflection measurements. A copper foil is adhered to the ferrite to be a reflective metal back. For easy of fabrication, the metasurface which is composed of copper strip lines is not processed on the ferrite directly. Instead, it is separately made from a 0.2-mm-thick FR-4 copper-clad plate by an engraving machine (DCD3800, Create Tech. Co., China). The width and spacing of the grid lines are both 1 mm. The sample is finally obtained by covering the fabricated metasurface to the ferrite.

2.3. Measurements

The reflection of the sample is measured using a waveguide method. The test set is mainly composed of a Vector Network Analyzer (VNA, N5230 A, Agilent Technologies), a standard WR284 waveguide (HD-32WAL7, Xian Hengda Microwave Tech. Co., China) and a permanent magnet with a diameter of 10 cm. The waveguide has an inner cross-section of 72.14×34.04 mm, which can be fully covered by the sample of 80×40 mm to prevent leakage of EM waves. The magnet which has a diameter of 10 cm is also able to full cover the sample and provide a relative uniform magnetic field.

In a typical measurement, the response of the waveguide is first calibrated in the range of 2.1 to 4 GHz by a thick aluminum block. The sample is then mounted on the waveguide port, with the metasurface side facing to the waveguide. The magnet sticks to a lifting platform so as to provide an adjustable magnetic field in the range of 0–1000 Oe by tuning the distance between the magnet and the sample. The magnetic field near the sample is recorded using a Gauss Meter, and the measured S_{11} is transferred to a computer connected to the VNA.

3. Results and discussion

A square area with a side length of $p = 4$ mm is selected to illustrate the bi-unit cell structure of the tunable MMA, which is shown in Fig. 1(a). The MMA is made of a metasurface layer, a Garnet-type ferrite [43] layer and a reflective metal back. The metasurface layer on the topmost is composed of parallel metal strips with a width $w = 1$ mm separated by a gap $g = 1$ mm. The ferrite layer has a thickness $t = 1$ mm. The reflective metal back is a continuous metal film with a thickness large enough to block all microwave transmission. As depicted in Fig. 1(a), the metal strips of the metasurface are made to perpendicular to the electric field of the normal incident transverse magnetic (TM) plane wave. The absorption performance of the MMA is adjusted by applying an external magnetic field (H_0) along the z axis direction. Fig. 1(b) presents the simulated absorption of the MMA under different H_0. It reveals that the MMA exhibits a narrow absorption peak depending on H_0. With increasing H_0, the frequency corresponding to the absorption peak increases and the full width at half maximum (FWHM) becomes a little broad. When H_0 is between 10 and 2600 Oe, the MMA almost show an absorption peak of about 0.9 or more, corresponding the frequency from 0.2 to 7.6 GHz. This reveals that the MMA may show a strong absorption with frequency tunable in a wide range of around 7.4 GHz by H_0.