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Permanent magnetic ferrite based power-tunable metamaterials

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ABSTRACT

Power-tunable metamaterials based on barium permanent magnetic ferrite have been proposed and fabricated in this research. Scattering parameter measurements confirm a shift in resonant frequency in correlation to changes in incident electromagnetic power within microwave frequency band. The tunable phenomenon represented by a blue-shift in transmission spectra in the metamaterials array can be attributed to a decrease in saturation magnetization resulting from FMR-induced temperature elevation upon resonant conditions. This power-dependent behavior offers a simple and practical route towards dynamically fine-tunable ferrite metamaterials.

1. Introduction

Metamaterials, materials of common constituents yet elaborately tailored on their mesoscale structure, offer peculiar physical properties that promise to extend and transcend their conventional counterparts. Into the 21st century, the novel idea of metamaterials has brought forth state-of-the-art electromagnetic functional materials, including negative refraction materials [1–3], invisible cloak [4], perfect lens [5], that had been theoretically proposed, fabricated and experimentally demonstrated, based upon this very concept, opening up a brand new gateway towards realizable technological advances.

Among this field under intensive research, ferrite based metamaterials stand out owing to their excellent tunability [6]. Soft magnetic ferrite, such as yttrium iron garnets (YIG), can be structured to achieve negative permeability utilizing the phenomenon known as ferromagnetic resonance (FMR) [7]. This resonance takes place at a frequency which shifts along with externally exerted DC bias magnetic field [8,9]. Through the combination of ferrite inclusions with metallic wires, negative refractive index may also be achieved and the frequency band of which might be altered with applied magnetic field [10,11]. Other implementations such as perfect absorber [12] and ferrite CRLH transmission lines [13] have also been studied. In spite of eminent magneto-tunability, exerting DC bias magnetic field for soft magnetic ferrite under certain circumstances can be quite inconvenient. Gu et al. experimentally demonstrated left-handed property with self-biased strontium ferrite rods [14]. Bi et al. achieved negative and near zero refraction via the combination of permanent magnetic barium ferrite and metallic wires [15].

In this work, we study the power-tunable property of permanent magnetic ferrite based metamaterials. Similar method was first introduced to tune ceramic based metamaterials by varying incident electromagnetic power [16]. Our experimental observations and simulation results match well, confirming the viability of this approach towards FMR-induced tunability.

2. Experiments

The permanent magnetic ferrite chosen for this research as metamaterials unit constituent, known as barium ferrite ($BaFe_{12}O_9$), is a typical ferrite with M-type hexagonal crystal structure which finds many an application in recording devices, magnetic stripe cards, as well as speaker magnets. The saturation magnetization ($4\pi M_s$), remanent magnetization ($4\pi M_r$), ferromagnetic resonance linewidth (ΔH), and relative permittivity (ε_r) are 2800 Gs, 2600 Gs, 120 Oe, and 16.4, respectively. The ferrite is cut into small cubes with sides that are 4 mm in length. Schematic view of metamaterials array is shown in Fig. 1. The magnetization direction is along z-axis and the spacing between adjacent cubes in x-axis and y-axis are both represented in Fig. 1 with d = 4 mm. All ferrite cubes are glued onto a thin slat of wood to form a metamaterials array. The wood slat proves to have almost no effect on measurement. The metamaterials array is then inserted into a rectangular X-band (8–12 GHz) waveguide, with the size of 22.86 mm × 10.16 mm. TE_{10} mode microwave propagates inside the waveguide along y-axis with its electric field direction and magnetic field direction pointing

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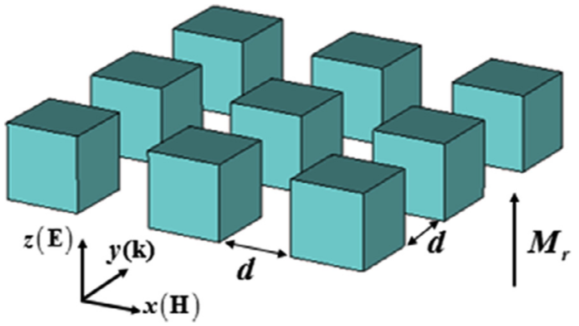

Fig. 1. Schematic view of metamaterials composed of permanent magnetic ferrite cubes.

to z-axis and x-axis, respectively. Electromagnetic signal is generated from a vector network analyzer on one of its two ports (Port 1) and is received on the other (Port 2) to obtain scattering parameters. In order to measure the electromagnetic response of metamaterials under the condition of different incident power, a power amplifier is connected to Port 1 to produce microwave with higher intensity. And an attenuator is connected to Port 2 to prevent potential damage to instrumentations.

3. Results and discussions

Fig. 2(a) shows the transmission spectra of permanent magnetic ferrite cubic array under different incident signal power (−15 dBm ~ 0 dBm). All curves are measured when they are sufficiently stabilized. As incident microwave power is increased, the whole S_{21} parameter curve shifts toward higher frequency, and it is noteworthy that the shifting of S_{21} curve is much more pronounced around its resonant peak than in other positions. The difference between the magnitude of resonant peak at high power settings (−5 dBm and 0 dBm) and low power settings (−15 dBm and −10 dBm) is mainly attributed to less-than-ideal signal-to-noise ratio of instrumentations. Fig. 2(b) shows the resonant frequency – incident power relationship derived from Fig. 2(a). The resonant frequency is simply chosen as the frequency at which the S_{21} parameter reaches its minimum. The resonant frequency undergoes a blue-shift with the increase of incident power. It is clearly seen that the resonant frequency increases from 11.20 GHz to 11.30 GHz as the power increases from −15 dBm to 0 dBm. Such power-dependent behavior manifests the tunability of metamaterials in the X-band region.

It is well known that the magnetism of ferrite mainly originates from the spin magnetic moment of electrons and according to Landau-Lifshitz-Gilbert equation, the effective permeability of soft ferrite when applying bias magnetic field can be formulated as [10,15]

$$\mu_{eff}(\omega) = 1 - \frac{F\omega_{mp}^2}{\omega^2 - \omega_{mp}^2 - i\Gamma(\omega)\omega} \qquad (1)$$

where $\omega_{mp} = \sqrt{\omega_r(\omega_r + \omega_m)}$ is the magnetic plasma frequency, and ω_r, ω_m are the FMR frequency and characteristic frequency, respectively. $F = \omega_m/\omega_r$ and $\Gamma(\omega)$ represents a frequency dependent loss. As for permanent magnetic ferrite, which has a large remanent magnetization M_r, magnetocrystalline anisotropy field plays an important part when interacting with electromagnetic wave, and FMR can occur even without applied magnetic field. When the condition of FMR is satisfied, the transmitted power would reach its minimum and large amount of energy would be absorbed by the ferrite metamaterials, inducing a temperature rise until thermal equilibrium is attained in the system. Thus, by increasing the output power of vector network analyzer, the temperature when heat generation and dissipation are balanced would increase correspondingly. The change of temperature affects transmission property and thus, scattering parameter can be tuned via varying temperature. The resonant frequency is therefore temperature-dependent, or to say more directly, power-dependent, which signifies tunable behavior in permanent magnetic ferrite metamaterials.

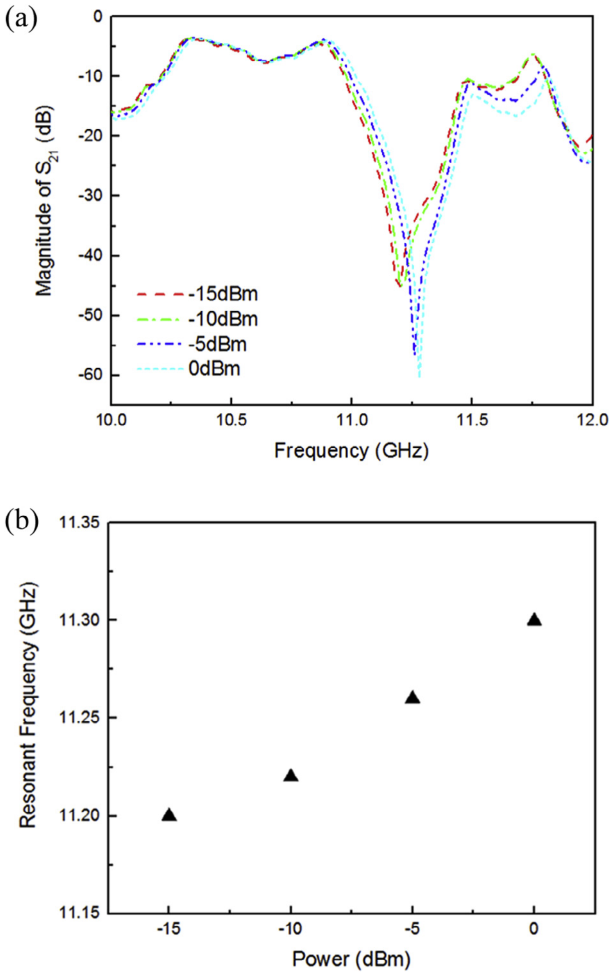

Fig. 2. (a) Measured transmission spectra under different incident microwave power. (b) The relationship between resonant frequency and incident power derived from (a).

In order to verify the analysis above, transmission spectra of metamaterials array under different temperature is measured. A heating belt is wound around the surface of rectangular waveguide and a temperature-control system is connected to the heating belt to provide precise control over the heating current and subsequently the system temperature. The output power of vector network analyzer is set to be −15 dBm which proves to have almost no effect on heating the sample as a result of its low value. The results which are obtained when thermal equilibrium is reached are shown in Fig. 3(a). One can see that the S_{21} curve moves towards higher frequency as a whole when increasing temperature. And the resonant frequency experiences a blue-shift as the temperature goes up. The results match well with Fig. 2(a) where the resonant frequency undergoes a blue-shift with the increment of incident microwave power. Fig. 3(b) shows the relationship between resonant frequency and temperature of metamaterials. The resonant frequency increases from 11.24 GHz to 11.32 GHz as the temperature increases from 30 °C to 70 °C. The trend coincides with data shown in Fig. 2(b). Within a narrow temperature