Design of Frequency-Dispersive Magnetic Material for Application of Microwave Attenuation

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***Abstract*—A concern of screen for microwave attenuation is its limited bandwidth. Thanks to unique properties of frequency-dispersive permeability at resonant frequencies, magnetic materials are applied for microwave attenuation. The operation mechanism and limitations of magnetic material screen (MMS) were studied and analyzed. To further expand bandwidth, a frequency-selective surface (FSS)-based MMS was proposed and designed. Compared with proposed MMS, the FSS-based MMS expands the operation bandwidth to 217% and decreases the overall thickness of the screen to 77.7%.**

Keywords—Magnetic material; mcirowave attenuation; bandwidth; impedance matching; FSS

I. Introduction

A big challenge of designing planar screens for microwave attenuation is the trade-off between narrow bandwidth and thick thickness [1]. Metamaterial screens were widely studied for controllable properties and excellent performance. However, they still suffer from this challenge theoretically because of their attenuation based on RLC resonant structures [2]. An improved method by using multi-resonance metamaterial was presented to expand bandwidth [3]. It has wide bandwidth by merging three attenuation bands of three metamaterial resonators. This metamaterial screen could operation from 8.4 GHz to 21 GHz with a thickness of 3.64mm. But, the design of combining multiple attenuation bands is complex. Another solution for microwave attenuation is depended on cancelling of different reflected waves. For example, Salisbury screen is widely studied and used. However, the bandwidth of Salisbury screen is quit narrow, because it normally use dielectric materials as substrate and has very high Q factor. Alternatively, FSS (frequency selected surface) layer was placed on traditional Salisbury screen to adjust its Q factor [4, 5] and the bandwidth could be expanded. For example, by placing double-ring FSS layer on 14.5mm-thick dielectric substrate, it can operate from 2.2 GHz to 9 GHz [4] which is much wider than that of Salisbury screen. It is interesting that the low Q factor and widened bandwidth is mainly due to the loss (by resistors) of FSS layer rather than material substrate. Furthermore, it also can use high loss material to achieve low Q factor. Lossy magnetic material is a good candidate [6].

In this work, magnetic materials was studied for the application of microwave attenuation. To further expand bandwidth of MMS, a novel design of broadband and ultrathin MSS was presented. It could obtain broadband attenuation by using both lossy FSS layer and lossy magnetic material substrate.

II. Magnetic Material Screen

A. Frequency-Dispersive Magnetic Materials

Generally, ferrite materials were widely applied for the application of microwave attenuation, thanks to their ferrimagnetic behaviors and high resonant frequencies. The initial permeability μ_0 and resonance frequency f_r of barium ferrites with uniaxial anisotropy obey the following equations [7]:

$$\begin{cases} \mu_0 = \dfrac{2}{3}\gamma\dfrac{4\pi M_s}{H_a} + 1 \\ f_r = \gamma H_a \end{cases} \tag{1}$$

where γ is the gyromagnetic factor, H_a is the uniaxial anisotropy field and $4\pi M_s$ is the saturation magnetization. In general, the barium ferrites have large H_a, which leads to a high f_r, and small μ_0. Since high magnetic loss occurs around nature resonance frequency f_r, it is important to adjust and control the resonance frequency of ferrites. By using TiMn substituted M-type barium ferrites, $BaTi_xMn_xFe_{12-2x}O_{19}$, as an example, $4\pi M_s$ is about 3-5 kGs and H_a can be from a few thousands to 16 kOe which depends on the TiMn substitution x. Therefore, f_r can reach high as 6-45 GHz, while μ_0 is rather small based on Eq. (1). μ_0 is only about 1.3 for the barium-ferrite/rubber composites.

The TiMn substituted M-type barium ferrites, $BaTi_xMn_xFe_{12-2x}O_{19}$, (namely MTM_x) were fabricated and their properties were measured based on coaxial line shown in Fig. 1. It is clear that, with ratio of TiMn, i.e. x, changes, the nature resonance frequency f_r of MTM_x ferrites shifts greatly. Hence, these barium ferrites could be designed for interested frequencies covering C, X and Ku bands. Moreover, complex permeability of these ferrites were modeled and could be represented as:

$$\mu(f)=\sum_{n=1}^{N}\frac{A_n jf+B_n}{C_n^2+D_n jf-f^2}+1 \tag{2}$$

where, N denotes the order of this model. A_n, B_n, C_n and D_n are fitting factors in the order of n^{th}. Here, we use second order model (N=2) and the fitted curves were plotted in Fig. 1 as well. It is seen that they are matched very well with each other. The modeled fitting factors are almost linearly change in term of x value. So, designers can approximately model permeability of MTM_x series ferrites with other x values. Ferrite composites could be mixed and the mixed complex permeability follows:

$$\mu_r-1=\sum_{i=1}^{N}V_{ci}\left(\mu_i-1\right) \tag{3}$$

where, V_{ci} is the weight or ratio of i^{th} ferrite and μ_i is its permeability. Hence, we can design the profile and resonance frequency of ferrites for our applications.

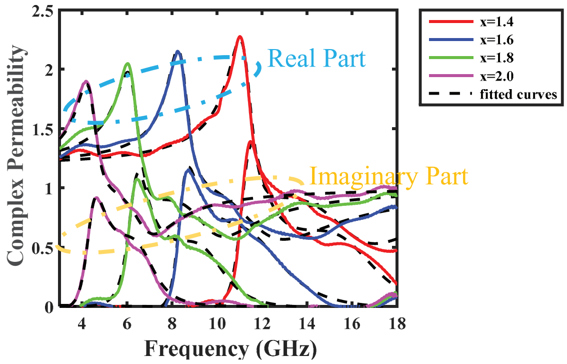


Fig. 1. Measured permeability of MTM_x series.

B. Input Impedance of MMS

The input impedance of the metal-backed substrate is represented as:

$$Z_d=\eta_d\tanh\left(jk_dt\right)=j\eta_d\tan\left(k_dt\right) \tag{4}$$

where, the $(\eta_d)^2=\mu_r/\varepsilon_r$ and k_d denote the characteristic impedance and wave number in the substrate (ε_r, μ_r), respectively. The t is thickness of the substrate. When thickness t increases and $(k_d t)\rightarrow\lambda/4$, imaginary Z_d is close to zero and its profile becomes flat for our interests. It is easy to match the screen to free space impedance at these frequencies. To study the properties of MMS, a mixed magnetic material was used as the substrate. In Fig. 2, measured complex permeability was shown. This magnetic material is the mixed composites of two MTM_x ferrites and W-type barium ferrite $BaCo_2Fe_{16}O_{27}$ (namely Co2W). The weight ratio of three magnetic ferrites is: MTM1.59:MTM1.50:Co2W=58:17:25 [1]. The mixed permeability can be easily modeled and calculated based on Equ. (2) and (3). It is seen in Fig. 2 that there is a resonance at X band and real permeability decreases with increasing frequency.

The input admittance of the metal-backed substrate, Y_d=1/Z_d, with different thickness, t, were calculated based on Equ. 2, which are shown in Fig. 3. It is inductive at lower frequency and capacitive at higher frequency. Thanks to the frequency-dispersive profile of complex permeability from 8 GHz to 15 GHz, the imaginary admittance (susceptance), Y_d, becomes flat at these frequencies for our interests. With thicker substrate, the flat susceptance moves to be zero. When the thickness is 2.2 mm, the MMS is almost matched to free space impedance and has attenuation band with 10dB attenuation, or its reflectivity less than -10dB, from 8.1 GHz to 14.5 GHz. It is shown in Fig. 7.

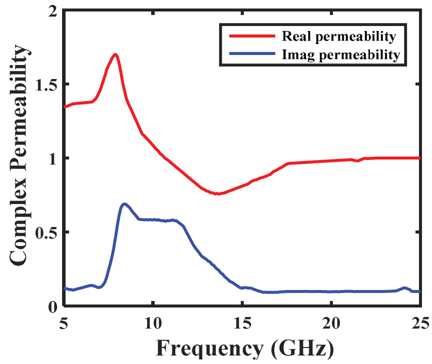


Fig. 2. Measured complex permeability of mixed magnetic material.

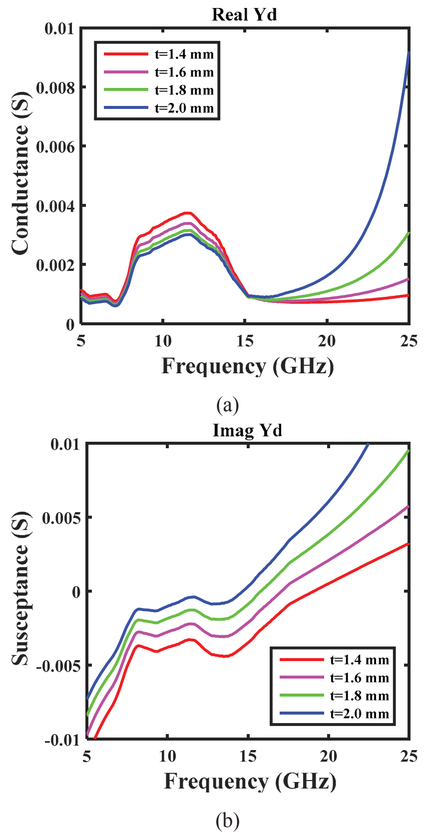


Fig. 3. (a) Real part and (b) imagninary part of input admittance (Y_d) of magnetic material substrate with different thickness (t).

To understand the attenuation mechanism, the wave number k_d was plotted in Fig. 4. Thanks to the real permeability decreases with frequency, i.e. $\mu' \sim 1/f^2$, from 8 to 14.5GHz, the wavelength in this material keeps almost constant in these frequency range. Therefore, the MMS with thickness of 2.2 mm attenuates EM waves based on quarter-wavelength resonance in whole attenuation band. The thickness of the MMS is depended both on permeability and permittivity.

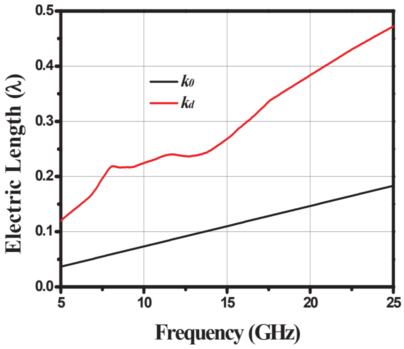


Fig. 4. Electric length of MMS with thickness of 2.2 mm.

III. FSS-Based Magnetic Material Screen

According to the analysis in section II, the attenuation bandwidth and thickness of MMS is fully depended on the properties of magnetic materials. Generally, ferrites follows follows the Kittel equation [8]:

$$\mu_r - 1 = \frac{\chi_0\left(1+i\sigma f/f_r\right)}{\left(1+i\sigma f/f_r\right)^2-\left(f/f_r\right)^2} \tag{5}$$

where, χ_0 is a constant, representing the static susceptibility. σ is the damping coefficient. The profile of complex permeability is the same as that of MTM_x ferrites in Fig. 1. The bandwidth of $\mu' \sim 1/f^2$ is narrow and cannot be expanded. To further expand the bandwidth of MMS, FSS-based MMS was presented and could be modeled as the equivalent.

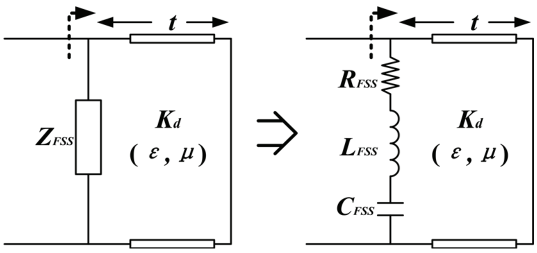


Fig. 5. Equivalent circuit of attenuation screen with FSS and substrate.

The surface impedance of the screen, Z_s, could be represented:

$$Z_s = \frac{Z_d Z_{FSS}}{Z_d + Z_{FSS}} \tag{1}$$

where, the impedance of FSS layer, Z_{FSS}, is represented by a resonance RLC circuit, and the Z_d denotes the input impedance of MMS.

The key challenge of achieving broadband screen is the impedance matching issue, because it is hard to realize zero susceptance in a wide frequency range. FSS layer was used here, which could be modeled as series RLC resonator. It provides frequency-dispersive surface impedance/admittance near resonant frequency. The admittances of FSS layer and magnetic material substrate were plotted in Fig. 4. Here, the thickness of substrate is t=1.6 mm and modeled values are R_{FSS}= 240 Ω, L_{FSS}=3.5 nH and C_{FSS}=23fF. Because of shunt of FSS layer and magnetic material substrate, the input admittance of the FSS-based magnetic material screen $Y_s=Y_{FSS}+Y_d$. To obtain impedance matching on conductance of the screen, the conductance value of the FSS layer, Y_{FSS}', cannot be too large, which demands low Q factor of the FSS resonator. Accordingly, profile of the susceptance of the FSS layer, Y_{FSS}'', is flat and its peak value is small. As seen in Fig. 3(a), the admittance of the substrate could be tuned with different thickness t. We need optimize the thickness of the substrate to match the susceptance of the screen. The matched susceptance of the screen, Y_s'', is almost equal to zero from 8 GHz to 20 GHz, as shown in Fig. 4 (b). Compared with dielectric screen [4], magnetic material offers much flatter susceptance, Y_d'', which could be cancel by the susceptance of the FSS layer, Y_{FSS}'', in a wider frequency range. The simulated reflectivity of the matched screen could be less than -10dB from 8 GHz to 22.4 GHz as shown in Fig. 8.

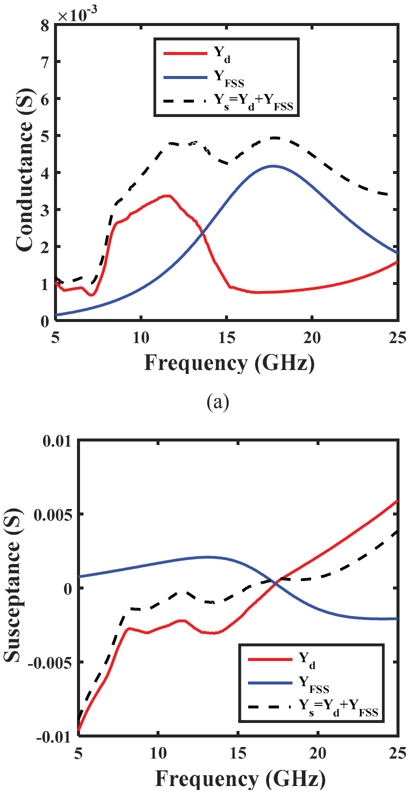
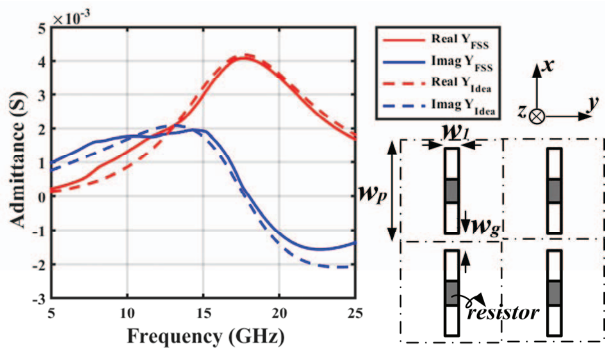


Fig. 6. (a) Real part and (b) imagninary part of admittances of FSS layer and magnetic material substrate.

Based on the analysis conducted, FSS layer can be used to expand bandwidth of magnetic material screen. Because FSS structures were well studied and modeled [9], they could be easily scaled to our design. In this case, large inductance (L_{FSS}) and small capacitance (C_{FSS}) are required. Periodic dipole wire was selected, as illustrated in Fig. 7. A unit cell has periodicity (w_p) of 5.2 mm. The width of the wires (w_d) is 0.5 mm and the gap between dipole wires (w_g) is 1.3 mm. Besides, there are 60-Ω resisters soldered in dipole wires. The extracted surface admittance of the dipole wire layer was plotted in Fig. 5 (a). It is seen that the dipole wire can approximately be equal to ideal RLC circuit. The attenuation performance of this screen is shown in Fig. 8, which could operate from 7.9 GHz to 21.8 GHz.



(a) (b)

Fig. 7. (a) Real and imagninary parts of admittances of FSS layer; (b) the structure of dipole wire FSS layer.

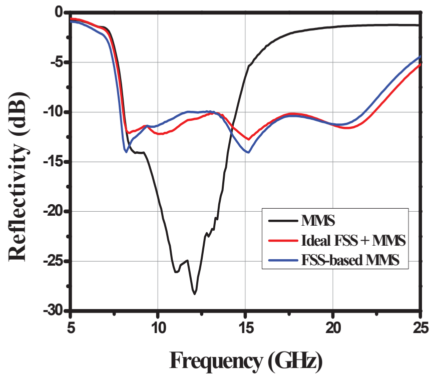


Fig. 8. Reflectivity of the screens.

TABLE I. COMPARISON OF BROADBAND AND THIN SCREENS

Work	Evaluate performance		
	Frequency (GHz)	*Thickness (mm)*	*FoM*
This paper	7.9 ~ 21.8	1.7	20.9
[6]	8.3 ~ 13.3	1.1	15.2
[10]	4.8 ~ 11.3	5	10.1
[4]	2.2 ~ 9	14.5	11.4
[3]	8.4 ~ 21	3.64	8.4

Fig. 8 reports the reflectivity of initial MMS and FSS-based MMS. It is clear that the attenuation band of MMS is the same as the band of μ’ decreasing with increasing frequency (i.e. 8~14.5 GHz shown in Fig. 2). Although the thickness of MMS could be decreased by using periodic capacitive patches [1], the attenuation band is still depended on the magnetic material. However, FSS-based MMS can provide extra attenuation band at higher frequency, because the power consumption is main on resistors at high frequencies and in lossy substrate at low frequencies. Hence, the proposed FSS-based magnetic material screen can fully cover X and Ku bands attenuation. Compared with initial MMS, FSS-based MMS can expands 117% bandwidth and decreases 22.3% thickness simultaneously.

To evaluate the attenuation performance of broadband and thin screens, a figure of merit (FoM) was used [1]. A comparison between the proposed work and other reported attenuation screens is shown in Table I. The FoM value of the screen in this paper is much higher than others.

$$FoM = \frac{\Delta\omega/\omega_0}{t/\lambda_L} = \frac{\Delta f}{f_0 f_L}\frac{c}{t} \tag{3}$$

IV. CONCLUSIONS

MMS was studied and analyzed for the application of microwave attenuation. The bandwidth and thickness of MMS are fully depended on properties of magnetic material and hard to be improved. A novel FSS-based MMS was analyzed and designed. It could operate from 7.9 GHz to 21.8 GHz with -10dB reflection when its thickness is only 1.7 mm. It provides a new method to expand bandwidth and decrease thickness of initial MMS simultaneously. The proposed dipole wire FSS layer is polarization-depended. However, it can be easily designed to be polarization-independed case by using dipole wire cross and related structures.

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