Improvement on the wave absorbing property of a lossy frequency selective surface absorber using a magnetic substrate

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(Received 23 June 2011; revised manuscript received 14 December 2011)

An equivalent-circuit model is used to analyse the improvement of the wave absorbing performance of the lossy frequency selective surface (FSS) absorber by using a magnetic substrate, showing that it is possible to widen the wave absorbing bandwidth. Three pieces of magnetic substrates are prepared. According to the complex permittivity and permeability, the reflectivity of the corresponding absorber is calculated by the finite difference time-domain (FDTD) method, and the bandwidth of the reflectivity below −10 dB is optimized by genetic algorithm. The calculated results indicate that the wave absorbing performance is significantly improved by increasing the complex permeability of the substrate; the reflectivity bandwidth below −10 dB of the single layer FSS absorber can reach 3.6–18 GHz with a thickness of 5 mm, which is wider than that with a dielectric substrate. The density of the FSS absorber is only 0.92 g/cm^3. Additionally, the absorption band can be further widened by inserting a second lossy FSS. Finally, a double layer lossy FSS absorber with a magnetic substrate is fabricated based on the design result. The experimental result is consistent with the design one.

Keywords: wave absorbing performance, lossy frequency selective surface (FSS), bandwidth

PACS: 52.25.Os, 68.35.bt, 68.43.Fg **DOI:** 10.1088/1674-1056/21/5/055201

1. Introduction

Recently, increasing attention has been paid to high-performance wave absorbing materials due to the growing demand for stealth technology. In the past decades, many studies have been carried out to realize a broad band, strongly absorbing and light-weight absorber.[1−4] However, the low permeability and high density of the microwave absorbent obstruct the further improvement of the conventional absorber performance. Recently, the lossy FSS absorber, composed of a lossy FSS and grounded dielectric substrate, has been found to be the most promising candidate for high-performance wave absorbing materials due to the multi-resonance of the FSS and the grounded substrate.[5−7] The lossy FSS absorber is a ramification of the Salisbury screen, which is one of the simplest types of resonant absorbers, and consists of a loss screen located at the place a quarter wave-length above a conducting surface, and exhibits a very narrow response around the resonant frequency.[8] Adopting the configuration of a lossy FSS to construct the absorbers has achieved the effect of increasing the bandwidth.[9−13] Filippo *et al.*[14] analysed the impedance of the lossy FSS absorber by an equivalent-circuit model, and provided a detailed explanation of thin absorbers based on high-impedance surfaces, then a wide band absorber with a reflectivity below −10 dB in a frequency range of 6–22 GHz was obtained.

To obtain the optimal absorption of the absorber, genetic algorithm (GA)-based optimization techniques were developed by Yeo *et al.*[15] Wang and Lu improved the bandwidth.[15,16] However, under a certain thickness of the absorber, the parameters that can be optimized are exiguous. Some new variables should be introduced into the optimization process to further enhance the wave absorbing property. A double-layer lossy FSS absorber and a fractal FSS absorber are two means and they were found to exhibit a better frequency-response performance.[17,18] The absorbers discussed hereinbefore are all based on dielectric substrates. To date, the lossy FSS absorber based on a magnetic substrate has not been studied. In the present paper, the effect of the magnetic substrate on the improvement of the wave absorbing bandwidth is investigated.

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2. Equivalent-circuit analysis of the absorber with a magnetic substrate

The schematic of the lossy FSS absorber and its equivalent-circuit model are shown in Fig. 1.

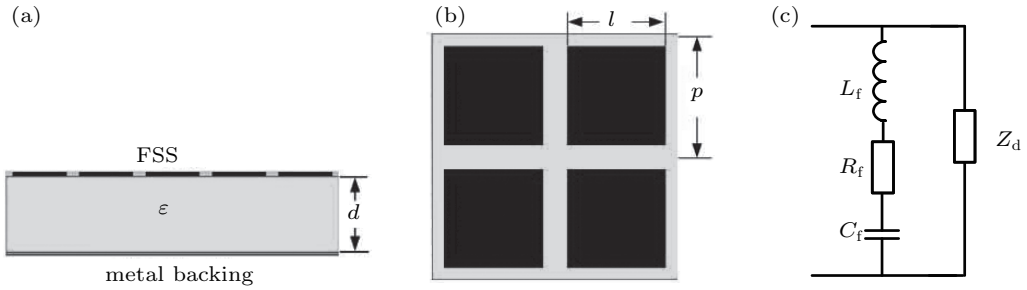


Fig. 1. Schematic of the lossy FSS absorber based on a magnetic substrate: (a) the side view, (b) the front view, and (c) the equivalent-circuit model.

The input impedance of the dielectric substrate with a grounded plane is represented by Z_d. The fringing capacitance between the FSS patches and the equivalent inductance of the FSS determined by the dimension of the FSS along the electric field direction are represented by C_f and L_f, respectively. The existence of the R_f is due to the finite conductance of the FSS.

The absorption coefficient $A(\omega)$ could be expressed as $A(\omega) = 1 - R(\omega) - T(\omega)$, where $R(\omega)$ and $T(\omega)$ represent the reflection and transmission, respectively. As a consequence of the grounded substrate, the transmission of the FSS absorber almost approaches zero. Therefore, the minimal value of $R(\omega)$ indicates the maximal value of $A(\omega)$. Thus, the reflectivity is proposed to represent the absorbing performance of the FSS absorber.

The impedance of the lossy FSS, Z_{fss}, can be represented through a series RLC circuit as

$$Z_{fss} = R_f + j\omega L_f + \frac{1}{j\omega C_f}. \quad (1)$$

The values of C_f, R_f, and L_f can be calculated using the method given in Ref. [19]. The impedance of the grounded substrate can be calculated analytically according to the transmission-line method as

$$Z_d = jZ_0\sqrt{\mu_r/\varepsilon_r}\tan\Big(\frac{2\pi f}{c}\sqrt{\mu_r\varepsilon_r}d\Big), \quad (2)$$

where Z_0 is the impedance of the free space, ε_r, μ_r, and d are the relative permittivity, permeability, and thickness of the substrate, respectively, and c is the velocity of light in a vacuum. The impedance of the absorber can be obtained through the parallel connection of the lossy FSS to the grounded substrate. The reflectivity nulls of the absorber appear around the frequency where the capacitive and inductive impedances of the lossy FSS are assumed to have the same value as those of the inductive and capacitive impedances of the grounded substrate respectively (see f_1 and f_2 in Fig. 4 in Ref. [13]). At f_1 and f_2, the absorbing structure is actually a high-impedance surface and the incidence can mostly be absorbed by it. The reflectivity between the two apexes can be optimized by adjusting the dimension and square resistance of the FSS. Therefore, the distance between f_1 and f_2, which can be modulated by changing Z_{fss} and Z_d, nearly exhibits the reflectivity bandwidth.

Figure 2 shows the imaginary impedances of the grounded substrates with different relative permeabilities.

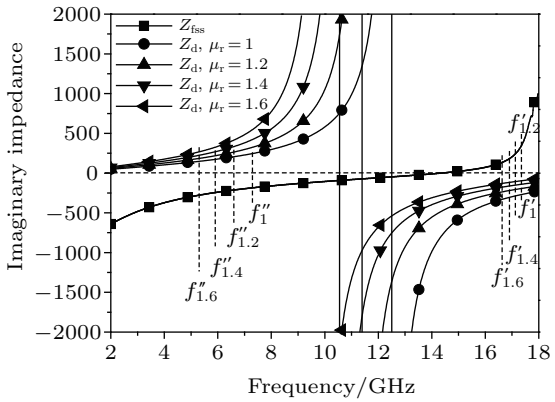


Fig. 2. Impedances of the grounded substrate with different relative permeabilities.

The results illustrate that the upper resonance frequency has a slightly red shift with the increase of the relative permeability, but the lower resonance frequency shifts toward lower frequency acutely, indicating that the low frequency absorbing performance is

improved. The bandwidths of the absorbers with different substrate relative permeabilities are calculated and optimized. The thickness and relative permittivity of the substrate are kept at 5 mm and 3, respectively. The optimal results are shown in Fig. 3.

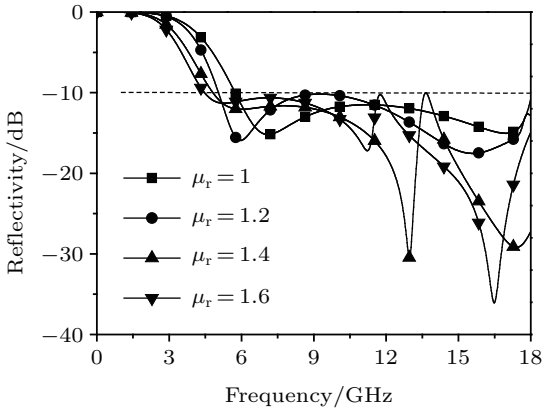


Fig. 3. Optimized reflectivities of the absorbers with different relative permeabilities.

The results imply that the appropriate increase of the relative permeability can broaden the bandwidth of the absorber, which is consistent with the analysis results by the circuit model.

3. Design and optimization

The magnetic substrate is obtained by adding flake ferrous microwave absorbent to the polyurethane foam which is prepared by mixing 50 g polyether polyol and 55 g 4.4'-methylene diphenyl dissocyanate (MDI) at 65 °C in the die with a standard size of $300\times300\times5$ mm^3. Three pieces of magnetic substrates with the flake ferrous microwave absorbent mass of 150 g, 200 g, and 250 g are fabricated and numbered as 2#, 3#, and 4#, respectively. Their complex permittivities and permeabilities are calculated from the S parameters measured by the free space method,[20] and the results are shown in Figs. 4(a) and 4(b).

With the increase of the absorbent content, the real part and imaginary part of the permeability increase slightly. Based on the prepared magnetic substrate, the bandwidth with the reflectivity below −10 dB is optimized by GA. The absorption intensity and bandwidth are considered in the goal function. The goal function is established as follows:

$$g = (nBW \times 100 + R_a)/100, \tag{3}$$

whose optimal value is null. Here R_a is the average linear reflectivity and nBW is the relative bandwidth unsatisfying the reflectivity threshold. The optimized results are shown in Fig. 4(c) and the corresponding parameters are listed in Table 1.

Table 1. Bandwidths of the optimized reflectivity and the corresponding parameters of the absorber based on a magnetic substrate. BW is the bandwidth of the corresponding absorber with the reflectivity below -10 dB.

	p/mm	l/mm	$R_s/(\Omega/\square)$	p_1	BW(GHz)
1#	23.23	18.32	112.68	1	5.21–18
2#	12.36	9.01	40	0.44	4.75–18
3#	12.01	8.74	40	0.51	4.07–18
4#	15.30	10.86	26.59	0.44	3.71–18

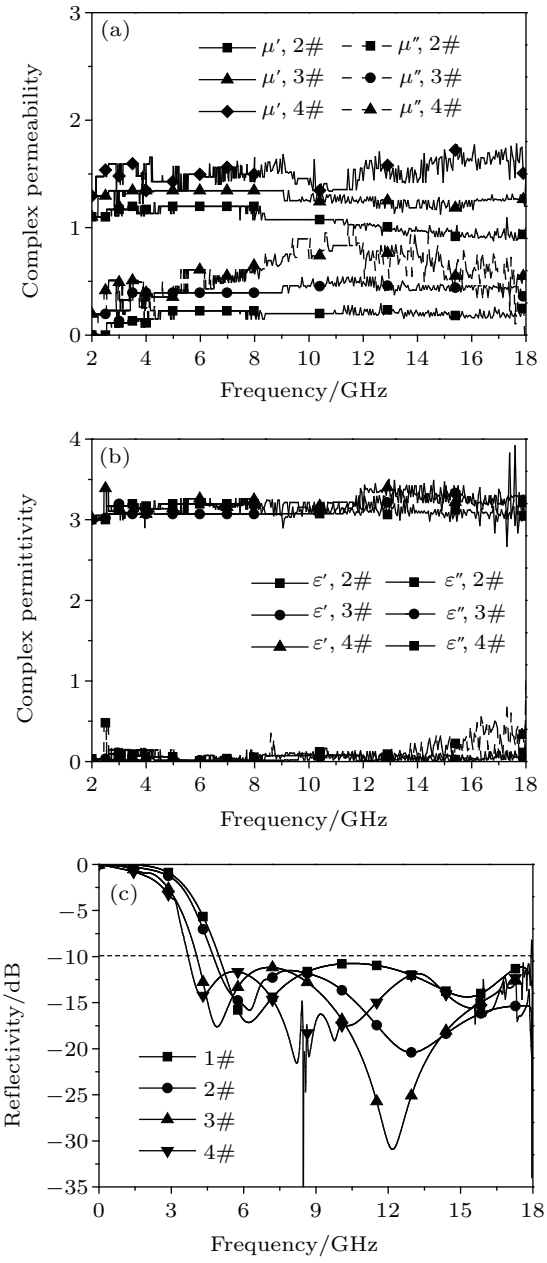


Fig. 4. Complex permittivities (a) and permeabilities (b) of the magnetic substrates with different flake ferrous absorbents versus frequency. (c) The optimized reflectivities of the corresponding absorbers versus frequency.

The number 1# represents the FSS absorber based on a dielectric substrate, whose relative permittivity is 1.04. To increase the dimension of the optimizing space, the location of the lossy FSS in the substrate, represented by the parameter p_1 in Table 1, is considered and the value 1 indicates that the FSS is on the surface of the substrate.

The magnetic substrates themselves have little absorption of the microwave energy because of the low permeability, but they can lower the frequency of the absorption apex obviously and the absorption bandwidth is widened. The improvement of the absorbing performance is due mainly to the perfect impedance matching between the magnetic substrate and the free space, and the incident wave is consumed by the lossy FSS.

As shown in Ref. [17], the double-layer lossy FSS absorber has more excellent wave absorbing performance than the single-layer one, which inspires us to insert a second lossy FSS into the magnetic substrate to further widen the bandwidth. In light of the 3# substrate, a double-layer lossy FSS absorber based on a magnetic substrate is designed and optimized by GA. The goal function is shown in Eq. (3), and the parameters of the absorber are listed in Table 2.

Table 2. Bandwidth of the optimized reflectivity and the corresponding parameters of the double-layer lossy FSS absorber.

p(mm)	l_1/mm	l_2/mm	$R_{s1}/(\Omega/\square)$	$R_{s2}(\Omega/\square)$	p_{s1}	p_{s2}	BW (GHz)
16.68	12.78	5.04	43.87	56.05	0.6	1	3.2–18

The subscripts 1 and 2 in the parameter symbol represent the first and second layer lossy FSS absorbers, respectively. The optimized result is shown in Fig. 5.

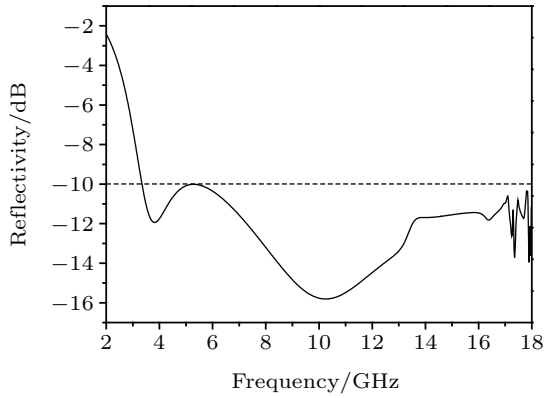


Fig. 5. Reflectivity of the double-layer lossy FSS absorber optimized by GA.

The absorber with a double-layer lossy FSS has more excellent wave absorbing property than the one with single-layer lossy FSS. The bandwidth of the reflectivity below −10 dB is 3.2–18 GHz, and the double-layer lossy FSS absorber is fabricated to confirm the design result.

4. Experiment

The absorber is prepared by fabricating two pieces of substrates. The thicknesses of the substrates are represented by the parameters p_{s1} and p_{s2} in Table 2. The corresponding lossy FSS absorbers are printed on the substrates by screen painting technology, and then the two layers are assembled together. Their optic photographs are shown in Figs. 6(a) and 6(b).

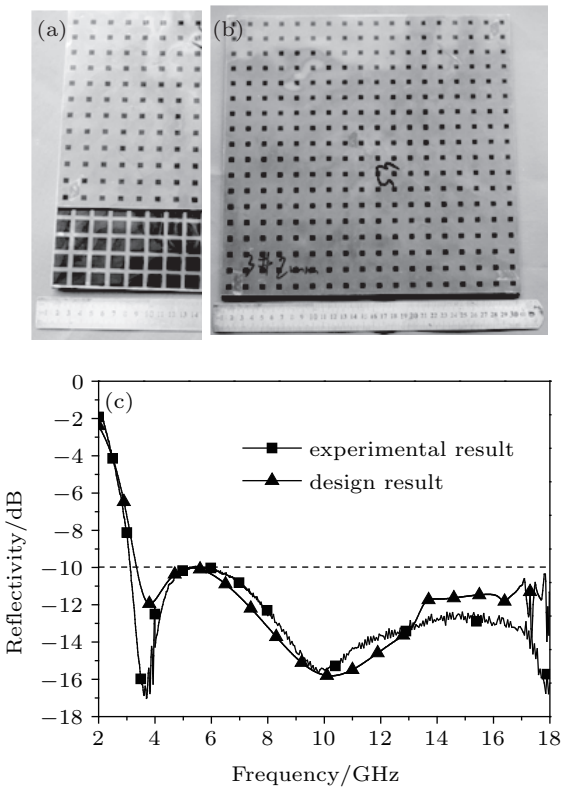


Fig. 6. Optic photographs of the two-layer lossy FSS absorber: (a) the two parts of the absorber, (b) the panorama of the absorber. (c) The design and experimental reflectivities of the absorber.

The reflectivity of the absorber is measured by the free space method, the design and experimental results are shown in Fig. 5(c). The experimental result shows

that in a frequency range of 3.15–18 GHz, the reflectivity is below −10 dB, which is nearly consistent with the design one; the error is ascribed reasonably to the fabrication tolerance. The density of the absorber designed in this paper is 0.92 g/cm^3, which is far less than that of the conventional magnetic coating. Its absorption property is more excellent than that of the lossy FSS absorber based on dielectric substrate.

5. Conclusion

The lossy FSS absorber based on a magnetic substrate is studied. The impedance of the magnetic substrate matches with the free space impedance very well and the incident wave is mostly consumed by the lossy FSS. Compared with the density of the conventional magnetic wave absorbing coating, the density of the absorber is lightened, and a high-performance wave absorbing material can be obtained with low permeability of the substrate. With the thickness of 5 mm, the bandwidth of the reflectivity of the single-layer lossy FSS absorber designed in this paper below −10 dB is 3.6–18 GHz, and the bandwidth can be widened to 3.2–18 GHz by designing a double-layer lossy FSS absorber based on a magnetic substrate. The experimental results confirm the design ones.

References

[1] Zou Y H, Jiang L Y, Wen S C, Shu W X, Qing Y J, Tang Z X, Luo H L and Fan D Y 2008 *Appl. Phy. Lett.* **93** 261115.

[2] Xie W, Cheng H F, Chu Z Y, Zhou Y J, Liu H T and Chen Z H 2009 *Mater. Design* **30** 1201

[3] Jiang T J, Zhen L, Zhang B Y, Shao W Z and Xu C Y 2008 *Scripta Mater.* **59** 967

[4] He Y F, Gong R Z, Wang X and Zhao Q 2008 *Acta Phys. Sin.* **57** 5261 (in Chinese)

[5] Liu H T, Cheng H F, Chu Z Y and Zhang D Y 2007 *Mater. Design* **28** 2166

[6] Alireza K Z and Anders K 2009 *IEEE Tran. Antenn. Propag.* **57** 2307

[7] Sun L K, Cheng H F, Zhou Y J and Wang J 2011 *Acta Phys. Sin.* **60** 108901 (in Chinese)

[8] Knott E F, Shaeffer J F and Tuley M T 1985 *Radar Cross Section* (Dedham: Atech House)

[9] Che Seman F, Cahill R, Fusco V F and Goussetis G 2011 *IET Microw. Anten. P.* **5** 149

[10] Che Seman F, Cahill R and Fusco V 2009 *IET Electron. Lett.* **45** 10

[11] Simms S and Fusco V 2005 *IET Electron. Lett.* **24** 1311

[12] Engheta N 2002 *IEEE Antennas and Propagation Int. Symp.* **2** 392

[13] Lee W J, Lee J W and Kim C G 2008 *Compos. Sci. Technol.* **68** 2485

[14] Filippo C, Agostino M and Giuliano M 2010 *IEEE Tran. Antenn. Propag.* **58** 1551

[15] Yeo J, Ma F T and Mittra R 2005 *Microw. Opt. Technol. Lett.* **44** 6

[16] Wang J B and Lu J 2011 *Acta Phys. Sin.* **60** 057304 (in Chinese)

[17] Liu J C, Liu C Y, Kuei C P, Wu C Y and Hong Y S 2006 *Microw. Opt. Technol. Lett.* **48** 449

[18] Sourav C, Raj M and Neil R W 2002 *IEEE Tran. Antenn. Propag.* **50** 284

[19] Costa F, Monorchio A and Manara G 2009 *International Conference on Electromagnetics in Advanced Applications* **9** 852

[20] Smith D R, Vier D C, Koschny Th and Soukoulis C M 2005 *Phy. Rev.* E **71** 036617