Design of a tunable frequency selective surface absorber as a loaded receiving antenna array*

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An effective approach to designing a tunable electromagnetic absorber is presented and experimentally verified; it is based on an idea that an existing frequency selective surface (FSS) absorber is regarded as a loaded receiving antenna array. The existing absorber is effectively simplified by withdrawing half of the loaded resistors; a more compact one is obtained when lumped capacitors are introduced. Building on this, a varactor-tunable absorber with a proper bias network is proposed. Numerical simulations of one tunable absorber with 1.6 mm in thickness show that a wide tuning range from 3.05 GHz to 1.96 GHz is achieved by changing the capacitance of the loaded varactor from 0.5 pF to 5.0 pF. An experiment is carried out using a rectangular waveguide measurement setup and excellent agreement between the simulated and measured results is demonstrated.

Keywords: electromagnetic absorber, frequency selective surfaces (FSS), varactor

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1. Introduction

Over the years, there has been a considerable amount of interest in the development of new design methods for electromagnetic absorbers. To design an ultra-thin absorber, a design method, in which resistive electrical current is placed at a position close to an artificial magnetic conductor (AMC), has attracted much attention; several attempts to employ AMCs in the form of frequency selective surface[1] and high impedance surface[2] have been made.[3–16] These absorbers usually exhibit a narrow bandwidth response, then new design methods to achieve tunable capability for them have been proposed.[13–16]

In this paper, we explain the principle of an existing FSS absorber loaded with lumped resistors in another way; we regard it as a loaded receiving antenna array. According to the idea, the FSS absorber is effectively simplified by withdrawing half of the loaded resistors; a more compact absorber is constructed when film capacitors are introduced. Based on the second thought, a novel varactor tunable absorber is proposed, which is slightly distorted due to the introduction of the bias network for loading varactors. The performances of these proposed absorbers are demonstrated through numerical simulations using Ansys HFSS software. To verify the simulations, we fabricate two homo-typical samples using fixed lumped capacitors with different capacitance values and measure the reflection coefficients at TE incidence using a waveguide measurement setup.

2. Design and simulation

The existing FSS absorber is shown in Ref. [12]; it is composed of a two-dimensional periodic array of square patch cells printed on a grounded dielectric substrate and surface mount resistors, each with a resistance of 392 Ω, which is close to the characteristic impedance of free space 377 Ω, are located between adjacent patches in both the x- and y-axis directions, as shown in Fig. 1(a). A relevant mechanically tunable absorber, shown in Ref. [13], is constructed by displacing the ground plane.

In the existing FSS absorber, each of the square patches is loaded with surface mount resistors at the edges; it can be seen as a loaded receiving edge-fed micro-strip antenna. For a loaded receiving antenna cell, the received power P_r consumed in the matched load is

$$P_r = A_e(\theta, \varphi) S_i, \tag{1}$$

where the effective area $A_e(\theta, \varphi)$ is a function of the angle of incidence. For a large antenna array consisting of n cells with total actual area A_t, when the effective area A_e of each antenna cell is close to its actual area A_c in an operating frequency range and incidence angle range, the total received power P_r is

$$P_r = nA_eS_i \approx nA_cS_i = A_tS_i. \tag{2}$$

In this way, the loaded receiving antenna array will effectively receive the incidence power and can be used as an effective absorber. The existing FSS absorber is just like a loaded receiving antenna.

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Now we regard the FSS absorber as a loaded dual-polarized receiving antenna array; its unit cell is an edge-fed micro-strip patch antenna cell. There are four loaded feed ports for each antenna cell, while two feed ports at mutual-vertical edges are adequate for making a dual-polarized patch antenna. According to the above idea, we simplify the FSS absorber. Now half of the surface mount resistors are withdrawn and four adjacent patches are combined into a large square unit, as shown in Fig. 1(b), which is the section in the dashed line loop; the resistors are no longer located between adjacent patches in different cells. In addition, the values of resistance R of the resistors are reduced to half their normal values to keep an effective absorption.

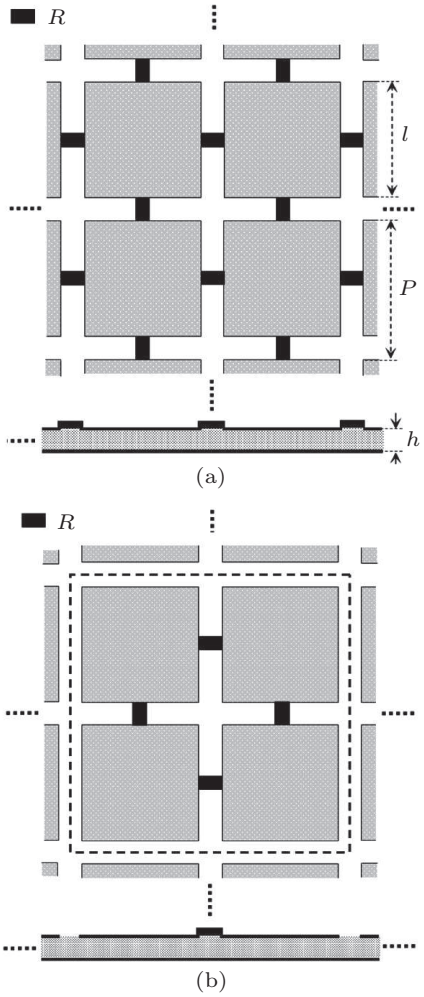


Fig. 1. Primary (a) and simplified (b) FSS absorber.

To validate the simplified FSS absorber, we perform computer simulations using the commercial finite element method solver (Ansys HFSS). The program is for simulating a single unit cell with periodic boundary conditions, the phase delays $\Delta\phi_x$ and $\Delta\phi_y$ of two pairs of periodic boundaries in x- and y-axis directions respectively with respect to the direction of the incident wave (θ, ϕ) are expressed as

$$\Delta\varphi_x = Pk_0 \sin\theta \cos\varphi, \tag{3}$$

$$\Delta\varphi_y = Pk_0 \sin\theta \sin\varphi, \tag{4}$$

where P is the side length of the unit cell. We can introduce an incident planar wave coming from the arbitrary direction (θ, ϕ) through the Floquet port over the absorber and obtain the reflection coefficients effectively. The simplified absorber, as well as the primary one, is simulated. The primary absorber is constructed on a $h = 1.5$ mm thick dielectric substrate with relative permittivity $\varepsilon_r = 9.6$, the dimensions of the unit cell are as follows: $P = 13.65$ mm, $l = 12.45$ mm and the resistance values (R) of these loaded resistors are all 392 Ω, i.e., $R = 392$ Ω. After simplification, the resistance R is reduced to half, i.e., $R = 196$ Ω. The simulated frequency-dependent reflection coefficients $R(\omega)$ at vertical incidence are shown in Fig. 2, where it is shown that the reflection losses of the simplified absorber are almost identical with those of the primary one; the reflection losses of the two absorbers are both better than −45 dB at a central frequency of 3.25 GHz.

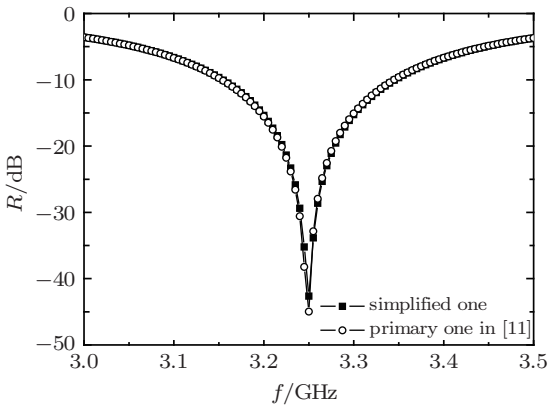


Fig. 2. Reflection losses of the primary and simplified absorber versus frequency.

Now we load the simplified absorber in Fig. 1(b) with surface mounted film capacitors, each with capacitance C at the positions where the resistors have been withdrawn, as shown in Fig. 3(a). Now the effective capacitance between the adjacent cells is improved, the central frequency f_0 of the absorber is greatly reduced, such a more compact absorber is designed. The designed compact absorber is simulated when the capacitance C is assumed to have different values. The simulated results, shown in Fig. 3(b), indicate that the central frequency f_0 is greatly reduced with the augment of capacitance C; the proper augment of the resistance R has kept a strong absorption. When the capacitance C of the film capacitor is assumed to be 5.0 pF, i.e. $C = 5.0$ pF, the central frequency f_0 falls to 1.89 GHz and the over-thickness of the absorber is just only $0.01\lambda_0$; in addition, the reflection loss is −37 dB when the resistance R is changed into 500 Ω, i.e. $R = 500$ Ω. According to the above analysis, a novel notion to design a tunable absorber is brought out.

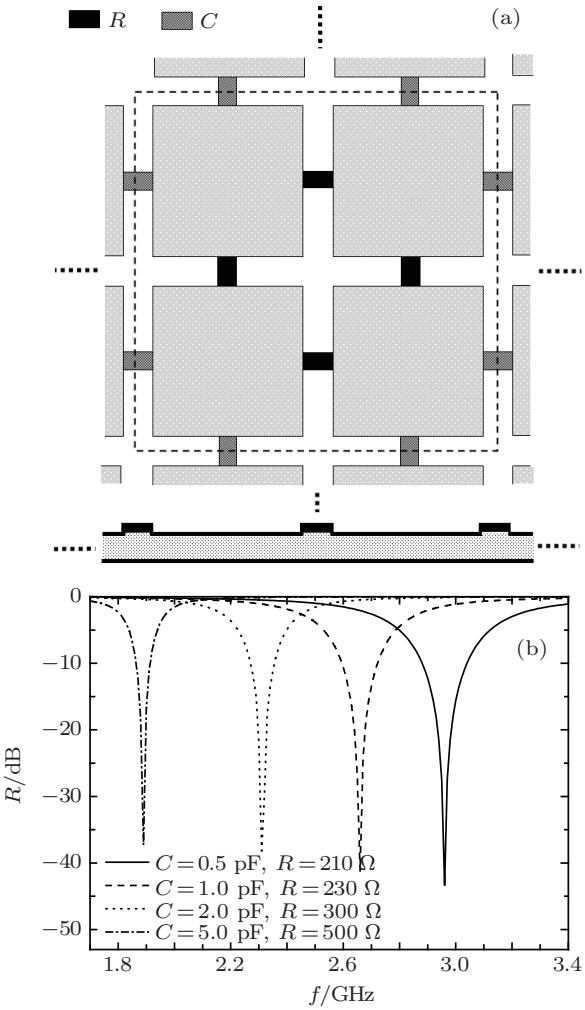


Fig. 3. Compact absorber loaded with surface mounted film capacitors (a) and variations of reflection loss with frequency for different values of capacitance and resistance (b).

To design an electrically tunable absorber, we replace the film capacitors of the compact absorber with a kind of surface-mount varactor. In addition, the unit cell is shaped to locate these loaded varactors. The designed tunable absorber is shown in Fig. 4. Firstly, we etch the primary ground plane as a bias network and attach another ultra-thin grounded sheet to the bottom of the absorber. The bias network is composed of an array of square patches, while these patches are diagonally connected using oblique strips in a single direction, which is shown in Fig. 4(a), where the section in the dashed line loop is in one cell. Secondly, the square patches in the absorber were originally regarded as loaded edge-fed patch antennas, now we change them into the corner-fed ones, the loaded resistors are transferred to the corner of the square patches. In one cell, the loaded resistors are all connected with a small rhombic patch, which is located in the center of the cell, as shown in Fig. 4(b); the small rhombic patch is electrically connected with the bias network through a via at the center. In this way, a common DC voltage can be introduced between the adjacent patches in different cells and bias all of the varactors in parallel when the DC voltage is applied to the bias network, as shown in Fig. 4(a). Now the central frequency of the absorber can be electrically tuned with the alteration of the DC voltage and thus a tunable absorber is designed.

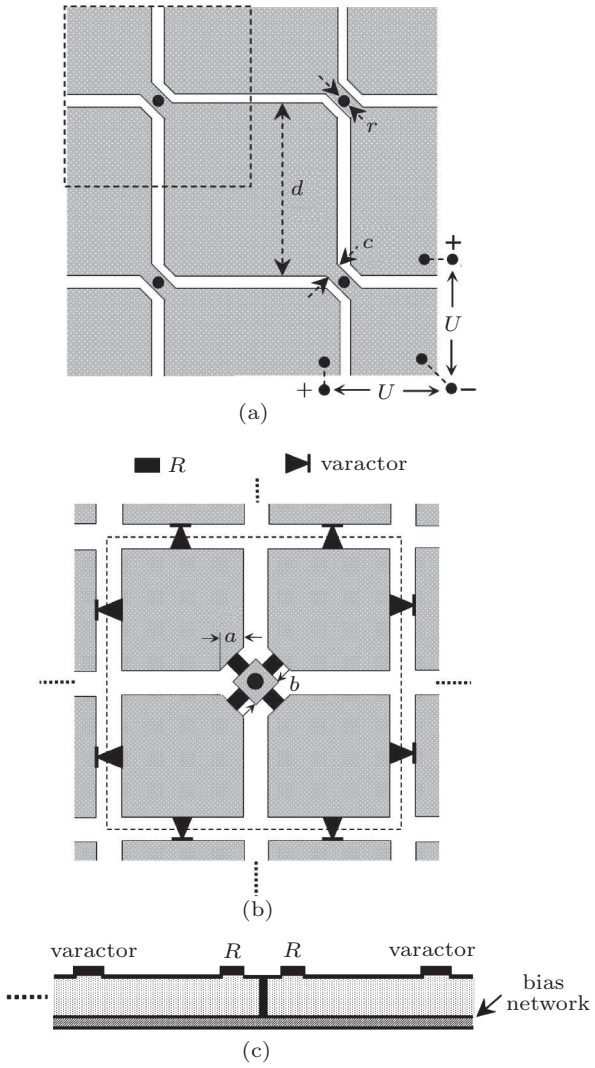


Fig. 4. Tunable absorber structure: (a) the bias network, (b) vertical view and (c) side view of one cell.

One varactor-tunable absorber is constructed and simulated based on the above simulated structure. We keep its basic dimensions as given above, the dimensions of the remodeled parts are as follows: $a = 3.00$ mm, $b = 3.00$ mm, $c = 2.00$ mm, $d = 26.10$ mm, $r = 0.50$ mm and the attached ultra-thin grounded sheet is only 0.10-mm thick with relative permittivity $\varepsilon_r = 2.2$. After optimizing the simulation, the resistance R is chosen to be 125 Ω, i.e., $R = 125$ Ω. To observe the tuning capability of the absorber, it is simulated when the values of capacitance C of the varactors are assumed to be different. As indicated by the simulated results, the reflection coefficients at vertical incidence are shown in Fig. 5. It is shown that a wide tuning range from 3.05 GHz to 1.96 GHz with an almost constant relative bandwidth is achieved by changing the capacitance from 0.5 pF to 5.0 pF. When the capacitance C is assumed to be 2.0 pF, i.e. $C = 2.0$ pF, better than

−32 dB reflection loss is realized at a frequency of 2.40 GHz, while the absorbance weakens a little when the capacitance C is augmented or reduced, because the resistance R cannot be changed, it should be optimized at different resonant frequencies.

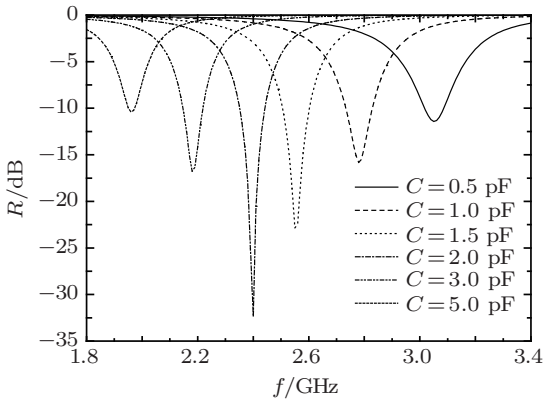


Fig. 5. Variations of reflection loss of the tunable absorber with frequency for different values of varactor capacitance.

3. Experimental validation

To verify the above tunable absorber, an experiment is carried out in a rectangular waveguide simulator. The waveguide simulator, developed by Brown and Carberry (1963),[17] is a convenient experimental setup. In the rectangular waveguide simulator, a metallic rectangular waveguide is terminated in a section of an array containing a small number of elements. The section of the array can represent an infinite array, because the TE_{10} waveguide mode in the waveguide can be decomposed into two TE oblique incident plane waves that reflect from the side waveguide walls; the waveguide perfectly conducting walls can mirror an infinite series of images, as sketched in Fig. 6(a).

The experimental setup is shown in Fig. 6(b), in which the WR-430 waveguide is used. The cross-sectional area of the WR-430 waveguide is $a \times b = 109.2\ \text{mm} \times 54.6\ \text{mm}$, the fabricated samples of the above absorber consist of a 2×4 array of unit cells with a period of $P = 27.4$ mm; their dimensions accord with those of a waveguide cross section. In addition, to overcome biasing problems in the waveguide simulator, varactors are replaced with lumped capacitors with different capacitance values. As the operating frequency range of the TE_{10} mode in the WR-430 waveguide is between 1.72 GHz–2.61 GHz, according to the simulated results in Fig. 5, we fabricate two homo-typical samples in which the values of capacitance C of lumped capacitors are chosen to be 2.5 pF and 4.0 pF respectively. The fabricated samples are shown in Figs. 6(c) and 6(d).

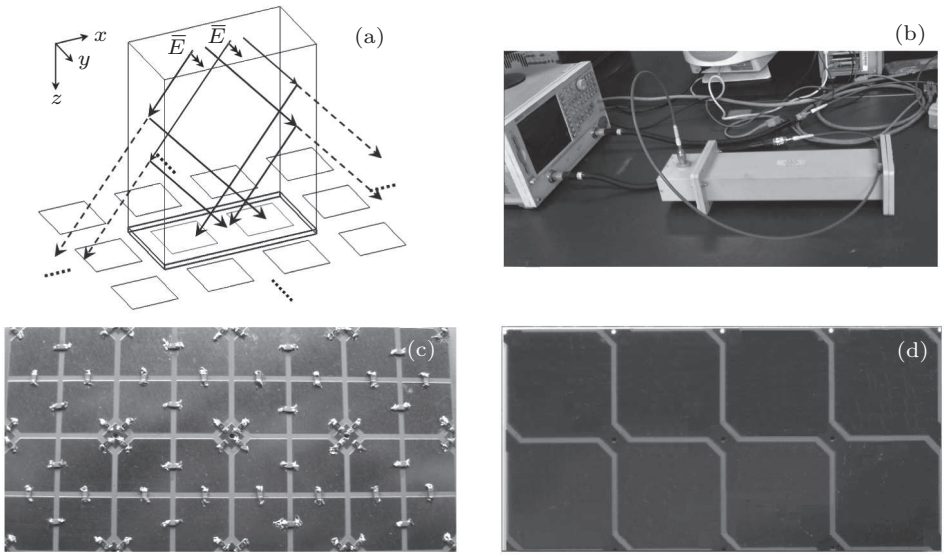


Fig. 6. Experiment structure: (a) sketch of the waveguide simulator, (b) experimental setup, (c) vertical view of the sample, (d) bias network.

As the measured results, the comparison between the measured data and the simulated results at TE incidence with proper incident angle θ is shown in Fig. 7. The incident angle is given by the formula

$$\theta = \arcsin(c_0/2af), \tag{5}$$

where $a = 0.1092$ m is the width of the WR-430 waveguide and f is the central frequency of the absorber. The values of frequency f are adopted to be 2.38 GHz and 2.14 GHz when the values of capacitance C_{Lu} are chosen to be 2.5 pF and 4.0 pF respectively. In Fig. 7, it is shown that the experimental results are in good agreement with numerical results, except that there are a few differences at the frequency devi-

ating from central frequency f_0, which may be attributed to the change of the incident angle θ with the frequency in the waveguide.

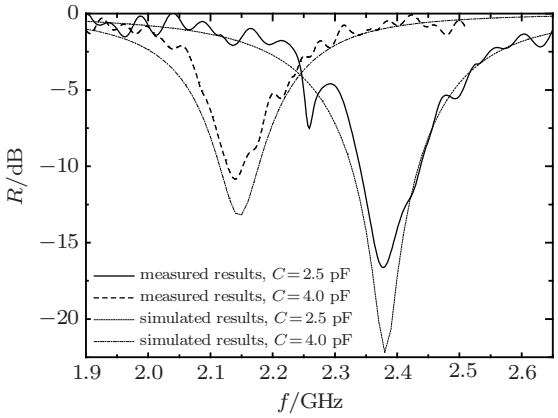


Fig. 7. Comparisons between experimental results and simulated results.

4. Conclusions

In this paper, an effective approach to designing a varactor-tunable absorber is presented and experimentally verified. The designed absorbers are regarded as a loaded receiving dual-polarized micro-strip patch antenna array. The frequency tuning capability of the proposed absorber is demonstrated through numerical simulations. A wide tuning range from 3.05 GHz to 1.96 GHz is achieved by changing the capacitance values of the varactors from 0.5 pF to 5.0 pF, better than −10 dB reflection losses are obtained at all times. Two homo-typical samples with different fixed capacitors are fabricated and measured using a standard waveguide measurement setup. The simulation and experimental results are observed to be in good agreement with each other.

References

[1] Munk B A 2000 *Frequency Selective Surfaces – Theory and Design* (New York: John Wiley & Sons)
[2] Sievenpiper D, Zhang L and Jimenez R F 1999 *IEEE Trans. Microw. Theory Technol.* **47** 2059
[3] Wang J B and Lu J 2011 *Acta Phys. Sin.* **60** 057304 (in Chinese)
[4] Lu J, Chen X Y and Wang J B 2008 *Acta Phys. Sin.* **57** 7200 (in Chinese)
[5] Sun L K, Cheng H F, Zhou Y J and Wang J 2011 *Acta Phys. Sin.* **60** 108901 (in Chinese)
[6] Chen Y Z, Wang Y and Nie Y 2012 *Acta Phys. Sin.* **61** 134102 (in Chinese)
[7] Cheng Y Z, Xiao T, Yang H L and Xiao B X 2010 *Acta Phys. Sin.* **59** 0536
[8] Sun L K, Cheng H F, Zhou Y J and Wang J 2012 *Chin. Phys. B* **21** 055201
[9] Sakran F and Neve O Y 2008 *IEEE Trans. Antenn. Propag.* **56** 2649
[10] Li M, Xiao S Q and Bai Y Y 2012 *IEEE Antenn. Wireless Propag. Lett.* **11** 748
[11] Gu C, Qu S B, Pei Z B, Zhou H, Xu Z, Bai P, Peng W D and Lin B Q 2010 *Chin. Phys. Lett.* **27** 117802
[12] Simms S and Fusco V. 2006 *Proceedings of the* 36*th European Microwave Conference*, September, 2006, Manchester, UK, p. 1167
[13] Simms S and Fusco V 2006 *Electron. Lett.* **42** 1197
[14] Fusco V F, Cahill R, Hu W and Simms S 2008 *Electron. Lett.* **44** 586
[15] Mias C and Yap J H 2007 *IEEE Trans. Antenn. Propag.* **55** 1955
[16] Tennant A and Chambers B 2009 *IEEE Trans. Antenn. Propag.* **58** 808
[17] Brown C and Carberry F 1963 *IEEE Trans. Antenn. Propag.* **11** 715