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A VARACTOR-TUNABLE HIGH IMPEDANCE SURFACE FOR ACTIVE METAMATERIAL ABSORBER

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Abstract—One varactor-tunable High Impedance Surface (HIS) is proposed and used in design of an active metamaterial absorber. The proposed HIS structure is based on mushroom-type HIS, in which varactors are introduced to adjust the effective capacitance and tune the resonance frequency. The primary ground plane is etched as the bias network for these loaded varactors, and another ultra-thin grounded sheet is attached to the bottom. In addition, the absorbing characteristics are introduced for dielectric loss to construct an active metamaterial absorber. Numerical simulations show that a wide tuning range can be achieved by adjusting the varactor capacitance, and effective absorption is realized at different states. Two identical absorbers, which are loaded with fixed-value chap capacitors of different capacitances, are fabricated and measured using a waveguide measurement setup. Excellent agreement between the simulated and measured results is demonstrated.

1. INTRODUCTION

High impedance surfaces (HIS) are a kind of meta-material structure which exhibits unique electromagnetic characteristics, namely an in-phase reflection coefficients for incident plane waves and suppressing of surface waves over a frequency range [1]. HISs are often referred to as artificial magnetic conductors (AMCs) and are widely used in design of low-profile antennas [1], ultra-thin electromagnetic absorbers [2] and leaky-wave antennas [3]. A number of HISs have already been proposed with different morphologies, while these HIS structures usually exhibit limited frequency bandwidth. The electromagnetic response of a HIS

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cannot be changed once designed and manufactured. Recently, studies of active HIS have been made to improve the performance of the HISs in the application. A well-established method for tuning HIS is incorporating electronically tunable components into its unit cells. A limited number of electronically tunable HISs have been designed using solid-state varactor diodes [4–9]. For biasing the varactor diodes, the tunable HIS requires a separate circuitry. Because of the effect of the bias network on the HISs' frequency response, biasing the varactor diodes properly is a major difficulty in the design of a tunable HIS.

In this work, we propose a novel varactor-tunable HIS for active metamaterial absorber. It is based on a Sievenpiper mushroom-type HIS. The tunability is achieved by connecting adjacent patches with varactors, and one proper bias network is designed to bias the varactors. The active metamaterial absorber is realized by introducing proper dielectric loss in the tunable HIS. The flexibility of the obtained active absorber is demonstrated through extensive numerical simulations. Two identical absorbers loaded with fixed-value capacitors are fabricated and measured to verify the simulations.

2. DESIGN PROCESS

A conventional mushroom-type HIS consists of small metal patches with grounding vias. This metasurface can be modeled as a parallel LC resonant circuit, as shown in Fig. 1(b), where the effective inductance L results from the currents flowing in the grounding vias and the effective capacitance C from the electric fields between adjacent metal patches. At the resonance frequency, the surface impedance of this metasurface is infinity and behaves as AMC, where in phase reflection will occur. Based on the ultra-thin HIS, resonance absorption can be realized when

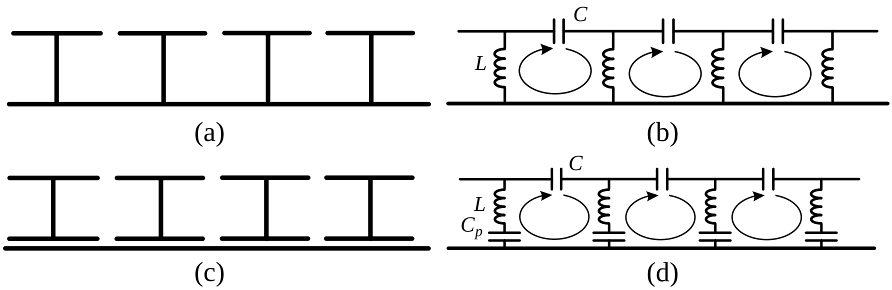


Figure 1. (a) Sievenpiper HIS structure and (b) equivalent circuit; (c) the proposed transformed HIS structure and (d) equivalent circuit.

proper electric loss is introduced.

The resonance frequency of a mushroom-type HIS will be tuned by adjusting the values of its effective circuit parameters. A relevant electrically tunable HIS is presented in [4, 5], in which the adjacent patches are connected by varactors, and the bias network for the loaded varactors is located on a separate circuit layer on the back of the ground plane.

In this work, we propose one novel varactor-tunable HIS structure based on a mushroom-type HIS in a square array. The design process is detailed as follows.

Firstly, varactors are loaded in a simpler manner to adjust the equivalent capacitance. In [4, 5], each metal patch in the periodic surface texture is connected to all of the adjacent patches by reverse biased varactors. To simplify the structure, we only connect the patch with two of the adjacent ones. Now four adjacent patches are united as one larger unit cell, and the varactors are only loaded between the adjacent patches in the same unit cell, as shown in Fig. 2(a). In this way, the loaded varactors are reduced to half.

Secondly, a transformed HIS structure is proposed for the design of the bias networks for loaded varactors. In the primary mushroom-type HIS, all metal patches with grounding vias are electrically connected, while the adjacent patches shall be electrically separated to introduce DC bias voltages. We propose a transformed HIS structure, in which each cell is electrically independent. The transformed HIS is based on the mushroom-type HIS and etched on the ground plane as a square patch array, which is the same as the one on the upper surface, and then attach another ultra-thin grounded sheet to the bottom, as shown in Fig. 1(c). Now two pieces of effective capacitance C_p, which belong to a similar parallel plate capacitor comprising parallel square patch and the ground plate, are serially connected in the parallel LC resonant circuit as shown in Fig. 1(d). The capacitance C_p is much larger, such that the change of the HIS's geometric topology has little effect on the parallel LC resonance, and the resonance frequency keeps almost the same as that of the primary mushroom-type HIS. In addition, when the varactors are loaded, the resonance frequency will be still dominated by the varactor capacitance C_v.

Finally, the varactor-tunable HIS with a proper bias network is constructed based on the transformed HIS. After the varactors have been loaded in the transformed HIS, we connect these patches in the nether patch array by a set of parallel diagonal strips, and the patches are only connected diagonally in a certain direction, as shown in Fig. 2(b). These connections have little effect on the effective capacitance C_p, and the parallel LC resonance will keep almost the

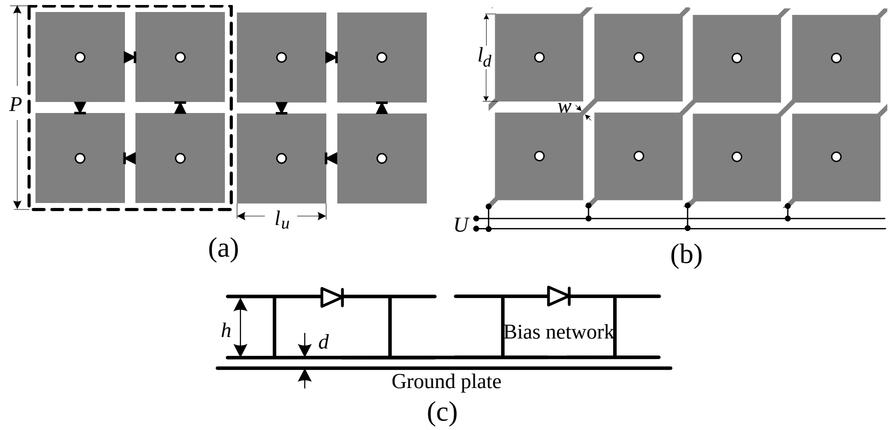


Figure 2. The proposed varactor-tunable HIS: (a) top view, (b) bias network, and (c) lengthwise cross-section.

same as that of the transformed HIS. In this way, a proper bias network is constructed, and the DC bias voltages can be introduced between the adjacent parallel diagonal strips as shown in Fig. 2(b). Now the lengthwise cross-section of the constructed varactor-tunable HIS is shown in Fig. 2(c).

Based on the proposed varactor tunable HIS, we choose its dielectric layer as a lossy dielectric medium — FR4 epoxy, and the proper dielectric loss can be introduced through the choice of the design value. Finally, one effective active absorber is constructed conveniently.

3. NUMERICAL SIMULATIONS

To demonstrate the properties of the proposed active absorber, three absorbers, which are based on the mushroom-type, transformed and varactor-tunable HIS respectively, are constructed and simulated at the same time. The basic parameters of the three absorbers are as follows: $P = 54.6\,\text{mm}$, $l_u = l_d = 25.7\,\text{mm}$, $w = 0.8\,\text{mm}$ and $a = 15.0\,\text{mm}$. The lossy dielectric layers with relative permittivity $\varepsilon_r = 4.6$ and loss tangent $tg\delta = 0.035$ are $h = 1.0\,\text{mm}$ thick. In addition, the attached ultra-thin grounded films in the transformed and varactor tunable HISs are 0.1 mm thick with relative permittivity $\varepsilon_r = 1.1$.

The first absorber is just the active one based on the varactor-tunable HIS. When the capacitance C_v of loaded varactors is assumed as different values and as the simulated results using HFSS software, the reflection phases and coefficients at vertical incidence are shown

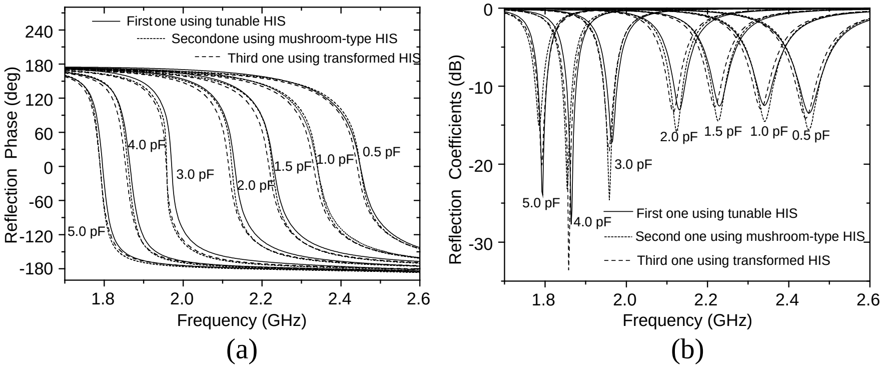


Figure 3. Frequency responses of the proposed absorber as the change of varactors' capacitance: (a) reflection phase and (b) reflection magnitude.

in Figs. 3(a) and (b), respectively. The phase diagram in Fig. 3(a) shows that in phase reflection occurs because of the parallel LC resonance. The frequency of in-phase reflection is tuned over the frequency range from 2.45 GHz to 1.79 GHz when the capacitance C_v is altered from 0.5 pF to 5.0 pF. In addition, better than 10 dB reflection loss is realized every time at the resonant frequency as shown in Fig. 3(b). Because these absorbers have a back metal film, the transmission coefficients will be zero, and the reflection loss indicates effective resonance absorption.

The second and third absorbers are based on the mushroom-type and transformed HIS, respectively, which are supposed to be loaded with chip capacitors in the same manner as shown in Fig. 2(a). Fig. 3 shows the simulated results of the second and third absorbers at the same time. It is shown that the resonant frequency is reduced by increasing the values of capacitance C_c. When the capacitance C_c of the loaded chip capacitors is assumed as the same value of capacitance C_v in the active one, the reflection phases and coefficients of these three absorbers, which are based on the tunable varactor, mushroom-type and transformed HIS, respectively, are basically uniform. It is indicated that the bias network of the varactor-tunable HIS has little effect on the parallel LC resonance.

In addition, to observe the absorbing capability of the active absorber at oblique incidence, it is simulated when C_v are assumed as 4.0 pF. The reflection coefficients at TE and TM incidences are shown in Fig. 4. It is shown that the absorptivity is kept well for a wide range of incident angles for different polarizations.

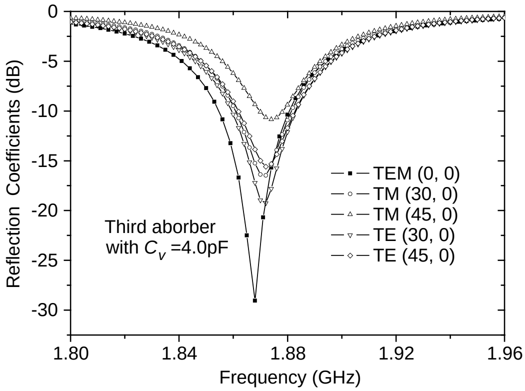


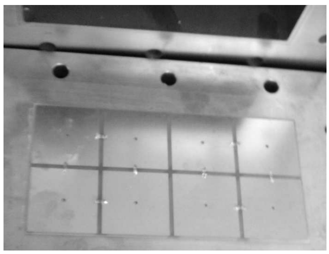
Figure 4. Reflection coefficients of the proposed absorber ($C_v = 4\,\text{pF}$) at oblique incidence.

4. EXPERIMENTAL VALIDATION

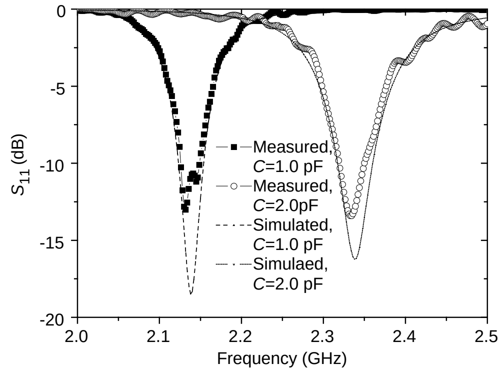
One experimental verification for the active absorber is carried out in a rectangular waveguide simulator. The waveguide simulator, as a convenient experimental setup, is developed by Brown and Carberry (1963) [10]. In the experimental setup, a metallic rectangular waveguide is terminated in a section 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 off the side waveguide walls, and the waveguide perfectly conducting walls can mirror an infinite series of images.

In our experimental setup, a WR-430 waveguide is used, its cross-sectional area is approximately $a \times b = 109.2\,\text{mm} \times 54.6\,\text{mm}$, and the fabricated absorber consists of a 2×4 array, as shown in Fig. 5(a). To overcome biasing problems in the waveguide simulator, the varactors are replaced with fixed-valued capacitors. Two same absorbers are constructed, in which the capacitances of the chap capacitors are chosen as $1.0\,\text{pF}$ and $2.0\,\text{pF}$, respectively.

The comparison of the measured S_{11} and simulated reflection magnitudes at TE incidence with corresponding incident angle θ is shown in Fig. 5(b). The incident angle θ is found by the formula $\sin\theta = c_0/2af$, where $a = 0.1092\,\text{m}$ is the width of the used waveguide WR-430. It is shown that the experimental results are in good agreement with numerical prediction.



(a)



(b)

Figure 5. Experimental structure and measured results of the active absorber: (a) photographs of experimental structure and (b) measured results versus simulated ones.

5. CONCLUSION

In this paper, one varactor-tunable HIS is proposed, in which a wide tuning range from 2.45 GHz to 1.79 GHz is achieved by altering the varactors capacitance from 0.5 pF to 5.0 pF. In addition, one effective active absorber is constructed when a proper dielectric loss has been introduced, and better than −10 dB reflection loss is obtained each time. Two same absorbers loaded fixed-valued capacitors of different capacitances are fabricated and measured using a standard waveguide measurement setup. A good agreement between the simulated and experimental results is observed.

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