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Development of a Resistor-Loaded Ultra-Wideband Absorber with Antenna Reciprocity

Xian Qi Lin, Peng Mei, Peng Cheng Zhang, Zhi Zhang (David) Chen and Yong Fan

***Abstract*—A novel method of developing an electromagnetic absorber is proposed through the designing of a ultra-wideband resistor-loaded planar dipole absorber. With the method, an antenna array structure is firstly designed for its best transmission performance and configured as an absorber with the application of the reciprocal principle. The designed planar dipole antenna has achieved the fractional bandwidth of 105% for an absorbing rate more than 90% under the normal incident. In addition, the thickness of the proposed structure is 0.128 λ_0 with λ_0 being the wavelength at the center operating frequency. Good agreement between simulated and measured results demonstrates the validity of the proposed method.**

***Index Terms*— Absorber structure, dipole antenna, resistor loaded, ultra-bandwidth absorber.**

I. Introduction

An electromagnetic absorber is, by its name, intended to absorb electromagnetic waves impinging on it and thus form a cloaking devices. It is desired to be of ultra-bandwidth, low profile, simple in configurations and versatile for applications. The early design of an absorber can be traced back to the screen proposed by Salisbury [1] in 1952; it uses a resistive sheet placed at a quarter-wavelength from a metal ground and its absorption bandwidth is relative narrow. Many structures have since been proposed in order to have wide-band absorption, especially in recent years. Among them are multi-resonance structures [2]-[4] and resistor loaded absorbing structures [5]-[6], the former achieving wide bandwidth at the cost of increased total structure thicknesses, the latter having the issue of requiring soldering many resistors on circuit boards. [7] presents a single-layer absorber structure that has a bandwidth of about 98.4% with the thickness of the substrate being 0.25 λ_0 (λ_0 is the wavelength at the center operating frequency). [8] reports a two-layer absorber structure of resistive Hilbert curve arrays that achieves a fractional bandwidth of 81% and 78% for horizontal and vertical polarizations, respectively; it has the thickness of 0.17 λ_0. [9] uses resistive triple-square loops to theoretically realize three resonances and a bandwidth of 92.2% with the thickness of 0.132 λ_0. [10] proposes a periodical structure with a resistive square loop being the unit cell; it achieves a wide-band absorption with a theoretically predicted bandwidth of 112% and a thickness of 0.225. [10]-[14] apply resistive inks to achieve broadband absorption, which circumvent the issue of soldering resistors and increase the circuit integration ability of the absorbers, albeit at the expense of high costs.

Most of the above reported absorbers were analyzed based on the equivalent circuit theory. For the absorbers based on simple structures, the equivalent lumped capacitance and inductance can be accurately computed [15]-[17], and simulations present the relatively accurate results that are in good agreements with those obtained with the full wave simulations [5]. But for the absorbers of multi- resonance or complex structures, the circuit theory or models cannot present accurate results. In addition, the equivalent circuit theory or models are not adequate or effective for designing structures since the designs need to take into account of electromagnetic field interactions.

In this paper, a novel method is proposed for designing absorber structures: an antenna array structure is first configured and optimized for its best transmission or radiation. By reciprocity, it will have the best absorption performance when it is used for signal receiving with the optimized source impedance terminated as a load. Without loss of generality, in this paper, we use the planar dipole arrays as the design case and show this new design method and its effectiveness.

II. The New Design Method and A Narrowband Dipole Array Absorber

In this section, we describe the proposed new design method through the design of a narrowband planar dipole array absorber.

First, the array or periodical structure with the planar dipole (shown in Fig. 1) as the unit element or cell is considered for its best radiation or transmission performance. To model it, the periodical boundary conditions are applied in both the x- and y-directions. A lumped port is set at the middle of the cell and dimensions of the unit cell are given in Fig. 1. Ansoft HFSS was used to simulate the structure.

Fig. 2 presents the simulated input impedance. The antenna input impedance Z_{in} has both the resistance and reactance. At 6 GHz, the input admittance of the dipole unit cell is $Z_{in} = 118.1 + j54.66$ (Ω) and the corresponding admittance is:

$$Y_{in} = 1/Z_{in} = 1/(118.1 + j54.66) = 0.00697 - j0.00323 \text{ (S)} \quad (1)$$

The capacitor of the following value can be placed at the input of the dipole element to cancel the reactance of the input impedance:

$$C_p = -imag(Y_{in})/(\omega) = 0.00323/(2\pi * 6 * 1e9) = 0.0857 \text{pF} \quad (2)$$

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Once the reactance is cancelled, the input impedance of the overall dipole antenna element with the capacitor is:

$$Z_{in} // Z_c = \frac{1}{Y_{in} + Y_c} = \frac{1}{0.00697} = 143.5\ (\Omega) \tag{3}$$

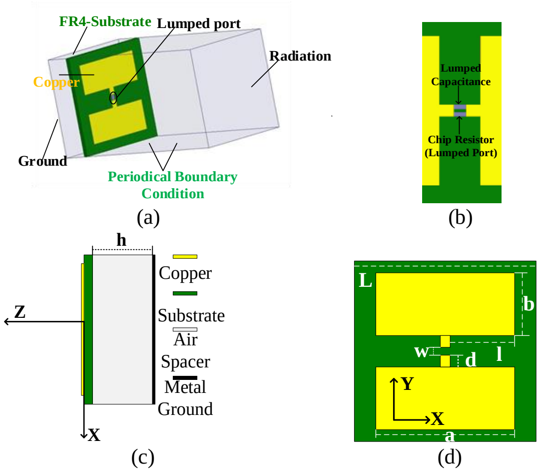

Fig. 1.The geometry of a dipole antenna array with randomly given sizes. (a) Perspective view. (b) Details of the port. (c) Side view. (d) Top view. (The permittivity, dielectric tangent loss and thickness of the substrate are 4.4 , 0.02, and 0.8 mm respectively; the distance between ground and FR4-Substrate is 5mm. and the dimensions of the antenna are a=15mm, b=6mm, L=20mm, l=6.9mm, d=1.4mm, w=1.2mm, h=5mm.)

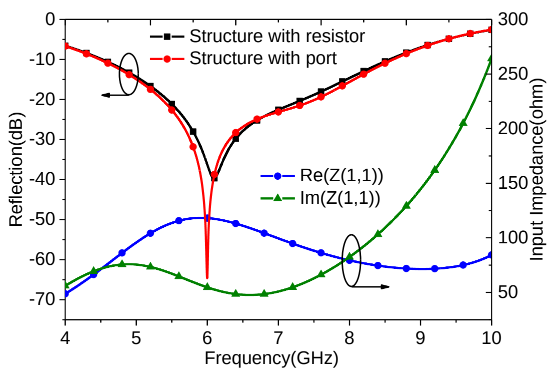

Fig.2.The input impedance of the dipole antenna array and the reflection coefficient comparison of the random antenna with port and resistor, respectively.

To achieve maximum power radiation, the source impedance of the generator connected to the dipole element should be $143.5\ \Omega$ which is a resistor. If the reference characteristic impedance is taken to be $143.5\ \Omega$, the simulated reflection coefficient is shown in Fig. 2. In it, we can see a very lowest reflection coefficient at 6 GHz as expected.

Based on the reciprocal principle, the above periodical antenna structure can also be used to receive or absorb electromagnetic wave. The only thing we need to do is to remove the generator and retain the capacitor of 0.0857pF and resistor of 143.5Ω which are placed at the input of the dipole element (as shown in Fig. 1(b)). As a result, the array or the periodical dipole array structure, originally designed for best radiation, now simply turn into a best performing absorber.

The above design can be expanded to the absorber array using other type of the unit cell. The design flow chart of our proposed method can be summarized as follows:

Step 1: choose the type of antenna element or cell based on the specifications for an antenna array configuration;

Step 2: simulate and optimize the structure terminated with the periodical boundary at the desired central frequency;

Step 3: compute the input impedance of the antenna element;

Step 4: compute the values of lump capacitor and resistor based on equations (1) to (3).

Step 5: prototype and measure the structure; fine tune the structure for fabrication errors.

III. Development of an Ultra-Bandwidth Absorber

The absorber developed above is of narrowband due to the frequency varying nature of the dipole input impedance and lump capacitance. In addition, the soldering of capacitors and resistors is required at a relatively high cost. In this section, we will show the design of an ultra-wideband absorber without the use of the lumped capacitors.

In our design, to achieve a wide bandwidth, the dipole element shown in Fig. 1 is modified to be of fan-shape as shown in Fig. 3. The ground plate is parallel to the fan-shaped dipole at a distance of h1 as similarly shown in Fig. 1(c). A common FR4 substrate with a loss tangent of 0.02, a relative permittivity of 4.4 and a thickness of 0.8 mm is used.

The proposed structure is simulated and optimized with the periodical boundary conditions for an input impedance of 50Ω and zero reactance (i.e., the dipole element is optimized for $Z_{in} = 50\Omega$) over a wide bandwidth. Ansoft HFSS was used for the simulation and optimization. The final optimized input impedance are shown in Fig. 4. We can see that the resistance and reactance of the input impedance vary not much and the reactance is close to zero within a relative wide band.

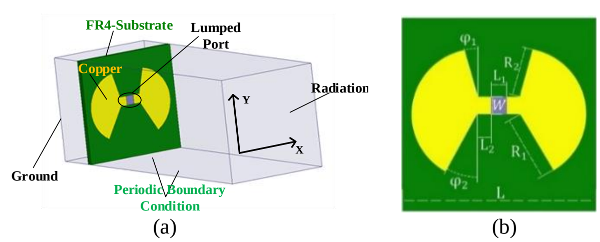

Fig. 3.The geometry of the proposed dipole antenna array. (a) Perspective view. (b) Front view. The dimensions of the proposed dipole antenna are L=15mm, R_1=5mm, R_2=3.733mm, L_1=1.2mm, L_2=1.0mm, W=1.3mm, $\varphi_1 = 15^\circ, \varphi_2 = 30^\circ$, h1=6mm.)

When a resistive load are connected to the antenna element, the reflection coefficient can be computed. Fig. 5 shows the results. It can be seen that the load of 82Ω presents the overall smallest reflections.

As mentioned before, a passive antenna is a reciprocal device that can either receive or transmit electromagnetic waves. When the designed array is used to receive electromagnetic waves from the atmosphere, it will become an electromagnetic absorber. As a result, by simply using the proposed fan-shape dipole array and terminating it with the chip resistor of 82Ω as shown in the inset of Fig. 6, we have obtain the wideband electromagnetic absorber.

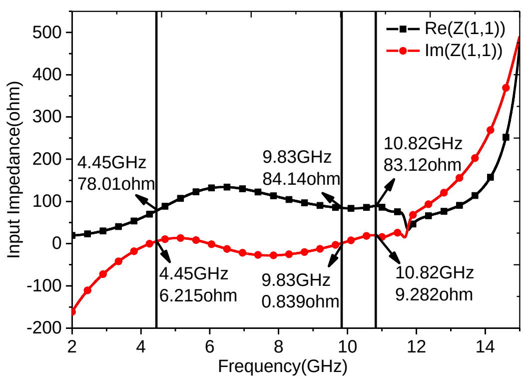

Fig. 4.The input impedance of the proposed antenna.

In order to prove that the impinging EM wave is indeed received and absorbed by the chip resistor, a simulation was run with a plane wave incident normally onto the antenna. In such a simulation, |S11| is the measure of the reflections from the absorber, which essentially measures the absorbing performance of the absorber. Fig. 6 shows the simulated result. As can be seen the absorption (A), which is defined as

$$A = 1 - |S_{11}|^2 \tag{4}$$

is quite good from 3.78 GHz to 11.78 GHz; it is more than 90%.

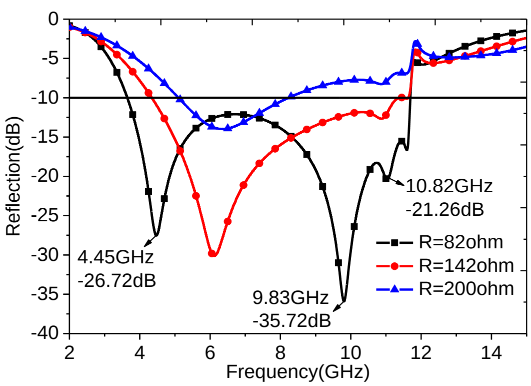

Fig. 5. The reflection coefficient under different resistance value.

A prototype was made as shown in Fig. 7.The plastic screws are used to fix the absorber structure. The test set up is shown in Fig. 8. Two horn antennas were used to measure the reflections of electromagnetic waves from the absorber. Pyramid foam absorbers were placed around the prototype to reduce electromagnetic coupling at low frequencies. We enlarge the distance from horn antennas to sample as far as possible to realize normal incidence. All the tests were performed in our anechoic chamber.

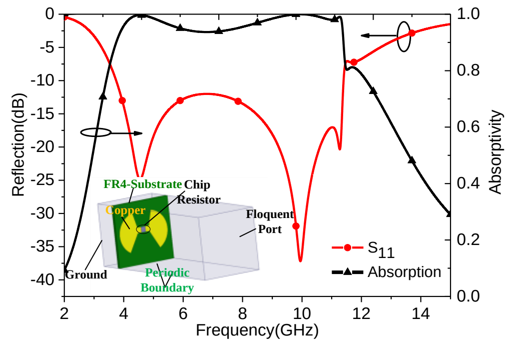

Fig. 6. The reflection and transmission of the proposed absorber structure (the inset shows the schematic of proposed absorber structure.)

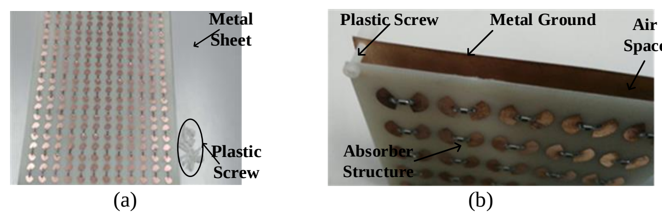

Fig. 7. The photo of fabricated absorber structure. (a) Top view. (b) Side view.

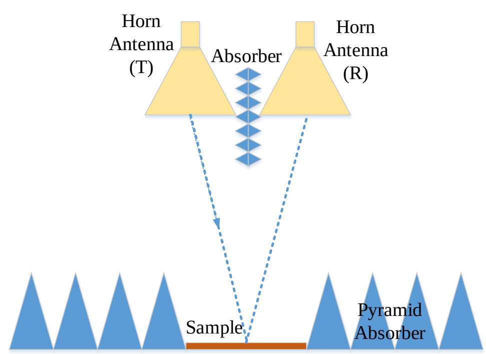

Fig. 8. The schematic diagram of the test.

The measured reflectivity of the prototype under normal incidence is shown in Fig. 9. The fractional bandwidth of the reflectivity below -10dB is 105%. In comparisons with the simulated results, although there is a frequency shift towards a lower frequency due to fabrication errors, simulation and test results do corroborate well, which verify the validity of our proposed design method.

By moving the transmitting and receiving horns away at the normal direction, the reflectivity or absorption of the absorber can also be measured at different TM and TE polarization incident angles, respectively. Fig. 10 present the results under TM and TE polarization wave. As can be seen, when the incident angle changes, the absorptions vary but still, wide absorption frequency bandwidths maintain for the incident angles of 0º to 30º. At 30º, there exists strong variations in absorption; they may be due to the fact that the dipole element was optimized for best radiation at the normal direction. With the incidence angle increasing, different side lobes of the dipole unit will be emerging, which will not ensure the uniform absorption at all frequencies. In order to obtain wide incidence angle absorption, a method named wide angle impedance matching (WAIM) surface can be introduced. The WAIM surface placed in front of the dipole array compensates the susceptance to realize the wide angle absorption. However, the bringing of WAIM surface will have a great impact on its profile and weight.

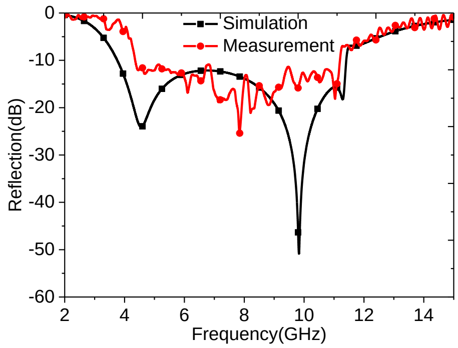

Fig. 9. Comparison of reflectivity for simulation and measurement.

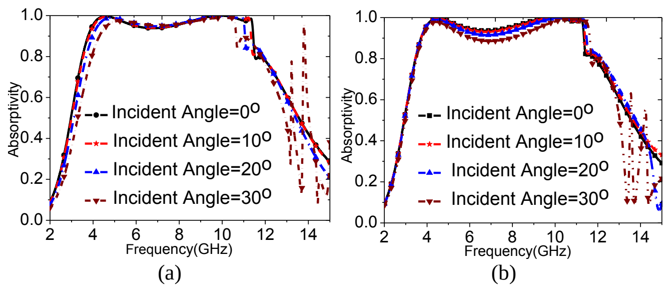

Fig. 10. The rate of absorption under different incident angle of polarization wave (a) TM polarization wave. (b) TE polarization wave.

Table I Bandwidth and Thickness Comparison of the Existing Single-Layer Absorber Structure

Ref.	FB	Thickness	Unit cell	Polarization
5	98.4%	$0.25\lambda_0$	Resistive square patch	Dual-polarization
6	81.7%	$0.13\lambda_0$	Hexagonal with resistors	All-polarization
14	117%	$0.20\lambda_0$	Hexagonal with film surface	Dual-polarization
This Work	105%	$0.128\lambda_0$	Dipole antenna with resistors	Single-polarization (can easily realize all- or dual-polarization)

A compare between the absorber we developed and those reported in open literature is shown in Table I. It is observed that the proposed absorber structure has a relative wide bandwidth and relative small substrate thickness. Although the proposed absorber is single-polarization only, the dual- or all-polarization can be easily realized based on our proposed design method.

IV. Conclusion

In this paper, a novel method is proposed for absorber design through the developments of a resistor-loaded ultra-wideband absorber. It applies the antenna array design theory and then use reciprocity for absorbers. The good agreements among theoretical analysis, simulation and test results have demonstrated the validity of the proposed method. The design case of the planar dipole antenna array presents the structure with relative small sizes and thickness.

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