Design of tunable metamaterial absorbers based on PIN diodes

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Abstract: A tunable metamaterial absorbers (MA) comprised of a new combination shaped metal elements printed on a dielectric substrate loaded with PIN diodes were demonstrated. Through biasing at different voltages to control the diodes, the reflectivity characteristics of the structure can be varied over the entire 2–18 GHz range. A qualitative analysis by a simple visualization method is carried out on the parameters of the tunable MA. Both numerical calculations and microwave measurements have verified the performance.

Keywords: tunable, metamaterial absorbers, PIN diodes

Classification: Electromagnetic theory

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1 Introduction

Electromagnetic metamaterials is basically an assembly of identical metallic elements arranged in a one or two-dimensional infinite array with a high frequency selectivity of electromagnetic waves. Up to now, it can be widely used in negative refraction [1], perfect lens [2], invisibility cloak [3], perfect absorber [4] and so on. Recently, many types of MA were demonstrated with high absorption [5, 6]. However, most of the MA have fixed reflectivity characteristics when it is well-done. Therefore, the tunable MA [7, 8] is required to meet the demands of ever changing application. Nevertheless, the tunable band is not wide enough.

In this paper, a tunable MA structure employing new combination shaped metal elements loaded with PIN diodes were presented. Under the guidance of the simple visualization analysis principles, a wide band tunable absorbing response is obtained by adjusting the diode bias voltage of PIN arrays.

2 Design and performance of tunable MA

2.1 Design and calculation

The MA sheet model is shown in Fig. 1. The absorbing panel consists of a single MA sheet is shown at the insert of Fig. 1(a). It is made of the metal film, thin substrate sheet and a grounded spacer. The overall thickness of the structure is d . The unit cell of MA is an assembly of identical elements arranged on a rectangular lattice. The elements loaded at their centers have been arranged in a rectangular array with inter-element spacing D . The equivalent circuit for the MA is shown in Fig. 1(b). Y_g denotes the input admittance of the ground plane, Y_a denotes the admittance of the freestanding elements alone, Y_{in} denotes the free-space input admittance of the MA for normal incidence.

The schematic view of composite MA is shown in Fig. 1(c). The PIN diodes are loaded between the combination shaped metal film. The reflectivity responses of the MA can be adjusted by changing the bias voltage of the active PIN diode array. The thickness of the grounded spacer which is adjustable to needs can also change the reflectivity responses. It can be regarded as an assistant cofactor for bias voltage regulation.

2.1.1 Prediction of the reflectivity by changing R_s

Phillips, BAP70-03 PIN diode is current controlled RF resistor for attenuators. As for the discrete nature of the PIN diode, it can be equal to an adjustable resistor with values of R_s ranging from 10 ohm to 1000 ohm. The change of R_s in fact changes the real part of Y_a and has little effect on the imaginary part. The analysis process of the tunable MA is shown in Fig. 1.

Fig. 1(c) shows a reflection coefficient of the free-space elements obtained by using the FEM code. In the frequency range of 2 GHz to 18 GHz one perfect reflection frequency to be around 10 GHz and one null at 15.4 GHz was observed. The admittances of the free-space elements sheet is calculated as

$$Y_a = -2Y_0\Gamma_1/(1 + \Gamma_1) \quad (1)$$

Fig. 1. The analysis process of the tunable MA (a) Side sketch of MA (b) Equivalent circuit of MA (c) Free-standing elements reflection coefficients (d) Admittances of a 5 mm grounded slab and free-standing elements (e) Measured Reflection coefficient of the 5 mm MA for different R_s compared with the computed result (f) Admittances of grounded slab of different thickness and free-standing elements (g) Measured Reflection coefficient of the MA for different values of d compared with the computed result.

in Fig. 1(d) where Y_0 represents the admittance of free-space, Γ_1 is the free-space reflection coefficient of the elements which can be computed after a full-wave calculation.

Fig. 1(d) shows the visualization analysis of the admittance match between Y_g and Y_a . The admittance of the 5 mm grounded dielectric substrate and the admittance of the elements are reported. At the lower frequencies in the band of 2 GHz to 10.4 GHz the value of the imaginary

part of the input admittance Y_g of ground plane behaves as an inductor and at high frequencies in the band of 10.4 GHz to 18 GHz behaves as a capacitance. Correspondingly, the elements sheet Y_a turns from capacitive to inductive behavior in the band of 2 GHz to 18 GHz. The elements sheet resonates at 10.4 GHz while the substrate equals acting as a high-impedance wall. Two parallel resonances between the elements and the grounded substrate can be generated at the first resonance around 5.5 GHz and the second resonance 16.7 GHz as shown in Fig. 1(d). Such resonance is obtained when the capacitive admittance of the elements assumes the same value of the inductive admittance of the substrate.

The reflection coefficient of the 5 mm MA for different R_s can be predicted as

$$\Gamma = 20\log_{10}((Y_0 - Y_{in})/(Y_0 + Y_{in})) \quad (2)$$

in Fig. 1(e) where $Y_{in} = Y_g + Y_a$ and $Y_g = -jY_m \cot(2\pi d\sqrt{\epsilon_r}/\lambda)$. From Fig. 1(e) it can be seen that the calculated reflectivity characteristics of MA can be varied over the entire 2–18 GHz range, but that there are two “dead-spots” at approximately 8 GHz and 18 GHz which are related to the mismatch between Y_{in} and Y_0 . In the frequency range of 2 GHz to 8 GHz, the absorption effect has increased gradually with the increase of R_s . The first absorption peak is located in 5.5 GHz corresponds to the first parallel resonance in Fig. 1(d). In the frequency range of 8 GHz to 18 GHz, the performance -8 dB in the band from 9.8 GHz to 17 GHz is obtained.

In order to verify the reliability of the calculated result, the PIN diode was replaced by chip resistor. The measured reflection coefficient of three samples realized by different chip resistor value (one declared for 180 ohm, another for 270 ohm, the third for 390 ohm) is presented in Fig. 1(e) compared with the computed results. Compared the curves of computed results with that of experiment, the curves changing trend are basically the same. It is seen that there is a difference in the computed and measured peak frequencies. The main reason of this frequency shift should be attributed to the parasitic effect of the chip resistors at high frequencies, in addition to the fabrication error and the coarse soldering process for inserting the chip resistors into the elements. Besides, the finite elements array which is supposed to be infinite at the time of computation.

2.1.2 Prediction of the reflectivity by changing d

The change of d in fact changes the imaginary part of Y_g . The analysis process is shown in Fig. 1.

Fig. 1(f) shows the visualization analysis of the admittance match between Y_g and Y_a . By increasing the thickness of the grounded spacer (from 4.5 mm, to 5.8 mm, and to 7.5 mm), the high-impedance wall of the substrate shifts from high frequency to low frequency (from 10.1 GHz, to 8.5 GHz, and to 7.1 GHz). As a result, the parallel resonances between the elements and the grounded substrate generated at the first resonance decreases from 5.4 GHz to 4.9 GHz and the second resonance decreases from 16.7 GHz to 15.1 GHz.

According to Eq.(2), the reflection coefficient of the MA can be predicted in Fig. 1(g). In the frequency range of 2 GHz to 8 GHz, the first absorption peak is moved to the low frequency with the thickness of absorbing material increasing. It is corresponding to the trends of the first

parallel resonance in Fig. 1(f). In the frequency range of 8 GHz to 18 GHz, the same performance was obtained which is corresponding to the trends of the second parallel resonance in Fig. 1(f).

The measured reflection coefficient of three samples realized by different d is also presented in Fig. 1(g) compared with the computed results. Similar with the law in Fig. 1(e), the curves changing trend of the predicted values and measured ones in Fig. 1(g) are basically the same.

2.2 Fabrication and measurement

The actual absorption performance of the fabricated tunable MA was measured in an anechoic chamber and compared with the calculated ones. The design example has 11×12 perfectly conducting elements loaded with one PIN diode (Phillips, BAP70-03) in the middle with a whole size of $180 \text{ mm} \times 180 \text{ mm}$ printed on an FR4 substrate. The whole view and near view photographs of this fabricated MA are shown in Fig. 2(a) and Fig. 2 (b), respectively. The substrate is commercial FR4 with permittivity equal to $4.5-j0.088$ with a thickness of 0.7 mm. The air spacer has been created by employing a homemade foam substrate with a relative permittivity of $1.05-j0.017$ with a thickness of 4.3 mm.

Fig. 2. Fabrication and measurement of the tunable MA
(a) Whole view of MA (b) Near view of MA (c)
Measured Reflection coefficient of the 5 mm MA
for different PIN-diode resistance.

The reflectivity characteristics of the tunable MA panel were measured between 2 GHz and 18 GHz in a calibrated NRL arch using an Agilent 82357E vector network analyzer. For these measurements the MA panel was modulated by a 10 MHz sine-wave signal with $V_{pp} = 2$ V. The MA panel can be controlled by varying the DC bias applied to the Pin diodes.

Fig. 2(c) shows the measured reflectivity responses obtained for various Pin diode resistance levels in the range of 47–1000 ohm. Similar with the trends of the test results in Fig. 1(e), there are also two “dead-spots” at approximately 8 GHz and 16 GHz. In the frequency range of 2 GHz to 8 GHz, the absorption effect has increased gradually with the increase of R_s . In the frequency range of 8 GHz to 18 GHz, as the Pin diode resistance is increased from 47 to 100 ohm, the reflectivity level reduces across a band of frequencies from 8 to 16 GHz and shows a single absorption peak response at around 4 GHz. At the Pin diode resistance of 180 ohm a reflectivity level of less than -10 dB is achieved from 9 to 14.5 GHz. For further increases in the Pin diode resistance from 150 to 1000 ohm, the reflectivity curve shows a double absorption peak response.

3 Conclusions

In this paper a deep-depth analysis and design are presented on the reflectivity of tunable MA structure consists of metallic film interconnecting with surface mount PIN diode. Measured results show that the structure can be tuned to provide a variable reflectivity response over a band of frequencies from 2–18 GHz. The results demonstrate that the use of the visual graphic method would provide a visualization aid to the transformation of appropriate parameters. These research results provide an effective theory instruction for the design of tunable MA structures for different frequency band usages.

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