Planar Metamaterial for Matched Waveguide Termination

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Abstract **─** We present the design, fabrication, and characterization of a novel matched waveguide termination based on planar artificial metamaterial. This matched termination is realized by recent developed planar metamaterial absorber, which can be designed to near-completely absorb the propagating electromagnetic energy at the edge of a shorted rectangular waveguide. Theoretical discussions, numerical simulations and microwave experiments are employed to illustrate the matched characteristics of the proposed waveguide termination. As an example, a matched waveguide termination with standing wave ratio of 1.23 is experimentally demonstrated at microwave frequency. Our result yields a promising approach to design of novel waveguide terminations by techniques of metamaterials.

Index Terms **-** Metamaterial absorber, waveguide, and termination.

I. INTRODUCTION

Matched waveguide termination, as a kind of important component, has been widely employed in waveguide systems to assist microwave measurements. The main functionality of such component is to absorb the electromagnetic field energy at the end of waveguides so as to eliminate the influences by waves reflecting at the edge. The origins of matched waveguide terminations could be traced to mid-20th century. Since that time, a great many approaches were developed to make matched terminations by, for examples, inductive and capacitive iris pairs [1], long sizes of tuners and dissipative elements [2], double-slug transformers and lossy dielectric loads [3], short-circuiting plungers and dissipative elements [4], and sliding loads by sections of lossless and lossy dielectrics [5]. Nowadays, the most commonly used waveguide matched terminations are built by merging the tapered wedges or slabs of lossy materials into waveguides (see [6]).

Unfortunately, all the existed matched waveguide terminations have the same disadvantage of large dimensions, restricting the possibility for integration application. Moreover, the present techniques of waveguide terminations are mainly focused on microwave frequencies, hardly suitable for terahertz and optical applications, such as silicon waveguide and nanophotonic integration. On the other hand, microwave absorbers have been rapidly developed in the past half century. Variety of absorbers was reported, such as dielectric absorbers, magnetic absorbers, ferrites, and ferroelectrics [7]. In particular, recent planar microwave absorbers, owning to the advantage of ultra-subwavelength thicknesses, have attracted considerable attention in design of communication radio frequency devices and antennas, some of which can be found in [8-11].

In the past decade, artificial structured

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materials, termed metamaterials [12–16], have gained extensive research interests. Theoretically predicted by Veselago [17] and experimentally realized by Smith et al. [18, 19], metamaterials enable a fantastic approach to control electromagnetic wave propagating inside such media by properly designing the “meta-atoms”. Due to the excellent flexibility introduced by design of metamaterials, various novel applications have been considered such as super-lens [20], invisibility cloaks [21], enhanced antennas [22], etc. Besides, there is another important application, using metamaterials to design planar absorber so called metamaterial absorber (MA) [23]. Such MA is impedance-matched with free space while exhibits high loss, which is able to absorb incident electromagnetic wave energy near perfectly [24]. It is commonly known that, for the conventional absorbers, the electromagnetic wave energy is transformed into heat in the absorbing materials. For the MA, the energy is mainly consumed by the metal metamaterial resonators, due to the high-strength resonance characteristics [25]. Moreover, the absorbing frequency band can be easily operated from microwave to terahertz and optical frequencies by scaling the geometrical sizes [26, 27] and the bandwidth can also be widened by various techniques [28–31].

Recently, in our previous works we have demonstrated that the rectangular waveguide can be used to experimentally demonstrate the absorptivity of MAs [32], giving an alternative method to analyze the configurations of MAs compared with the free space measurement method [33]. Most importantly, this method provides a fire-new approach to design the matched terminations, especially for the rectangular waveguide applications. Comparing with conventional matched waveguide terminations [1–6], the newly metamaterial-based termination exhibits high-flexible design tolerance by using various metamaterial configurations. In this paper, we present a novel design of the planar matched terminations for rectangular waveguide applications, for the first time to our knowledge, by using metamaterials. Such matched termination is realized by designing a metamaterial absorber that suitable for shorted rectangular waveguide, which matches the characteristic impedance of waveguide and can absorb incident electromagnetic (EM) energy. As an example, a matched waveguide termination operated at X-band (8 GHz – 12 GHz) is designed, fabricated, and characterized by means of numerical simulation and microwave experiment. This paper is arranged as follows: section II gives a briefly discussions on the theoretical relationship between absorptivity and effective constitutive parameters; a metamaterial absorber is numerically designed in section III, and its application as matched terminations is demonstrated in section IV.

II. THEORY

We start by considering electromagnetic wave propagating at an interface between medium 1 and medium 2, the material properties of which are characterized by the relative permittivity $\varepsilon_{r,i}$ and relative permeability $\mu_{r,i}$, where i = 1, 2 denotes each medium. Fresnel equations give the reflections of s-polarized and p-polarized waves to be,

$$R_s = \left| \frac{\eta_2 \cos\theta - \eta_1 \sqrt{1-(n_1 \sin\theta / n_2)^2}}{\eta_2 \cos\theta + \eta_1 \sqrt{1-(n_1 \sin\theta / n_2)^2}} \right|^2 \quad (1a)$$

$$R_p = \left| \frac{\eta_2 \sqrt{1-(n_1 \sin\theta / n_2)^2} - \eta_1 \cos\theta}{\eta_2 \sqrt{1-(n_1 \sin\theta / n_2)^2} + \eta_1 \cos\theta} \right|^2, \quad (1b)$$

where $\eta_i = \sqrt{\mu_{r,i}\mu_0 / \varepsilon_{r,i}\varepsilon_0}$ is the characteristic impedance and $n_i = \sqrt{\mu_{r,i}\varepsilon_{r,i}}$ is the refractive index. For sake of simplicity, we restrict our discussion on the normal incident wave (i.e., the incident angle $\theta = 0$) and medium 1 is free space with $\varepsilon_{r,i} = \mu_{r,i} = 1$. Equation (1) is therefore reduced to be,

$$R = R_s = R_p = \left| \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \right|^2 = \left| \frac{\sqrt{\mu_{r,2}} - \sqrt{\varepsilon_{r,2}}}{\sqrt{\mu_{r,2}} + \sqrt{\varepsilon_{r,2}}} \right|^2. \quad (2)$$

If we consider the metamaterial absorbers that consisted of electric-inductance-capacitor (ELC) resonators and backed metallic plate [23], in which case zero transmissivity is achieved, and thus the absorptivity could be simply expressed as,

$$A = 1 - R = 1 - \left| \frac{\sqrt{\mu_{r,2}} - \sqrt{\varepsilon_{r,2}}}{\sqrt{\mu_{r,2}} + \sqrt{\varepsilon_{r,2}}} \right|^2. \quad (3)$$

Equation (3) reveals the relationship between the absorptivity and effective material parameters ε_r and μ_r of metamaterial. By properly designing the geometry of metamaterial's unit cells and the coupling strength between those units and the metallic plate layers, one can successfully achieve the conditions of $\varepsilon(\omega) = \mu(\omega)$ and large loss tangents tan δ_ε and tan δ_μ. The MAs can, therefore, impedance-match with free space and absorb the electromagnetic waves completely.

III. NUMERICAL DESIGN OF METAMATERIAL ABSORBER

Before discussing the proposed planar matched waveguide termination, we first numerically design an MA with nearly complete absorption, the unit cell of which is shown in the insert of Fig. 1. The designed structure is similar to [23], made up of metallic ELC resonator (constructed by copper line with width of 0.2 mm and thickness of 0.017 mm, and the electric conductivity of copper is 5.8×10^7 S/m) on one side of the FR4 substrate and metallic ground plane on the other side.

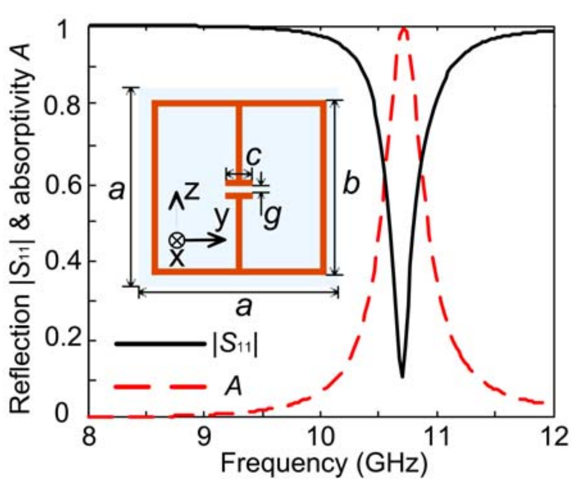

Fig. 1. Simulated reflection and absorptivity of the MA unit cell. The inset is the schematic representation of the MA unit cell with dimensional parameters: $a = 5$ mm, $b = 3.3$ mm, $c = 1$ mm, and $g = 0.2$ mm. The substrate is FR4 with relative dielectric constant $\varepsilon_r = 4.0(1 + 0.02i)$ and thickness of 0.8 mm.

In our simulation, perfect ***E*** boundaries along the *z*-axis and perfect ***H*** boundaries along the *y*-axis are applied to mimic a transverse electromagnetic (TEM) wave propagating to the periodically arranged unit cells. Through strict numerical calculation by Ansoft HFSS software, a group of geometrical parameters are obtained, as listed in the caption of Fig. 1. It is seen that, there is a reflection dip centered at 10.7 GHz (see the black solid line). Due to existence of the ground plane on the other side of the substrate, no EM power can be transmitted through the structure. Since the surface of the metamaterial is smooth enough compare to the wavelength of incident wave, the influence of scattering is negligible. Therefore, the absorptivity of the MA comes to be $A = 1-|S_{11}|^2$. The red dashed line in Fig. 1 indicates that more than 99.9 % EM energy is absorbed by the MA at the resonant frequency.

The surface current distributions on the ELC resonant and the ground plane are shown in Fig. 2 to reveal the resonant mechanism at resonance frequency 10.7 GHz. For EM wave normal incidence, the electric currents on the ELC pattern are symmetrical and thus provide the electric response. The antiparallel currents between the ELC cell and the ground plane show that a magnetic response is induced by the incident EM wave. The electric response and magnetic response appeared simultaneously at the given frequency so that enables the MA to absorb the incident electric and magnetic fields completely.

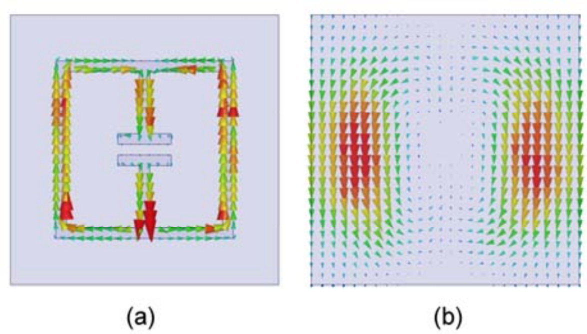

Fig. 2. The surface current densities on the metamaterial unit cell and ground plane at resonant frequency 10.7 GHz.

As analyzed in [23], the near-perfect absorption is mainly arisen from two aspects. The first one is that the metamaterial provides electric and magnetic resonances and enhances the local EM field. The other aspect is the losses in the coppers and substrate material. Both of the structure resonance and material losses provide the impedance-match and absorption properties. In the following section, we show the application of the proposed metamaterial absorber as a planar matched waveguide termination operated at microwave X-band.

IV. MATCHED WAVEGUIDE TERMINATION

The above-mentioned MA shows near-perfect absorption to the normal incident EM wave, it is expected that similar MA is also useful for rectangular metallic waveguides where the incident waves are restricted into transverse electric mode. In such a way, MA can be applied as a planar matched waveguide termination. As shown in Fig. 3, the fabricated matched waveguide termination is 22.86 × 10.16 mm^2 in size to fit the transverse size of the X-band rectangular waveguide and the other dimensional parameters are all the same as shown in the above section except the period space a = 4.5 mm.

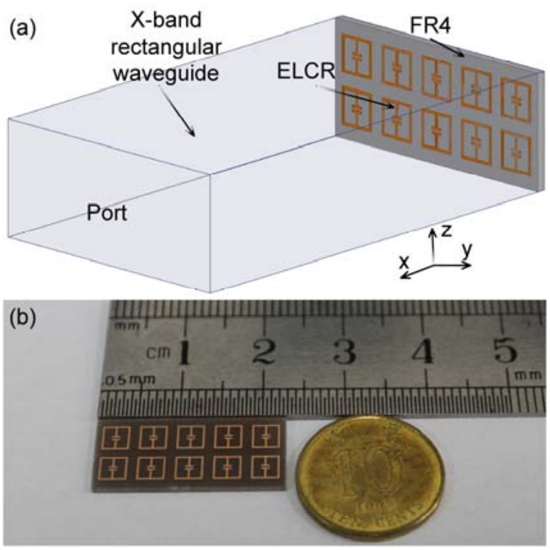

Fig. 3. (a) Schematic representation of the X-band matched rectangular waveguide termination based on the metamaterial and (b) fabricated metamaterial sample.

The performance of a matched waveguide termination is characterized by the standing wave ratio (SWR), commonly defined as the amplitude ratio of a partial standing wave at an antinode (maximum) to an adjacent node. For ideal case that free of any reflection, no standing wave is formed and thus SWR equals to 1. The measurement is performed by a vector network analyzer (Agilent N5230A) and coaxial-to-rectangular-waveguide transition. Figure 4 shows the measured SWR compared with the numerical result. It is seen that the matched termination exhibits a narrow matched band of about 80 MHz (SWR < 1.5) centered at 10.62 GHz with the dip value of SWR about 1.23. Comparing the measured and simulated results, there is a little shift of the matched band, mainly due to the fabrication tolerance. The reflection of the MA in rectangular waveguide is also in good agreement with that in free space, which verifies the equal effectiveness in both cases. Surface current distributions are further investigated in Fig. 5, where same resonance characteristics are found compared with that in Fig. 2.

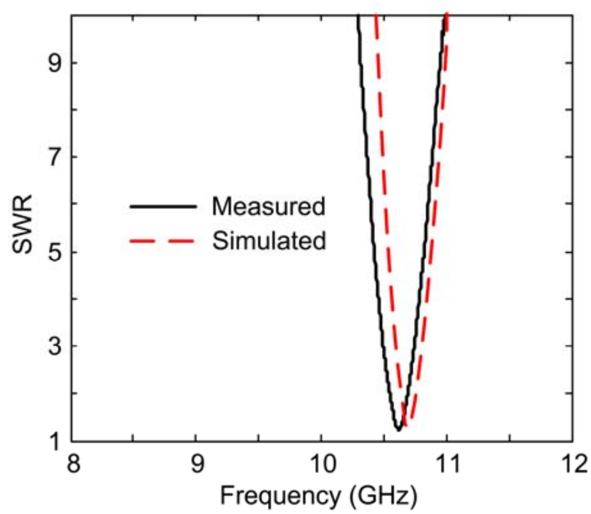

Fig. 4. Measured and simulated SWR of the proposed matched waveguide termination.

Moreover, the measured and simulated input impedance characteristics are presented in Fig. 6 to further show the impedance-match properties. In both measurement and simulation, the reference planes are chosen as close as possible to the metamaterial plane. The comparison shows a good agreement between the numerical and measured results near the resonant frequency. The measured result indicates a considerable mismatch which, leads to a big SWR at the design frequency (the circle of SWR = 1.5 is also shown in Fig. 6). To miniaturize the mismatch or SWR, some methods should be explored which, will be discussed in the next of this paper.

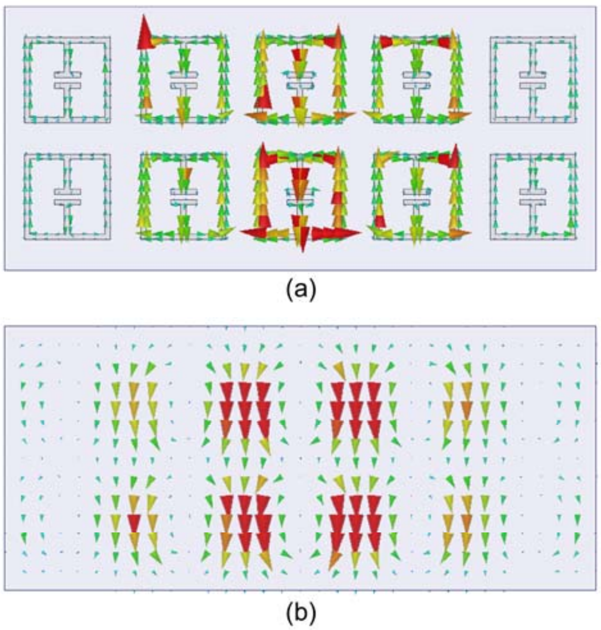

Fig. 5. The surface current densities on the metamaterial unit cells and the shorted wall at resonant frequency 10.7 GHz.

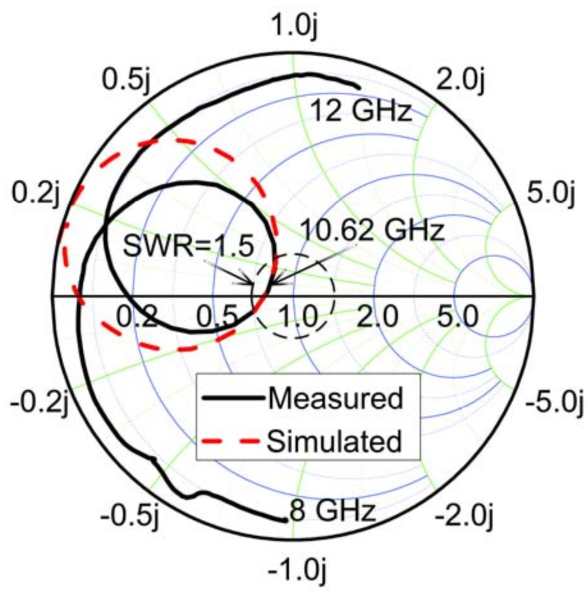

Fig. 6. Measured and simulated input impedances of the metamaterial based matched termination.

The performance of the above matched termination can be further improved to near perfect impedance-match by turning the thickness of the substrate or changing the substrate material with other loss values, as the same optimization method of MAs which, have been discussed in [23]. Here we give an optimized result of the proposed matched termination by adjusting the thickness of the substrate. Figure 7 shows the simulated SWR characteristics of the matched termination with different thicknesses of the substrates range from 0.8 mm to 1.0 mm. It can be known that the matched termination keeps a reasonable matched performance along the whole considered range (the SWR curves have a matched frequency band of wider than 70 MHz for SWR < 1.5). When the thickness of the substrate increases, the SWR first decreases and trends to the optimum value of 1.035 at 10.7 GHz and then arises back to the 1.23 at 10.7 GHz (see the inset figure of Fig. 7). In this case, the optimized thickness of the substrate is 0.9 mm. The optimized result shows a very well impedance-match characteristic, similar to the conventional matched waveguide terminations [1-6].

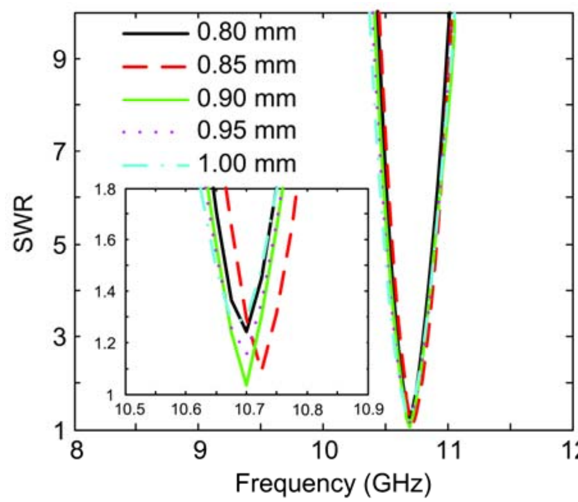

Fig. 7. Simulated SWR characteristics at different thickness of the substrate. The inset figure is the amplified SWR characteristics near the resonance frequency.

As a concluding remark, we would like to note that the unit cell of MA proposed in this paper is only for example, and it can be replaced by any other configurations reported in [34, 35]. Although our work is only focusing on microwave frequency, it can be expected that the behavior presented in this paper is quite general and can be also useful for THz or even optical range. Moreover, the narrow bandwidth can be widened by variety of techniques [26-31].

V. CONCLUSION

In this paper, a novel schematic design of X-band planar matched waveguide termination based on the metamaterial has been discussed for the first time to our knowledge. The measured and simulated results demonstrated that the proposed inclusion exhibited a narrow matched frequency band of about 80 MHz (SWR < 1.5) centered at 10.62 GHz. It was also shown that such near perfect matched characteristic could be optimized by adjusting the thickness of substrate. We expect that the matched frequency band can be operated from microwave to terahertz, and even optical frequencies by changing the structure sizes and the bandwidth can be enlarged by using some broadband techniques. It opens the way to design and fabricate the novel matched termination for waveguide by using the very interested metamaterials. It also has the broad applications in microwave engineering areas, for example, it can be used in design of traveling-wave antennas or leaky-wave antennas as matched terminations.

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