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A Novel Quasi-TEM Mode Planar Waveguide for Periodic Structure Measurement Applications

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Abstract—In this paper, a novel planar waveguide with quasi-TEM mode for periodic structure measurement applications is proposed. Unlike conventional parallel double conductor transmission lines (PDCTL) which suffer from mismatch to 50 ohms, the proposed planar waveguide consisting of an F4B substrate, a metal conductor line, and a metal base has easy access to match to 50 ohm through a special transition region and also has a satisfactory insertion loss in a wide band. The metal conductor line etched on one side of the F4B substrate, and the metal base is parallel to mimic a perfect electric wall, where a "fake" infinite plane is realized. The proposed planar waveguide has a wide measurement bandwidth with the reflection coefficient below −15 dB, which cannot be realized by a standard rectangular waveguide. Good agreements between the simulated and measured results are obtained. In addition, a simple periodic structure is designed as an example. The transmission characteristics of the periodic structure are simulated and compared in two different methods, namely, standard periodic structure simulation method in free space and proposed planar waveguide method. All the measured results demonstrate the validation of our designed planar waveguide, which is convenient and economical for periodic structure measurement applications.

1. INTRODUCTION

With the rising of metamaterial, amounts of researchers pay their attentions to metamaterial due to its peculiar properties such as single or double negative index [1, 2], zero refraction index [3], and gradient refraction index [4]. Taking the advantage of metamaterial, some amazing products, such as cloaking [5], perfect absorbers [6], frequency select surfaces [7–9], are produced. In general, some experimental works are carried out to verify performances of designed metamaterial structures, such as resonant frequency and transmission characteristics. Usually, there are two methods to measure transmission characteristics of periodic structures. The first one is the bow antenna measurement which is usually used to measure absorbers or frequency selective surfaces, where two wideband horn antennas are utilized to transmit and receive electromagnetic wave [10, 11]. In this case, a relatively large sample is preferred to ensure the accuracy of measurement results, which is highly costly. Moreover, the defect of the bow antenna test method is not avoided when the measurement frequency is below 4 GHz, since there exists strong coupling between transmitting and receiving antennas. The other method is using standard rectangular waveguide to measure transmission characteristics where the periodic structure is embedded in the waveguide. Due to finite main mode bandwidth, the standard rectangular waveguide is usually for narrow bandwidth measurement. In [12], a WR-430 standard waveguide is used to measure S-parameters of a split-ring resonator (SRR) structure in a narrow bandwidth to retrieve its effective electromagnetic parameters, where the SRR example is embedded inside of waveguide. In [13], some standard waveguides are used to measure the reflection coefficient in different frequency bands

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separately, and the ultima measured results are pieced together to obtain reflection coefficient in a wide frequency band. This method is troublesome and needs some different dimension under-test structures to accommodate different sizes of standard waveguides.

In this paper, we design a novel planar waveguide with a quasi-TEM mode to measure transmission characteristics of a periodic structure in a wide frequency band. The planar waveguide has a simple structure with an F4B substrate, a metal conductor line, and a metal base. The metal conductor line etched on one side of the substrate, and metal base is parallel to mimic the perfect electric condition, where a "fake" infinite plane is realized compared to the "authentic" infinite plane established in commercial software High Frequency Simulator Structure (HFSS). The proposed planar waveguide is derived from the conventional parallel double conductor transmission lines (PDCTL) and improves PDCTL's defects such as difficult matching to 50 ohms. In order to make the proposed planar waveguide have easy access to 50 ohm, a special transition region is introduced, whose characteristic impedance in every transverse section remains 50 ohms, and the simulated reflection coefficient below −15 dB in the whole band denotes the good transmission characteristics and high efficiency of the planar waveguide. Then, a simple periodic absorber structure is designed and measured with the proposed planar waveguide, where the periodic absorber structure is vertically embedded inside the planar waveguide. The results obtained from standard periodic structure simulation method in free space using HFSS are presented for comparison. All measured results demonstrate the effectiveness and validation of our design idea. Main advantages of the proposed planar waveguide are economical and meet the demand of wideband measurement.

2. ANALYSIS OF THE PROPOSED PLANAR WAVEGUIDE

A standard planar waveguide propagates electromagnetic wave in TEM mode. The basic structure to realize TEM mode transmission is parallel double conductor transmission lines (PDCTL) as shown in Fig. 1. However, there exists a tough problem to realize the PDCTL matching to 50 ohms in a wide band. In order to avoid a difficult mismatch case, we propose an improved planar waveguide based on the PDCTL. It has an easy access to match to 50 ohms in a wide frequency band as presented in Fig. 2. The proposed planar waveguide consists of a metal conductor line, an F4B substrate, and a metal base. The thickness, permittivity, and loss tangent of the F4B substrate used in our design are 1 mm, 2.65, and 0.002, respectively. Port 1 and Port 2 are both matched to 50 ohms and connected to SMA connectors in measurement. The under-test periodic structure is exactly embedded between the metal conductor line etched on the F4B substrate and metal base for practical measurement. The distance h between metal conductor line and metal base can be flexibly selected and determined based on dimensions of the under-test periodic structure cell. In order to ensure good transmission characteristics of the proposed planar waveguide, the transition region in Fig. 2(a) is introduced. Provided that the characteristic impedance of every transverse section maintains 50 ohms with distance h increasing, a good transmission from port 1 to port 2 with low reflectance will be achieved in our design.

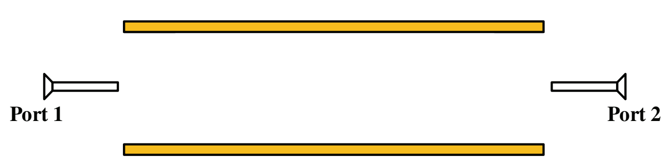

Figure 1. The geometry of double conductor transmission line (orange region is the conductor).

In fact, the proposed planar waveguide can be approximately served as a generalized microstrip line structure, where the supporting substrate is a hybrid of F4B-substrate and air spacer, and the height of air spacer is variable with the transition region forward in the meanwhile. It is widely acknowledged that the characteristic impedance of a microstrip line is closely related to the height of the metal conductor line respect to metal ground, width of metal conductor line, and properties of substrate (such as the thickness of substrate and permittivity of substrate). In this design, the substrate is chosen as F4B with 1 mm thickness and 2.65 relative permittivity. With the height of air spacer h increasing, the

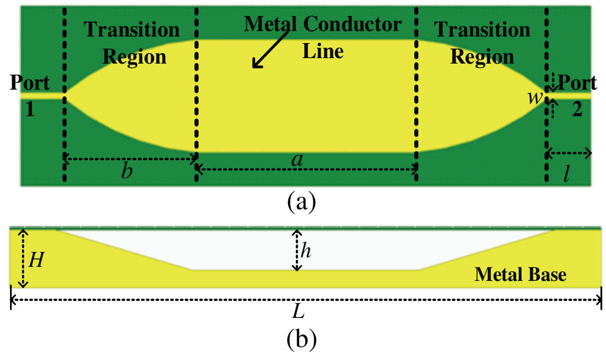

Figure 2. The geometry of proposed planar waveguide (The yellow represents metal conductor line and metal base, the green represents F4B substrate. The detail dimensions: $l = 20\,\text{mm}$, $L = 280\,\text{mm}$, $h = 24\,\text{mm}$, $H = 44\,\text{mm}$, $a = 100\,\text{mm}$, $b = 70\,\text{mm}$, $w = 2.9\,\text{mm}$.) (a) Top view. (b) Side view.

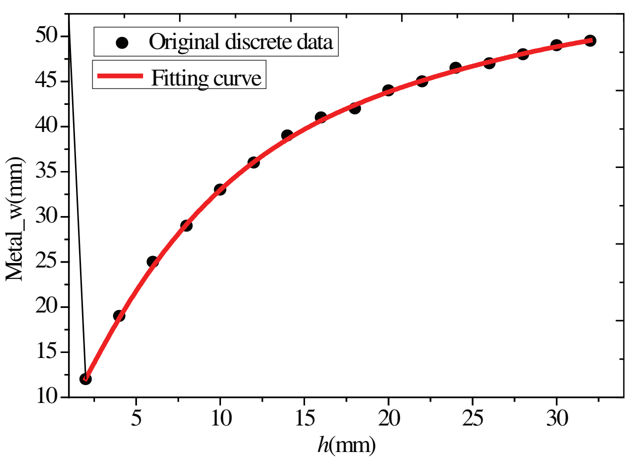

Figure 3. The comparison between original discrete data and fitting curve.

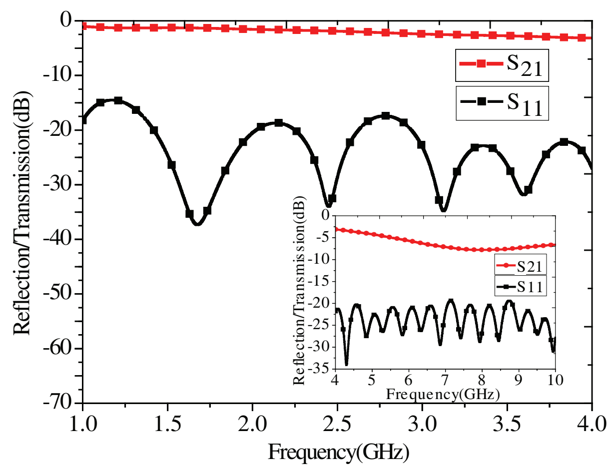

Figure 4. The reflection and transmission coefficient of proposed planar waveguide from 1 GHz to 4 GHz. (Inset: the reflection and transmission coefficient from 4 GHz to 10 GHz.)

width of metal conductor line etched on the substrate should be enlarged to keep the characteristic impedance 50 ohms unchanged. Thus, the specific mathematic function relation between the width of metal conductor line etched on the F4B substrate and the height between metal conductor line and metal base must be figured out firstly to design the transition region. The specific design work is carried out in two procedures. Firstly, the widths of metal conductor line on the F4B substrate under some different discrete air spacer heights (marked h as shown in Fig. 2(b)) are simulated and determined in numerical method, where the characteristic impedance maintains 50 ohms invariable in these different cases. The discrete relation between the metal conductor line widths and different heights is shown in Fig. 3. A mathematic three-order polynomial function is selected to fit the discrete data to obtain continuous relation between them. Fig. 3 demonstrates the compared results between the original discrete data and fitting curve, where great agreement between them is observed. The fitting three-order polynomial function satisfies:

$$y(Metal\_w) = \left(4.496\times10^{-5}\right)\cdot(x(h))^4+\left(4.832\times10^{-3}\right)\cdot(x(h))^3-0.2064\,(x(h))^2+4.562x(h)+3.371 \quad (1)$$

where $metal\_w$ is the width of the metal conductor line, and h is the height of air spacer. All their units used in the Eq. (1) are mm.

As a result, the transition region is established based on the polynomial function as depicted in Fig. 2(a). The transmission characteristics of the proposed planar waveguide are simulated with numerical method. From Fig. 4, the reflection coefficient is all below -15 dB from 1 GHz to 4 GHz, which verifies the good performances of transition region. Actually, the proposed planar waveguide can also operate in higher frequency band. The inset of Fig. 4 gives a satisfactory transmission characteristic from 4 GHz to 10 GHz. Due to the relatively weak coupling between transmitting and receiving horn antennas in bow antenna measurement system when the operation frequency is above 5 GHz, the bow antenna test method is widely employed. The low measurement frequency band is thus a significant advantage of the proposed planar waveguide.

In general, a TEM mode in the wave front of under-test periodic structure from radiation sources is preferred for accurate measurement results since its phase distribution in the wave front is uniform. For bow antenna test method, the under-test periodic structure is usually placed in the far field of the horn antennas to obtain TEM mode, which requests a large-scale under-test periodic structure and high source power. The double conductor structures of our proposed planar waveguide ensure the emerging probability of TEM mode. Actually, due to the discontinuity between F4B substrate and air, there exists a small E field component along the axis of the metal conductor line. Thus, the propagating mode of electromagnetic wave through the metal conductor line is not a pure transverse electromagnetic (TEM) mode but a quasi-TEM mode. The cutoff frequencies of high-order modes can be calculated and predicted on the basis of high-order modes principle of standard microstrip line. And the proposed planar waveguide is rigorously designed to operate at the main mode frequency band and avoid high-order modes. Quasi-TEM mode is still a satisfactory field mode that has a uniform phase distribution and electric field distribution in every transverse section. The aforementioned properties guarantee the proposed planar waveguide a good candidate for periodic structure measurement applications.

3. THE PERIODIC STRUCTURE SIMULATED UNDER PROPOSED PLANAR WAVEGUIDE

In this section, we take an electromagnetic absorber for example to verify the validation of proposed planar waveguide in low frequency band, where we use two different methods, namely, standard periodic structure simulation method in free space using HFSS and our proposed planar waveguide system, to analyze an absorber structure and compare their transmission characteristics. First of all, an absorber with operation frequency approximately 2 GHz is designed and simulated with standard periodic structure simulation method with numerical method.

Figure 5 presents the geometry of designed absorber structure cell, where its dimensions is determined by the height of h in Fig. 2(b). Here, we choose the length of cell unit 24 mm, where just a column of absorber structure is exactly embedded in the proposed planar waveguide as demonstrated in Fig. 6(a). The metal conductor line on the F4B substrate and metal base are approximately served as perfect electric condition (PEC) to mimic the infinite space. Since there are two ports in the proposed planar waveguide, we need a metal short plate installing inside the proposed planar waveguide, here, a

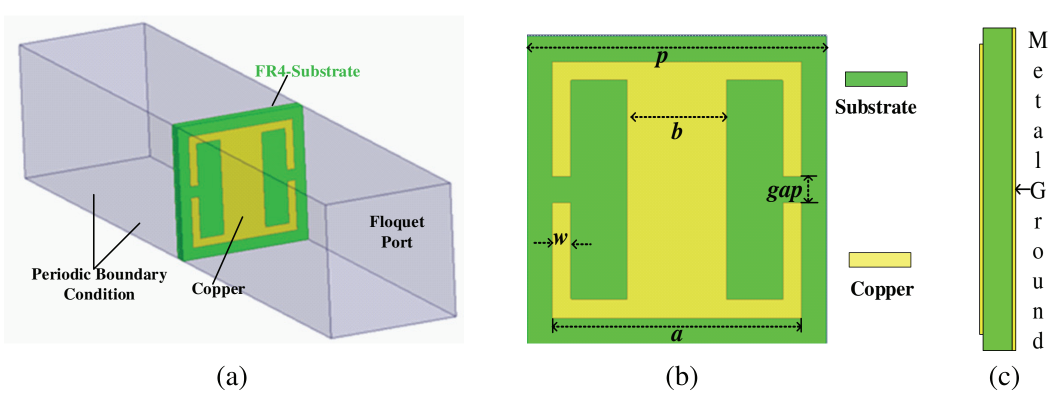

Figure 5. The geometry of designed absorber structure cell (the detailed dimension: $p = 24$ mm, $a = 20$ mm, $w = 1.5$ mm, $gap = 2$ mm, $b = 8$ mm. the thickness, relative permittivity and tangent loss of FR4 substrate is 2 mm, 4.4, 0.02, respectively). (a) Perspective view. (b) Top view. (c) Side view.

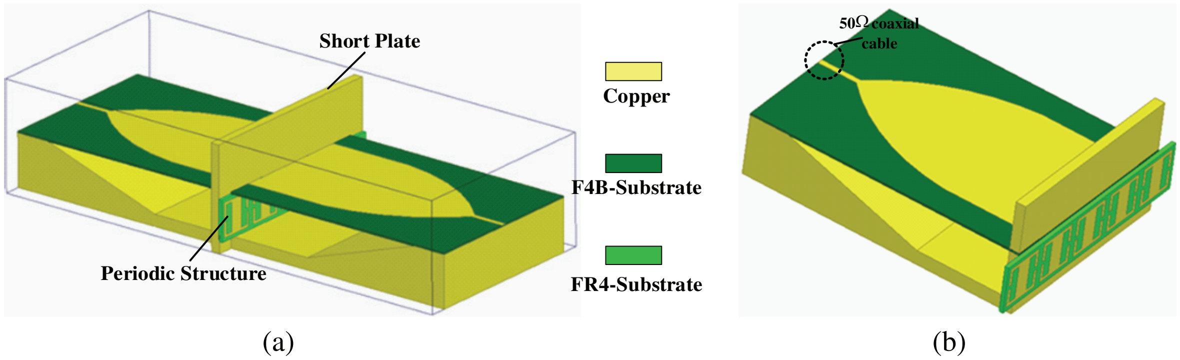

Figure 6. The geometry of proposed planar waveguide with designed absorber structure. (a) The completed model of schematic diagram. (b) The half model of schematic diagram.

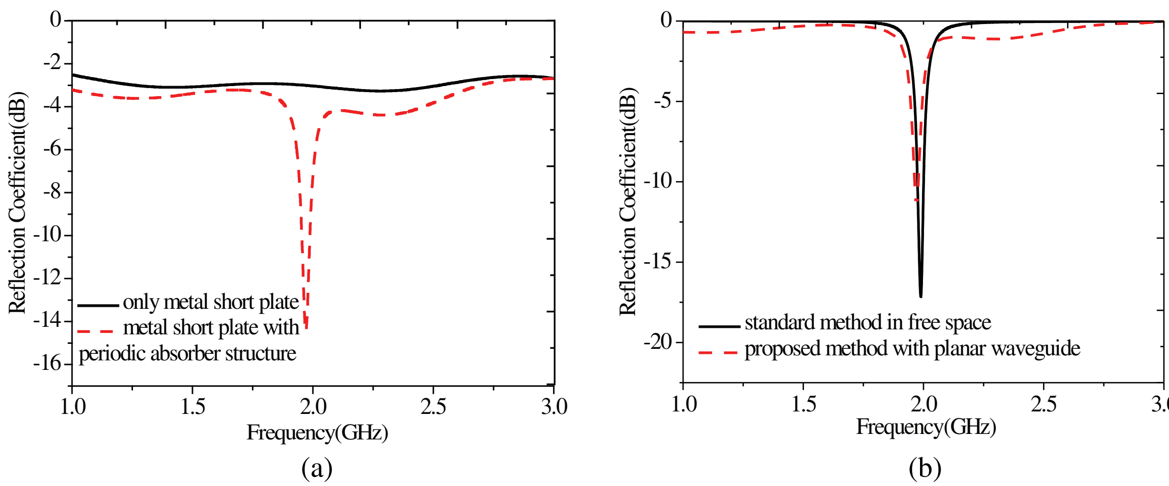

Figure 7. The reflection coefficient. (a) Under two different cases. (b) Under two different methods.

large short plate shown in Fig. 6(a) (removing periodic structure) is established in the back surface of the periodic absorber structure.

In order to obtain relatively accurate results, two steps are usually adopted. Firstly, the reflection coefficient is recorded (as shown in Fig. 7(a) solid black line) in the case that only the metal short plate is in the proposed planar waveguide. For convenience, we call it S_{11c}. Then, the periodic absorber example is put in the metal short plate as shown in Fig. 6(a). Another reflection coefficient is also recorded (shown in Fig. 7(a) as dashed red line), and we call it S_{11m}. The desired reflection coefficient is calculated with $|S_{11\mathrm{m}}|/|S_{11\mathrm{c}}|$.

Figure 7(b) presents the desired reflection coefficient, where the reflection coefficient obtained from standard periodic structure simulation method is given for comparison. There is a wonderful agreement between the two different methods. In fact, the periodic boundary condition in numerical method is used to mimic an "authentic" infinite plane while the proposed planar waveguide measurement method realizes a "fake" infinite plane. Thus, the result differences of reflection coefficients between the two methods are expected and can be easily understood.

4. THE FABRICATION AND MEASUREMENT

Based on the aforementioned analysis in Section 2 and Section 3, the proposed planar waveguide and under-test periodic unit are fabricated with the optimal dimensions shown in Fig. 2 and Fig. 5. Fig. 8(a) shows a photography of the fabricated planar waveguide. There are two scales attaching to two sides

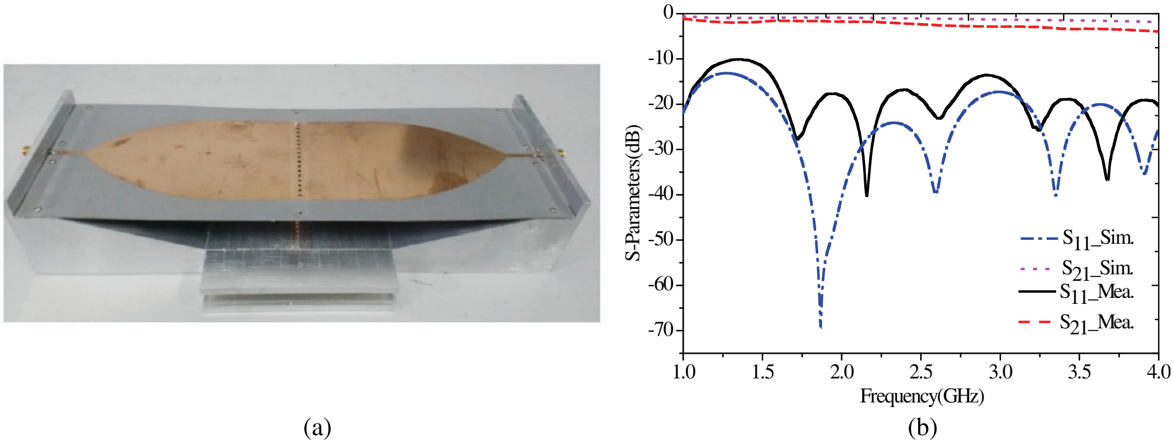

Figure 8. The measurement setup of proposed planar waveguide. (a) Photography of proposed planar waveguide. (b) The measured S-Parameters of proposed planar waveguide.

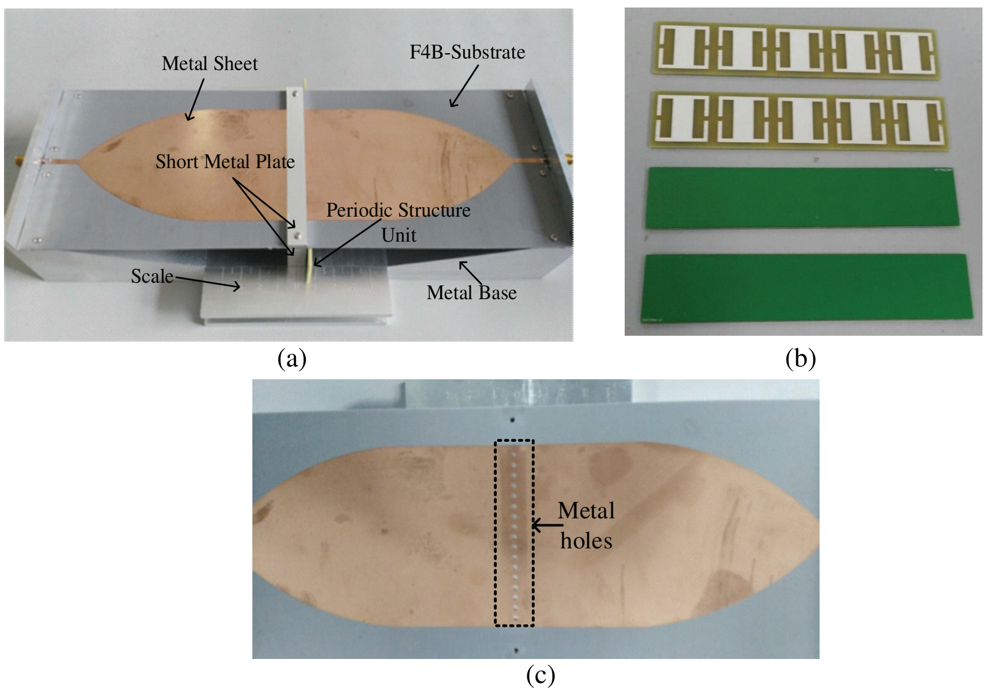

Figure 9. The measurement setup diagram. (a) Measurement platform. (b) Periodic structure unit. (c) The metal holes on the F4B substrate.

of the waveguide to determine the accurate location. The metal holes in the F4B substrate are used to eliminate the gap between F4B substrate and short plate to realize the near-perfect short plate. SMA connectors are welded with both ends of microstrip line to transmit signal. A photography of the absorber example is presented in Fig. 9(b).

Firstly, the transmission characteristics of the proposed planar waveguide are measured without short metal plate with Agilent network analyzer to test the efficiency of transmission from port 1 to port 2, and the measured results are presented in Fig. 8(b), where a relatively good agreement between the simulated and measured results is observed. Slight differences are due to fabrication tolerance and SMA connector loss.

In order to obtain accurate measurement results, some calibration works are carried out. A metal

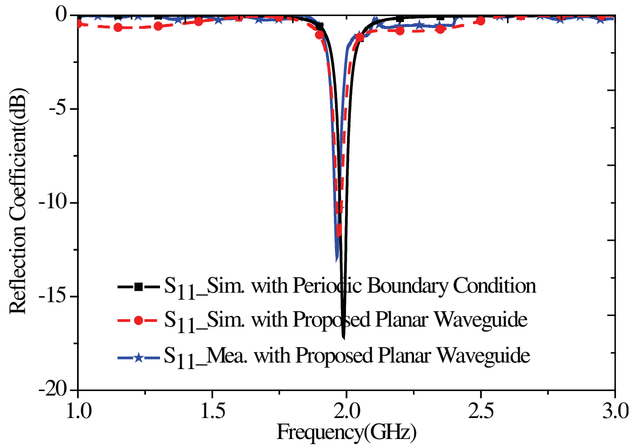

Figure 10. The simulated and measured reflection coefficient results.

short plate is firstly put in the proposed planar waveguide as shown in Fig. 9(a), and the reflection coefficient in this case is recorded. For convenience, we call it S_{11c}. Then, an absorber example is also put in the proposed planar waveguide, where its metal ground is attached exactly to the metal plate. The reflection coefficient in this case is also recorded, and we call it S_{11m}. The desired reflection coefficient is calculated with S_{11c} and S_{11m}. Good agreements between the simulated and measured results with the proposed measurement method can be observed in Fig. 10, and the measured absorption frequency is almost identical to two different simulation methods, which comfirms the validation of our proposed measurement idea.

5. CONCLUSION

In this paper, a novel planar waveguide to measure transmission characteristics of a periodic structure is proposed and investigated. The specific design theory is presented in details. In order to verify feasibility of the measurement method, a simple periodic absorber structure is selected as an example to carry out comparative experiments. The two different simulated results under standard periodic structure simulation method in free space and the proposed planar waveguide are analyzed and compared. At last, the proposed planar waveguide and simple periodic absorber structure are fabricated with optimal dimensions and then measured. Inherent transmission characteristics of the proposed planar waveguide are almost identical in simulated and measured results. The measured results with a periodic absorber structure placing inside the proposed planar waveguide are in great agreement with simulated results. All the measured results demonstrate the validation of our proposed planar waveguide, which is convenient, cheap and effective for periodic structure measurement applications.

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