CHARACTERIZATION OF ARTIFICIAL MAGNETIC CONDUCTOR STRIPS FOR PARALLEL PLATE PLANAR ANTENNAS

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ABSTRACT: *Metamaterial structures have unique properties in controlling the propagation of electromagnetic waves. In this work, we analyze the effect of artificial magnetic conductor (AMC) surface strips on the bottom face of an oversized parallel plate waveguide to enhance the wave guidance within it. The results using these configurations in a linear slot array antenna fed by a rectangular parallel plate waveguide are presented as an example of application.*

Key words: *artificial magnetic conductors; metamaterials; hard surfaces; parallel plate waveguides; planar antennas*

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1. INTRODUCTION

Over the last few years, there has been an interest in developing materials that exhibit novel electromagnetic properties not found in nature. Such structures, known as metamaterials, are artificially engineered structured materials exhibiting novel properties in comparison to the constituent homogeneous materials used to manufacture them.

Metamaterials are novel artificial periodic structures that have been investigated for their versatility in controlling the propagation of electromagnetic waves in one, two, or three dimensions. That allows designing new materials with properties that are not available in conventional materials. Recent studies on metamaterial structures have revealed that they are numerous applications able to enhance the performance of antennas and microwave circuits

Because of their different classes, they can satisfy such as artificial magnetic conductor (AMC) properties or high-impedance surfaces (HIS), frequency selective surface (FSS) structures, electromagnetic/photonic bandgap (EBG/PBG) materials, and creation of materials with negative permittivity and negative permeability called left-handed medium (LHM).

To date, AMC surfaces are receiving more and more attention because of their interesting properties that may overcome some of the problems of traditional perfect electric conductor (PEC) surfaces. In contrast, with the realization of PEC condition, the realization of AMC conditions remains as a difficult task because of the inexistence of materials with these properties in nature. Two basis classes of artificial magnetic surfaces have emerged: those based on a volume of artificial material and those based on a surface distribution of inhomogeneities. The mushroom structure of Sievenpiper is a member of the first class [2]. For the second class, surfaces composed of 2D square lattice with Jerusalem crosses as proposed by Itoh and coworkers is a good example These two surfaces belong to the class of electromagnetic bandgap structures that exhibit rich physical effects.

In that way, one possibility to model AMC behavior is to use EBG periodic structures as it is analyzed by Itoh which is extremely easy to design and fabricate using standard etching techniques, in contrast to many of other surfaces described in previous published work In contrast to the mushroom surface, the EBG structures realize the AMC properties without vias but with more complex element shapes. The EBG structures have been utilized for antenna, microwave circuit, and parallel plate waveguide-wall applications

AMC are not a new concept, of course. Corrugated planes and cylinders found early use as waveguides for surface wave and end-fire antennas for example The majority part of previous published works have proposed and analyzed several examples designs of AMC and HIS surfaces with 3D or 2D inhomogeneous structure or with lumped elements Other applications of AMCs are to realize standard rectangular waveguides that can support TEM waves Another important contribution is the relation between AMCs and the called "soft" and "hard" surfaces. The hard and soft surfaces are a terminology derived from the acoustics and consist of taking an AMC and transforming it to soft/hard surface by using metal tape in the form of narrow strip to enhance the wave guidance. This concept was introduced in the 1990s and used to define soft and hard surfaces in electromagnetic in terms of surface impedances and the boundary conditions in E- and H-planes. In short, the soft and hard surfaces are anisotropic. The soft surface behaves like a PEC in H-plane and as a perfect magnetic conductor (PMC) in E-plane, and vice versa for the hard surface. The preferred illustration of an ideal soft-hard surface is a PEC/PMC strip grid as a surface with electric and magnetic conductivity in one direction only.

The PEC/PMC strip grid represents a hard surface when the strips are oriented in the same direction as the wave propagates (longitudinal strips), and a soft surface when they are oriented orthogonal to this direction (transverse strips). Its purpose is to enhance the electromagnetic wave guidance

In this article, the AMC/PEC surfaces have been applied and analyzed as propagation strips in oversized parallel plate waveguides to control and guide efficiently the electromagnetic wave propagation.

For a future practical application, our aim will be to apply these structures to enhance the main radiation characteristics of the parallel plate planar antennas as aperture efficiency and radiation directivity As the first step of the investigation and the design of this kind of planar antennas, wave propagation in the oversized parallel plate waveguide for given excitation is studied

2. PRINCIPLES OF AMC SURFACES

2.1. EBG Structure Acting as AMC Surfaces

The main difference considering in the electrical properties between a PEC and an AMC surface can be determined by observing the reflection coefficient. Assuming no losses, an ideal AMC, also known as a PMC, is a surface that exhibits a reflection coefficient of $+1$ (amplitude is equal to 1 and phase is 0°) when applied in the situation of an uniform plane wave normally incident on an AMC plane; as opposed to a PEC, which has a reflection coefficient of -1 (amplitude is equal to 1 and introduces a phase shift of 180°). Strictly speaking, the AMC condition is characterized by the frequency or frequencies where the phase of the reflection coefficient is 0° (i.e., where the reflected wave is in phase with the incident wave).

In this work, the design of AMC surfaces with EBG structures is based on [3], in which Itoh and coworkers present the possibility to create AMC behavior with a novel 2D uniplanar EBG structure. This planar periodic EBG structure is particularly attractive and has been intensively investigated due to its advantage of being compact size, simple circuit, low cost, and easy to fabricate using a standard planar process without using any extra multilayer substrates or via holes.

In our design, the optimum operating point is 12 GHz, where a 0° phase in reflection coefficient in AMC surfaces occurs. It corresponds to the operating frequency where the EBG structure behaves like an AMC surface. The results show that the phase reflection coefficient of the AMC surfaces crosses 0° at just one frequency (for one resonant mode). The useful bandwidth of an AMC is in general defined as $+90^\circ$ to -90° on either side of the central frequency, because these phase values would not cause destructive interference between direct and reflected waves.

It is apparent from these results that the EBG structures behave as an AMC surface at least within a narrow frequency band near 12 GHz. This is true because the reflection coefficient magnitude is one while the phase angle is zero.

2.2. AMC-PEC-AMC Strips in Parallel Plate Waveguide

The standard rectangular waveguide is an excellent excitation network because of this low loss in transmitting energy. In this section, we are going to study and analyze the behavior of AMC-PEC-AMC strips in a parallel plate waveguide as shown in Figure 1. These structures are placed inside the parallel plate structure. The fundamental interest in using AMC-PEC-AMC strips consists of the possibility to imitate the effect of a conventional rectangular waveguide only by using this kind of planar structure, whenever it is in a parallel plate waveguide. The aim of this configuration is the improvement of the wave guidance, working as if the whole structure was a virtual waveguide.

The presence of the AMC strips should result in a deep decline of the electric field to stop the propagation in the transverse direction, as if they were the metallic walls of the equivalent real waveguide. On the other hand, the PEC strips are going to allow the propagation over it.

In literature, we find three kinds of distribution feeding waveguides for planar antennas: the radial waveguide, the oversized parallel plate waveguide, and the rectangular waveguide arrays. This last waveguide consists of two parallel plate delimited by physical metallic walls that define each rectangular waveguides inside the guided structure. The disadvantage of this kind of structures for planar antennas is that each rectangular waveguide is not completely isolated from each other because of the difficulty of

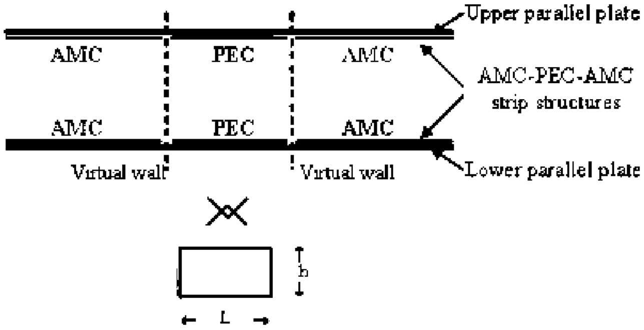
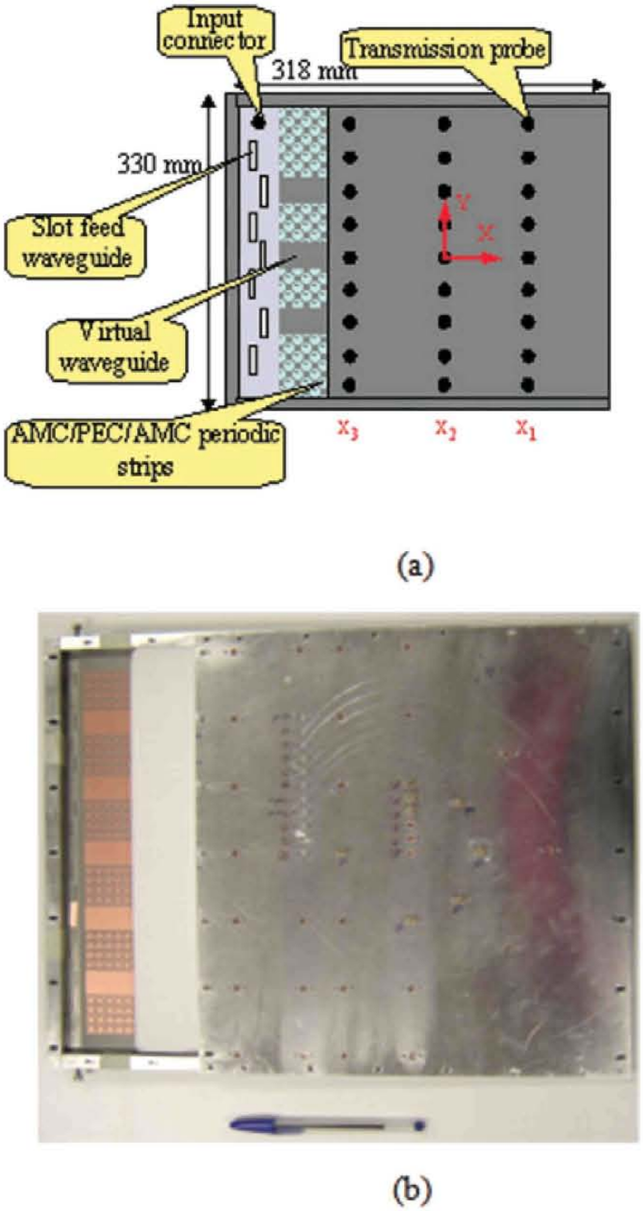


Figure 1 AMC-PEC-AMC strips in a parallel plate waveguide. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]



(a)

(b)

Figure 2 Prototype used to measure the field distribution over the periodic AMC-PEC-AMC strips inside the oversized waveguide: (a) upper view and (b) experimental prototype.

closing perfectly the vertical walls to the horizontal plate. Therefore, in these vertical apertures, the mutual-coupling field between each adjacent waveguides is important enough to deteriorate the propagation wave, which means the decrease in the efficiency of this kind of antennas. To solve this problem, we apply the periodic AMC-PEC-AMC strips in an oversized parallel plate structure described in the section before to avoid the presence of metallic walls for each rectangular waveguide as shown in Figure 2. The periodic AMC-PEC-AMC strips could be applied in parallel plate planar antennas.

3. AMC-PEC-AMC STRIPS: SIMULATION AND PROTOTYPE RESULTS

Some simulations have been carried out, analyzing the behavior of the AMC-PEC-AMC strips as components of a virtual rectangular waveguide. The simulations showed proper results of this behavior.

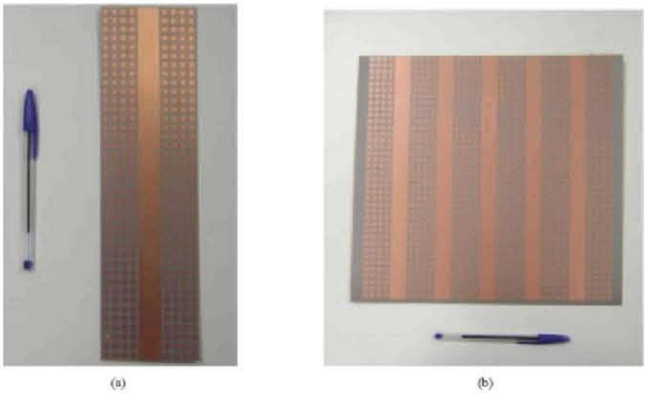
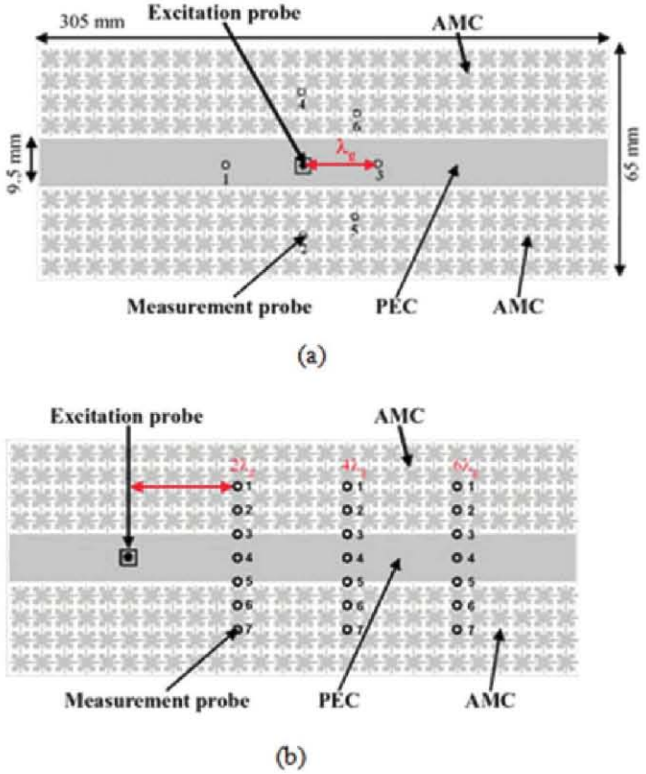

(a) (b)

Figure 3 AMC-PEC-AMC structure prototypes: (a) AMC-PEC-AMC strips and (b) periodic AMC-PEC-AMC strips. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

In the implementation process, two structures have been built to analyze and validate the simulation results, as it is presented in Figure 3. The first of them [Fig. 3(a)] is quite important to validate the theoretical and simulated results. For this reason, in this article, almost all the efforts are going to be placed in this first structure.

3.1. Prototype1: Single AMC-PEC-AMC Strips in a Parallel Plate Waveguide

Among the different ways of measuring the effect of enabling or disabling the propagation, those which better show the effects and



(a)

(b)

Figure 4 Experimental setup used to measure the distribution of the electric field over the AMCPEC-AMC strips: (a) in the "cardinal points" and (b) along the propagation direction.

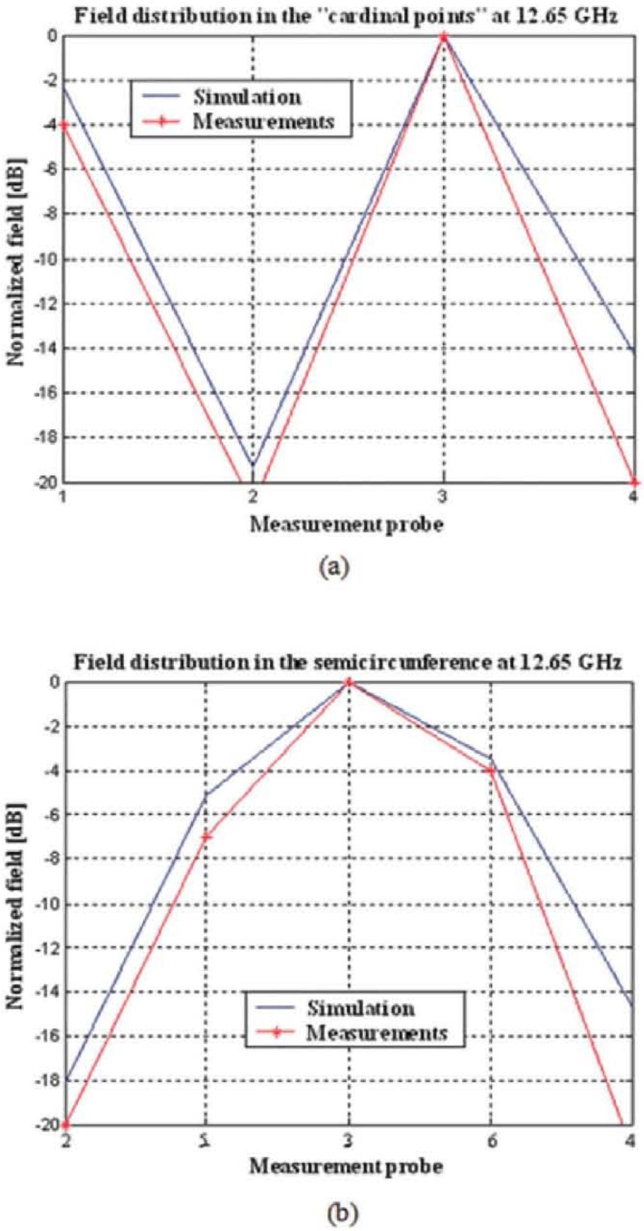


Figure 5 Electric field distribution amplitude over the AMC-PEC-AMC strips: (a) in the "cardinal points" and (b) in the semi circumference.

could be performed are presented. In this first prototype, the AMC-PEC-AMC strips enable the effect of wave guidance, allowing the propagation over the PEC zone, disabling it over the AMC zones.

3.2. Coaxial Excitation Analysis

In this assembly, it is supposed to maintain the dimensions used in the previous simulation step; in that way, the structure is located between two parallel plates, excited with a coaxial probe, analyzing the field in a $\lambda_g/2$ ring surrounding the excitation point. The test scheme is presented in Figure 4(a).

The use of a vectorial network analyzer helps us to verify that the excitation is clearly matched and to obtain the electric field amplitude in the different points of the ring, in a wide frequency range (12 –13.45 GHz). The best results appear at 12.65 GHz.

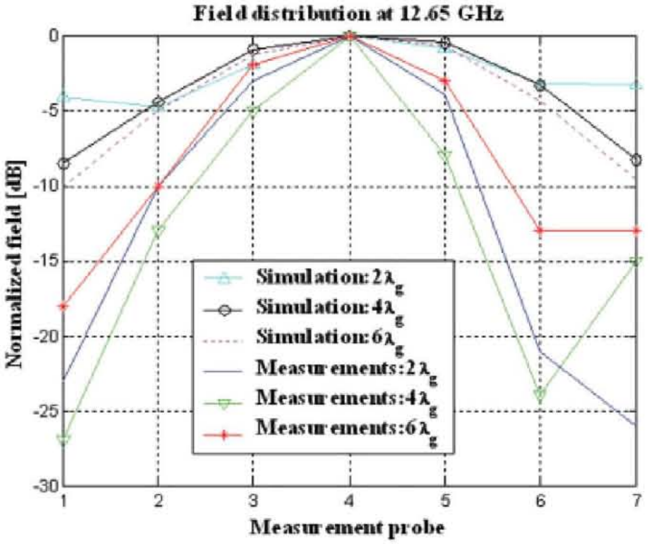


Figure 6 Electric field distribution amplitude along the propagation direction over the AMC-PECAMC strips.

To represent the results in a suitable way, two graphs are displayed [Figs. 5(a) and 5(b)]: for the "cardinal points " (points 1, 2, 3 and 4) and for the semicircumference (points 2, 5, 3, 6 and 4).

As it is seen in Figure 5(a) ("cardinal points"), points 1 and 3 (over PEC) present maximums of transmission, while points 2 and 4 present minimums (over AMC) with a difference of 20 dB.

3.3. Uniform Excitation Analysis

In addition to the previous analysis, another test has been done to assure the right behavior of the structure. A line is located over the structure without electrical contact with the AMC-PEC-AMC plane, so that it generates a uniform wave in amplitude propagating throughout the plane, as shown in Figure 4(b). Points in a parallel line to the feed are analyzed for different distances from the excitation.

The experimental results showed in Figure 6 verify the effect of wave guidance, allowing the propagation over the PEC strip and disabling it over the AMC strips. These results are quite similar to those obtained in simulations, as it was expected.

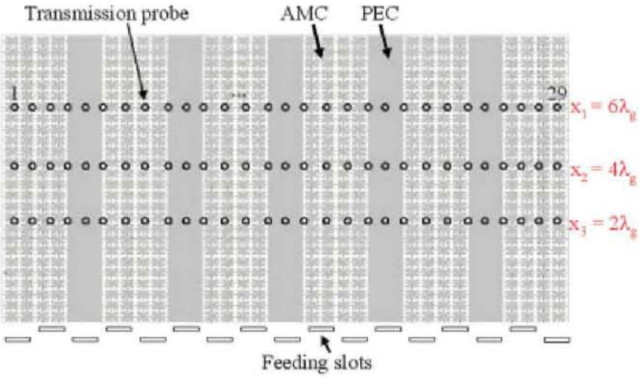


Figure 7 Experimental setup used to measure the distribution of the electric field over the periodic AMC-PEC-AMC strips inside the oversized waveguide.

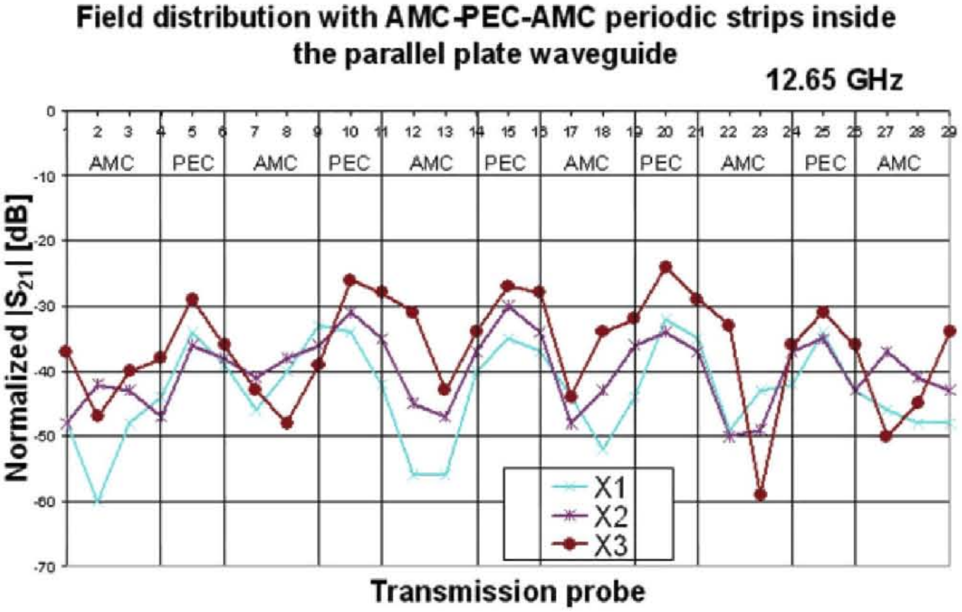


Figure 8 Measurement results: Electric field distribution along the propagation direction over the periodic AMC-PEC-AMC structure inside the oversized waveguide.

The results are quite satisfactory comparing the behavior of virtual waveguides propagating TE_{10} mode with the one in a standard rectangular waveguide with the same dimensions. The presence of the AMC structures in the measurements causes a deep decline of the field of about 20 dB along this surface.

The width of the AMC surface is an important parameter for the proper functioning of the structure. The results presented in this article are done over a structure of four periods of AMC [see Fig. 3(b)]. However, we have fabricated some other prototypes with less than four periods of AMC (two and three). In these cases, the results were not good enough, noticing that the field decline over the AMC surfaces is directly related to the number of periods of the AMC structure.

3.4. Prototype 2: Periodic AMC-PEC-Amc Strips in an Oversized Parallel Plate Waveguide

At last, measurements of the prototype 2 are presented. Because of the excitation (which is a slot feed waveguide) and its narrow band width, measurements are only related to 12.65 GHz (one of the working frequencies). Measurement scheme is shown in Figure 7. Measured results show a proper behavior (see Fig. 8).

Because of the convincing simulated and measured results obtained with a single AMC-PEC-AMC strip in parallel plate waveguide, we applied several structures working such as consecutive virtual waveguides. We observed the same behavior as before with a same decline of the field of about 20 dB. These experimental results validate the simulations and measurements obtained in the first prototype of a single AMC-PEC-AMC strip.

4. ANTENNA APPLICATION

4.1. AMC-PEC-AMC Strips in a Linear Slot Array Antenna Fed by a Rectangular Parallel Plate Waveguide

To validate all the previous results, it is decided to design a quite simple planar antenna, in which our AMC-PEC-AMC waveguide (prototype 1) is going to work as the feeding stage. One of the easiest models that can be thought about is a linear slot array excited by the structure in Figure 3(a), as it may be seen in Figure 9(a).

The value of the effective wavelength inside the waveguide (λ_g), considering all the materials in Figure 9, is fundamental when designing the linear slot array. Therefore, it is necessary to recover the simulation results of the first prototype.

The simulated value of the effective waveguide is $\lambda_g = 24.3$ mm for the layer distribution inside the structure at 12.65 GHz. Afterward, the slot layer is simulated, prototyped, and assembled with the rest of the components of the slot antenna. Figure 9(b)

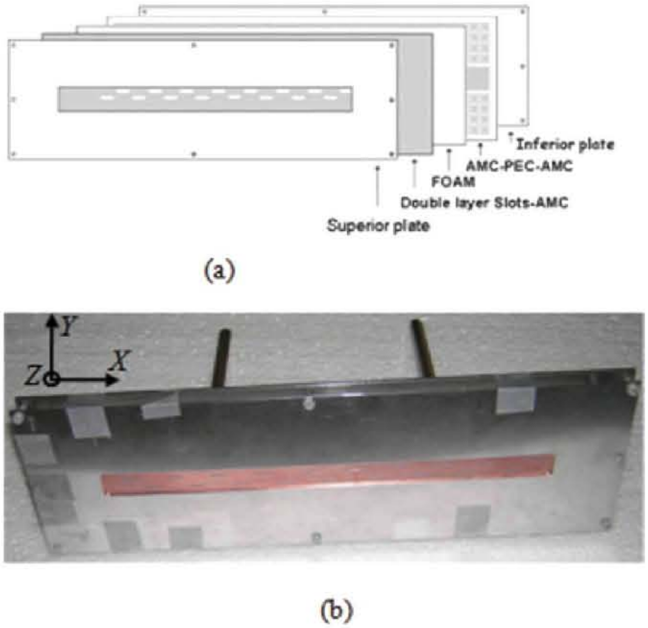


Figure 9 Linear slot array antenna with AMC-PEC-AMC strips: (a) assembly scheme and (b) antenna prototype. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

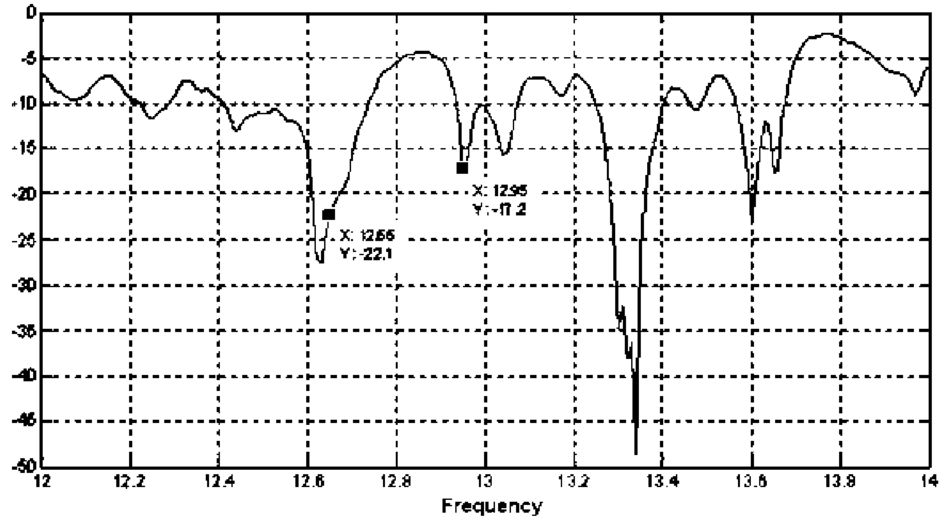


Figure 10 Return loss of the linear slot array antenna with AMC-PEC-AMC strips.

shows the manufactured antenna, after the assembly of the different parts.

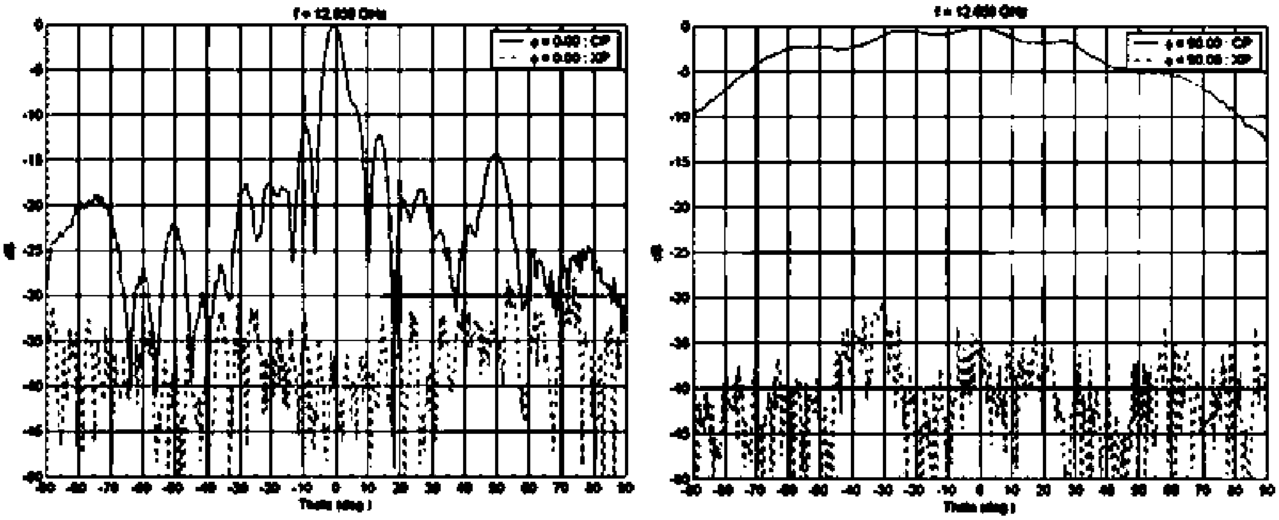
The antenna device is measured in the anechoic chamber of our research group. The return loss measurement of the linear slot array antenna with AMC-PEC-AMC strips is presented in Figure 10. At one of the working frequencies (12.65 GHz), the reflection is less than −20 dB.

Finally, the radiation pattern is measured in the anechoic chamber at 12.65 GHz (see Fig. 11). The horizontal radiation pattern [Fig. 11(a)] (*XZ* plane) has some phase errors due to the fabrication of the slots (bad matching level for some of them). The vertical radiation pattern [Fig. 11(b)] (*YZ* plane) shows ripples due to the feeding waveguide (the AMC-like walls decrease the electric field but they do not stop all the propagation and this effect cannot be neglected) and because of the finite ground plane in the *YZ* plane. Although the radiation pattern has to be improved, measurements demonstrate the proper operation of an antenna with an AMC-PEC-AMC waveguide as the feeding stage.

5. CONCLUSION

The effect of AMC-PEC-AMC strips to enhance wave guidance in parallel plate waveguides has been presented in a practical application. For this reason, this work includes some software simulations and the prototype measurements and evaluations. The measurements show promising results in using these structures to enhance, control, and guide the wave propagation in oversized parallel plate waveguides.

This work demonstrates the feasibility of applying the AMC-PEC-AMC configuration in parallel plate waveguides to enhance the properties of the wave propagation. In the case of using several AMC-PEC-AMC structures working like consecutive virtual



(a)

(b)

Figure 11 Antenna with AMC-PEC-AMC strips radiation pattern: (a) horizontal radiation pattern (array) and (b) Vertical radiation pattern (slot) waveguides in a plane, we reduce the coupling between each other. The results obtained let us consider different possibilities using this architecture to perform planar antennas with specific features.

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