# The Improvement of Radiation Characteristics of a Planar Inverted-F Antenna and Antenna Array on an Artificial Magnetic Conductor

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***Abstract*— The PIFA, Planar Inverted-F Antenna, is a type of antenna which has been used in many communication applications. It is a medium bandwidth radiator with reduced dimensions. A PIFA antenna on an EBG, Electromagnetic Band-Gap, structure is designed and measured, and is compared to a classical PIFA antenna. EBG structures have special electromagnetic properties that are very useful for wireless applications. The EBG structure presented in this paper is the AMC, Artificial Magnetic Conductor, also called mushroom-like electromagnetic band-gap structure. It is a metal-dielectric structure which presents high surface impedance and suppression of propagating surface currents within a frequency band. The AMC is used as the PIFA antenna ground plane to observe the improvement on characteristics such as bandwidth, gain and directivity. A PIFA antenna array is also presented on an AMC structure. The wide bandwidth achieved by the antenna array on AMC is shown. It is also shown that array radiation pattern is steerable in the azimuth plane. Besides, using the AMC, the overall antenna characteristics are improved.**

***Keywords*— Artificial magnetic conductor, high surface impedance, band-gap, PIFA, ground plane, antenna array, EBG.**

## I. INTRODUCTION

NOWADAYS, for wireless communication systems, it is normally necessary to design small, light weight and low profile antennas having a wide bandwidth [1], to work, for example, in multiband systems. Another desirable characteristic is a steerable radiation pattern, which is achieved by using antenna arrays. Antenna arrays have been shown to be very useful for communication systems, and will have their place in the 3G and 4G wireless communication systems [2]. An antenna array could improve the reliability and capacity of the system. It can provide an adaptive radiation pattern and a better gain than a one-element antenna, as well as, it can combine the signals from multiple antennas in a way that mitigates multipath fading [3].

It is chosen, for this work, the PIFA, Planar Inverted-F Antenna. It is a medium bandwidth antenna [4] which is widely used and has the size and weight requirements for wireless applications [5]. To improve PIFA characteristics as bandwidth, directivity, and gain it is necessary to increase the antenna dimensions. One way to have the desired antenna improvements is using a perfect magnetic conductor as the antenna ground plane. This type of material could improve the antenna performance by the creation of its equiverse image currents, but it is only theoretical material [6].

Structures that exhibit the perfect magnetic conductor properties within a frequency band, called band-gap, are classified under the broad terminology of "meta-materials"and EBG, Electromagnetic Band-Gap [7]. EBG structures are periodic objects that prevent the propagation of electromagnetic waves in a specific band of frequency. The EBG structure used in this paper is the AMC, Artificial Magnetic Conductor, proposed by Sievenpiper *et al.* [8]. The AMC is, within the band-gap, a high-impedance surface that suppress surface waves. It reflects an incident plane wave in-phase, as a perfect magnetic conductor, instead of a metal plane which reflects out-of-phase, working as a RF mirror. These properties can improve the antenna overall performance, being of great interest on antenna designing area. The purpose of this paper is to analyze the improvement achieved on a PIFA antenna and on a PIFA antenna array by the use of an AMC structure as their ground plane and without changing the dimensions of the radiator. The PIFA antenna and AMC design are in sections II and III. In section IV, the measurement comparison among the classical PIFA antenna, the PIFA on AMC and the PIFA on AMC with a LGP, Local Ground Plane, is presented. The LGP is a small ground plane just below the radiator element, surrounded by the AMC. In section V a PIFA antenna array on AMC is presented. The array is measured with and without the LGP, and its beam steering is shown. It is also shown the array improvement on overall characteristics to the classical PIFA antenna. The antennas and the AMC are designed to operate around the 2.4 GHz frequency.

## II. PLANAR INVERTED-F ANTENNA DESIGN

The PIFA is like a quarter-wave monopole antenna, folded parallel to the ground plane and stretched to form a plate [2]. The name PIFA is due to its side profile that looks like an inverted F figure, as shown in Fig. 1.The design frequency is 2.4 GHz. This frequency is chosen because it is desired that the antenna works in ISM band, then it could be used in WLAN or bluetooth applications. The PIFA antenna resonance frequency is approximately given by [9]:

$$f_r = c\left[4\alpha\left(W+L\right)\right]^{-1} \tag{1}$$

where: $c$ is the velocity of light, $\alpha$ is a constant approximately equal to 0.9, $W$ and $L$ are, respectively, the antenna width and

This work was partially supported by Ericsson EDB, Ericsson Research Center Brazil under contract Ericsson/Unicamp UNI.15 and by CNPq.

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length. The $x$ parameter, shown in Fig. 1, is defined as the distance from the feed line to the PIFA's shortened edge, and can control the antenna matching [10].

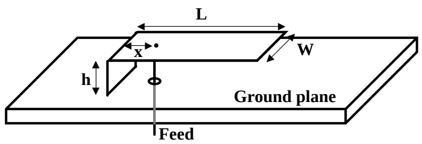
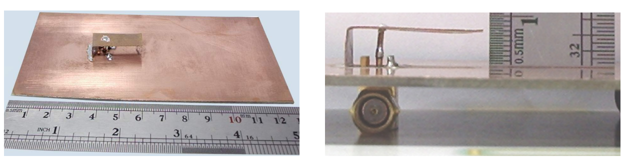



Fig. 1. PIFA Antenna Geometry.

To design the PIFA, equation 1 and the IE3D software, MoM, from Zeland Software Inc, are used. The final antenna dimensions, in millimeters, are $W = 11$, $L = 27$, $h = 7.5$, $x = 7.2$ and, for the ground plane, 130x70. The prototype is shown in Fig. 2. The comparison between PIFA antenna simulated and measured input return loss, $S_{11}$, results is depicted in Fig. 3. The measurements are carried out by a Rohde $\&$ Schwarz ZVRE network analyzer.



(a) Top view. (b) Side view.

Fig. 2. The classical PIFA antenna prototype views (the reference ruler is in cm and inches).

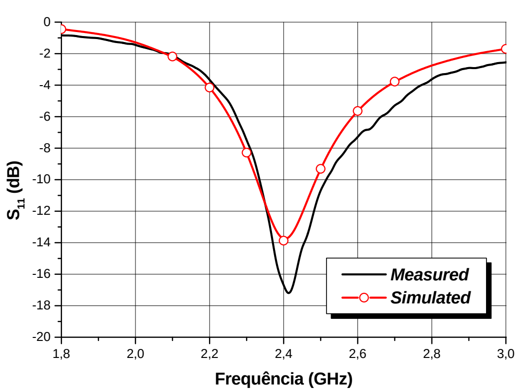
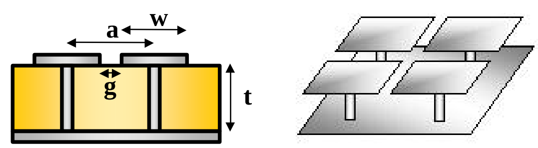



Fig. 3. Measured and simulated $S_{11}$ results for PIFA antenna prototype.

It is observed, from Fig. 3, that simulated bandwidth, according to $S_{11} < -10$ dB criterion, is 160 MHz, 7.5%, and the measured bandwidth is 180 MHz, 8.3%. The minimum measured input return loss is more than 3 dB better than the simulated one. The measured resonant frequency is 2.41 GHz, that is an error of 0.4%, which is considered acceptable. The simulated classical PIFA has directivity D=4.26 dB, efficiency $\eta = 95.71\%$ and gain equal to 4.08 dB.

## III. Artificial Magnetic Conductor design

The AMC, Artificial Magnetic Conductor, is a metal-dielectric structure which has a special texture. It is composed by a top capacitive FSS, Frequency Selective Surface, a bottom metal layer and a bed of nails (via array) embedded in a dielectric substrate connecting them, as shown in Fig. 4(a). The FSS layer can vary in shape but it is essentially a two-dimensional sheet of disconnected metal obstacles as can be seen in Fig. 4(b) [11]. The number of FSS layers could be more than one but, in this work, it is just one, composed by hexagonal metal patches. A patch is, in this case, a cell for the structure.




(a) Lateral view. (b) View without the dielectric layer.

Fig. 4. AMC structure views.

The AMC behaves as a resonant LC circuit where, near the resonance frequency, it shows a high surface impedance. The capacitance is provided by the fringing electric fields between adjacent cells and the inductance by the conducting path linking them. As a resonant LC circuit, the resonance frequency is given by [8]:

$$\omega = \left(\sqrt{L.C}\right)^{-1}, \tag{2}$$

where L is the sheet inductance and C is the sheet capacitance. The sheet inductance is given by [8]:

$$L = \mu.t, \tag{3}$$

where: $t$ is the structure thickness and $\mu$ is the magnetic permeability of the circuit board material, whose value is the unity at microwave frequencies. The sheet capacitance is given by the following equation [8]:

$$C = \left[w.\left(\varepsilon_1 + \varepsilon_2\right).\cosh^{-1}\left(a/g\right)\right]/\pi, \tag{4}$$

where: $w$ is the width of the capacitor, $\varepsilon_1$ and $\varepsilon_2$ are the circuit board material and the surrounding space dielectric constants respectively, $a$ is the center-to-center spacing of the vias, and $g$ is the gap between the cells. It was chosen for the cells a hexagonal shape in a triangular lattice. The band-gap produced by the AMC structure has the bandwidth given approximately by [12]:

$$BW = 2.\pi.t/\lambda_0, \tag{5}$$

where: $\lambda_0$ is the wavelength in the free space, therefore, the expected bandgap is 8%, at 2.4 GHz. Using equations 2, 3 and 4 for a frequency of 2.4 GHz, a standard fiberglass circuit board ($\varepsilon \approx 4.4$, t = 1.6 mm) and a gap of 0.3 mm between the cells, it is calculated a hexagonal cell width of 14.97 mm. The AMC formulation presented is very simple, however, its results are not very accurate [13], more accurate but complex model can be found in [11] and [14]. The calculated cell width is very large for the requirements on today wireless systems, however, for frequencies below 5 GHz the correct design is using two FSS layers [8], it makes the patch width smaller. It is chosen to build the prototype with just two metal layers due to the prototyping facilities available.

## IV. PIFA ANTENNA ON AMC GROUND PLANE

In this section is presented the AMC structure as the PIFA antenna ground plane. The same dimensions calculated in the previous sections for the antenna and the AMC structure are used. The antenna on AMC with a LGP, Local Ground Plane, is also analyzed. The LGP is emulated by short-circuiting the three nearest cells just below the antenna. A prototype view is shown in Fig. 5.

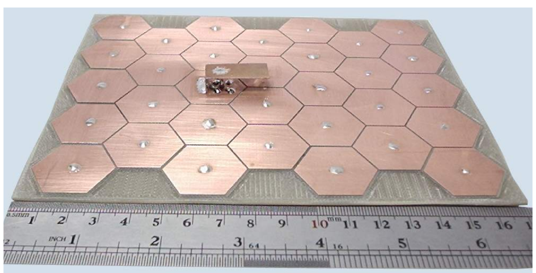


Fig. 5. The prototype of the PIFA on AMC (the reference ruler is in cm and inches).

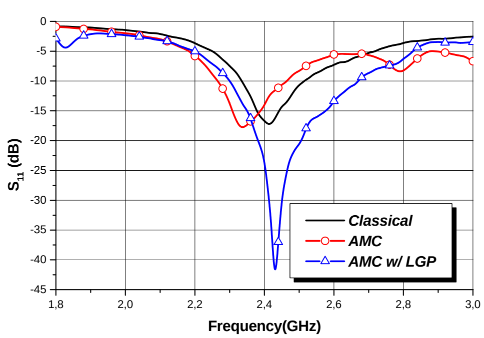



Fig. 6. Measured $S_{11}$ results for classical PIFA, PIFA on AMC and PIFA on AMC with local ground plane.

The $S_{11}$ measurement comparison among the three prototypes is depicted in Fig. 6. The LGP is used to observe the effect of the AMC structure surrounding a classical PIFA with a small ground plane. The total dimensions of the prototype are 170 mm x135 mm. The classical PIFA antenna has a bandwidth of 180 MHz,7.5%; the PIFA on AMC has a bandwidth of 200 MHz, 8.3%; and the PIFA on AMC with LGP has a bandwidth of 370 MHz, 15.4%, more than twice the classical PIFA bandwidth. The PIFA on AMC resonant frequency is 2.34 GHz and the PIFA on AMC with LGP is 2.43 GHz. Other simulated and measured characteristics are show in table I.

TABELA I
RESUME OF PROTOTYPE CHARACTERISTICS

| **Prototype** | **Maximum Beam (Elevation,Azimuth)** | **Directivity** | **Gain** | **Efficiency** | **BW** |
|---|---|---|---|---|---|
| | **degree** | **dB** | **dB** | **%** | **MHz** |
| PIFA | (85°,360°) | 4.26 | 4.08 | 95.71 | 180 |
| PIFA on AMC | (10°,180°) | 5.21 | 4.83 | 92.61 | 200 |
| PIFA on AMC with LGP | (70°,360°) | 4.77 | 4.20 | 88.2 | 370 |

## V. PIFA ANTENNA ARRAY ON AMC GROUND PLANE

In this section is presented an antenna array formed by three identical PIFA antennas in a triangular geometry. The AMC structure and the antennas have the same dimensions calculated in previous sections. In Fig. 7 is shown a view of the antenna array prototype. The total dimensions are 215 mm x185 mm.

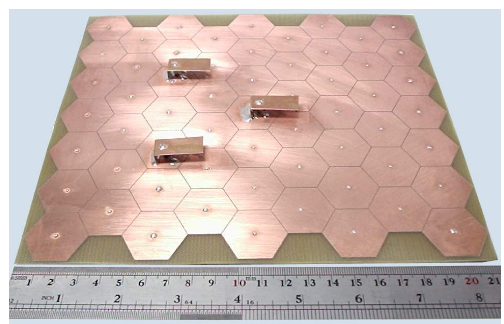
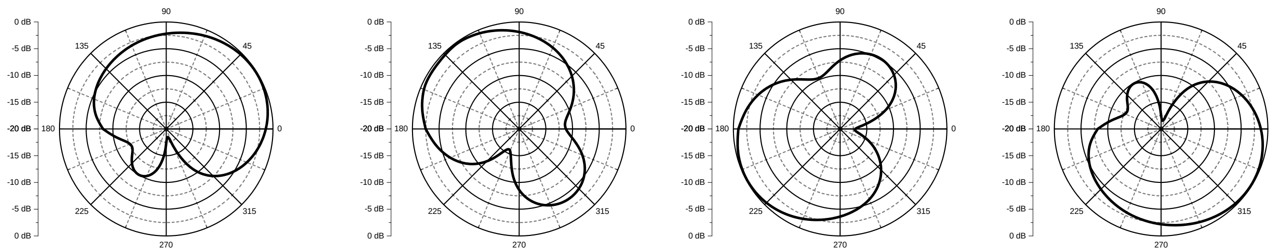


Fig. 7. The prototype of the PIFA antenna array on AMC (the reference ruler is in cm and inches).

The distance between the array elements is nearly $\lambda/2$. This distance was chosen to avoid grating lobes and to limit the mutual coupling [15] and is optimized by simulations on software IE3D. As in section IV, the antenna array with and without the LGP is measured and the comparison is depicted in Fig. 9. The PIFA array on AMC bandwidth around 2.4 GHz is 240 MHz, 10%, it is 40 MHz larger than the single antenna on this ground plane. But the PIFA antenna array with LGP has the wide bandwidth of 790 MHz, 35%, which is a bandwidth improvement of 113.5% comparing to the antenna array without the LGP and a bandwidth improvement of almost 340% comparing to the classical PIFA antenna. Besides the input return loss analysis, an important array characteristic is analyzed, the beam steering capability. This means that an array could have its principal lobe redirected to a determined angle. The presented array has this feature depicted in Fig. 8 for some angles in the azimuth plane. This beam steering is provided by different feed phase delays on the fed elements and by different number of fed elements. In table II is presented some simulated feed schemes for the antenna array. As can be seen, the directivity and the gain are improved with the use of more fed elements. As shown in table II for $\phi = 0$, the radiation pattern is steerable in the elevation plane too.



(a) $\phi = 30^0$. (b) $\phi = 130^0$. (c) $\phi = 210^0$. (d) $\phi = 330^0$.

Fig. 8. 2D Radiation pattern in the azimuth plane at the same elevation angle ($\theta = 65^0$) for different feed schemas for the PIFA antenna array on an AMC with LGP, showing the beam steering characteristic.

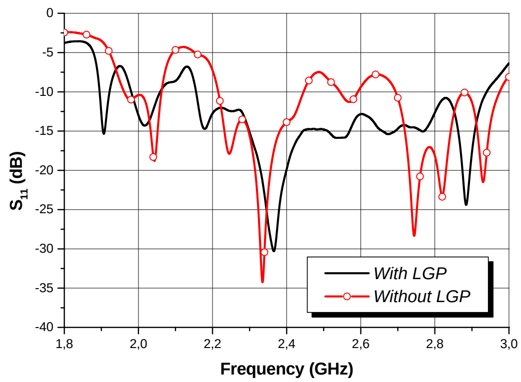



Fig. 9. Measured $S_{11}$ comparison between the PIFA array on AMC with and without a local ground plane.

TABELA II

DIFFERENT FEED SCHEMAS FOR THE FED ELEMENTS

| Phase delay between PIFA elements (N=Non fed element) | Maximum Beam (Elevation, Azimuth) degree | Directivity dB | Gain dB | Efficiency % |
|---|---|---|---|---|
| 0 N N | (65°,0°) | 5.36 | 4.6 | 85.9 |
| 0 0 N | (70°,70°) | 6.35 | 5.56 | 87.6 |
| 90 0 N | (70°,160°) | 6.9 | 5.34 | 77.33 |
| 0 N 0 | (70°,290°) | 6.35 | 5.56 | 87.56 |
| 90 N 0 | (70°,200°) | 6.89 | 5.33 | 77.35 |
| -30 90 90 | (65°,0°) | 8.41 | 7.56 | 89.9 |
| -60 -90 90 | (75°,90°) | 8.21 | 6.55 | 79.8 |
| 0 0 0 | (55°,180°) | 7.53 | 6.8 | 90.3 |
| -60 90 -90 | (75°,270°) | 8.21 | 6.55 | 79.8 |
| 0 90 90 | (50°,0°) | 6.8 | 6.46 | 95 |
| -60 90 90 | (70°,0°) | 9.54 | 7.87 | 82.51 |
| -90 90 90 | (75°,0°) | 9.83 | 7.76 | 78.9 |

## VI. CONCLUSION

It is showed, by measurements and simulations, some improvement on PIFA antenna characteristics achieved by the use of an AMC structure as its ground plane. The major improvement is in the bandwidth, which is more than twice the classical PIFA antenna bandwidth, when used a LGP. A triangular PIFA antenna array on an AMC structure is also presented. The antenna array achieved a wide bandwidth, allowing its use in several systems, such as WLAN, Bluetooth and others. Beside this, the directivity and the gain are improved. The array radiation pattern is completely steerable in the azimuth plane and in part of the elevation plane.

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