Analysis of the Electromagnetic Absorption in a New Design of PIFA Antenna Using Metamaterials

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Abstract
This paper presents the design, simulation and fabrication of a miniaturized wearable dual-band antenna put on a rigid substrate and operable at 2.45/5.8 GHz for wireless local area network applications. The electrical and radiation characteristics of the developed antenna were obtained by means of the technical insertion of a slot to tune the operating frequencies. To study the impact of the electromagnetic radiation of the structure of the human body, it is necessary to minimize the back radiation towards the user. Therefore, in this work, a multi-band artificial magnetic conductor (AMC) was placed directly above a dual-band planar inverted F antenna to achieve a miniaturization with excellent radiation performance. The simulations were carried out using the computer simulation technology CST Microwave Studio (CST MWS). A good agreement was achieved between the simulation and experimental results. The comparison of the measurement findings indicates that, when the antenna was backed by the AMC plane, the gain improved from 1.84 to 3.8 dB, in the lower band, and from 2.4 to 4.1 dB in the upper band. The front-to-back ratio of the AMC backed PIFA antenna was also enhanced. Then, to ensure that the proposed AMC structure is harmless to the human body, this prototype was placed on three-layer human tissue cubic model. It was observed that, due to the inclusion of an AMC plane, the peak specific absorption rate (SAR) decreased to 1.45 and 1.1 W/kg at 2.45 and 5.8 GHz, respectively (a reduction of around 3.7 W/kg, compared with an antenna without (AMC).

Keywords
Artificial magnetic conductor (AMC) · CST simulator · Dual-band antenna · PIFA antenna

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1 Introduction

In the last decades, Small Electric Antennas (SEA) have been widely studied by the research community due to their intensive application in communication systems and the role their miniaturization plays in minimizing the size of wireless communicating objects. Other types of commonly wireless antennas are: planar inverted-F antennas (PIFAs) and Microstrip Antennas (MSAs). The former, which are omnidirectional antennas with a lot of mixed polarization, are successfully used in static applications, but particularly with moving devices (e.g. wearable and mobile devices) and in ever-changing environments. They contain a ground plane, a top radiator, a coaxial probe and a short circuit linking the patch to the ground plane. To optimize these antennas by adding new parameters in their design, various techniques, such as strategically shaping the parasitic patch element near the radiating patch, judiciously locating loads [1], adjusting the parameters of the ground plane and the short-circuit and improving the feeding scheme [2, 3], were proposed.

Low profile antennas are always limited by impedance matching and they have a narrow bandwidth. Therefore, the PIFA antenna with only one single resonant mode and huge size is generally used to expand the impedance bandwidth to cover a WLAN band and achieve a low-profile structure [4, 5]. In addition, the design of the antenna must take into account the effects of this structure interaction with the human body to select its best design and location in wireless devices such as cellular telephones, cameras, watches, shoes, etc.

Indeed, the most challenging objective of wireless communication system consists in ensuring the continuous interconnection of everything everywhere with a reduced power consumption. It is assumed that, in the future, the number of interconnected devices will grow and each human body will probably be in contact with, at least, ten devices. Therefore, to study antenna/human body interaction, the implementation of an antenna was schematized, in the performed experiments, by a cyclical process following four steps: design, antenna analysis, human interaction study and, finally, meeting the desired electromagnetic parameters [6] (Fig. 1).

PIFA antennas can also provide high gain and high radiation efficiency due to their easy integration into mobile devices. Therefore, if backed by the reflector plane, they allow enhancing the radiation performance and protecting the body from back radiation. In [7], a planar dual-polarized antenna fabricated on a Rogers substrate, covering two frequency bands (GNSS and WLAN) and put on multi-band artificial magnetic conductor (AMC), was analyzed and studied. Authors showed that the AMC backed monopole antenna improved the radiation performance in terms of gain and FBR. It was also demonstrated that, in the GNSS and WLAN frequency bands, the front-to-back ratio increased from 11 to 21.88 dB and from 2.5 to 24.5 db. This rise was accompanied by a reduction of the SAR to 89.45%. Besides, in [9], a compact conformal antenna, operating at 2.45 GHz, was backed by anisotropic meta-surface. The obtained gain and the impedance bandwidth were equal to 6.2 dBi and 5.5%, respectively. This antenna provided a front-to-back ratio greater than 23 dB and a reduction in the specific absorption rate of 95.3%. To ensure a high degree of isolation between the antenna and human body and maintain a reasonably small profile, AMC ground planes were utilized in [10] and [11, 12]. Moreover, in [13], a multi-band antenna integrated into military beret was modelled to study the effects of the human head on the radiation characteristics. It performed well in various wearing positions on the head for indoor/outdoor positioning system.

We model, in this work, a dual-band antenna that can be used in wireless local area network applications. The design procedures as well as the analysis of the characteristics of
the AMC aircraft and the antenna are also described. The radiation mechanisms are determined by measuring the far-field pattern in the anechoic chamber.

This manuscript is organized as follows: In Sect. 2, we describe the design of the created antenna based on an appropriate parametric study. In Sect. 3, the simulation and experimental results as well as the integration of the meta-surface designed to reduce its back radiation are illustrated. The performance of the antenna placed near the human body is depicted to show how this structure allows minimizing the SAR value of the two operational frequency bands. Finally, Section 4 summarizes all the obtained results and presents some suggestions for future research work.

2 Antenna Design

2.1 Material and Methods

The created structure (the antenna and the AMC cell), developed at the required frequency, is a dual-band PIFA antenna supported by an AMC network (4 rows * 4 columns). To obtain an adjustable structure, we modelled the PIFA antenna using FR4 as substrate having the following characteristics: thickness $T = 1.6$ mm, relative permittivity $\varepsilon_r = 4.4$, relative permeability $\mu_r = 1$ and tangential loss tan$\delta = 0.02$ (constant adjustment).

As shown in Fig. 2, the basic PIFA consists of a radiating plate, quarter wavelength ($\lambda/4$), a short circuit plate and a supply wire connected to the resonating plate. Although
PIFA antennas have many advantages over the conventional antennas, they have narrow bandwidth [14].

The equivalent circuit of the designed dual-band PIFA antenna is represented in Fig. 3.

It is clear, from this figure, that the dual band PIFA antenna is represented by two parallel RLC circuits and the coaxial feed line modelled by an inductance L3. Furthermore, since each resonance frequency belongs to a parallel RLC, these parallel RLCs can be realized by designing different electrical paths; each of which is equal to a related resonance frequency of one $\lambda/4$[15].

The simulation results, such as RL (= S11) return loss and the radiation patterns of two resonant frequencies, were analyzed using the simulator CST Microwave studio. Then, they were verified by measurements taken in an anechoic chamber employing a vector network analyzer to determine the actual performance of the designed antenna (Fig. 4).
2.2 Parametric Study

Several parameters, such as the height, the feeding position and the width of the short circuit connecting the patch by the ground plane, must be taken into account when designing PIFA antennas. We first created a conventional PIFA \((L_p \times W_p)\) without any slots to operate at 2.4 GHz band. The dimensions of the PIFA antenna, fabricated on FR4 substrate with a thickness of 1.6 mm and fed by a 50 Ohm coaxial probe, are \(50 \times 50 \times 6.4\) mm\(^3\).

To disturb the current path, a rectangular open-ended slot with dimensions \(L_s \times W_f\) was added on the patch. The latter created obstacle and circulated the input current around it, generating the second band [16]. The optimized dimensions of the antenna, simulated and analyzed using the commercially available simulation CST Microwave Studio (CST MWS), are given in Table 1 (Fig. 5).

The resonance frequencies were approximated applying Eq. (1) as a function of the electrical lengths.

### Table 1 Antenna dimensions

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| \(L\)     | 50         | \(T\)     | 1.6        |
| \(W\)     | 50         | \(L_f\)   | 10.5       |
| \(L_p\)   | 24         | \(W_f\)   | 2          |
| \(W_p\)   | 24         | \(W_{c1}\) | 9          |
| \(H\)     | 6.4        | \(W_{c2}\) | 7          |

Fig. 5 a Configuration of the prototype (antenna and metamaterial), b 3D view of PIFA antenna, c Top view of the AMC
where $\varepsilon_r$ is the permeability of the used substrate and $C$ denotes the speed of light in free space. Several methods were proposed to properly study the obtained results. In fact, in [17], the two frequencies, $f_1$ and $f_2$, were calculated using the following relations:

$$f_r = \frac{C}{(L_p + W_p + H + T) \sqrt{\varepsilon_r}}$$
$$f_{r2} = \frac{C}{2 \times (L_f + W_f) \sqrt{\varepsilon_r}}$$

Moreover, in [18], a nonlinear fit of the least squares data, obtained using the Gauss–Newton technique, showed the good adaptation of the PIFA antenna modelization.

### 2.3 Full-Wave Simulation Setup

An AMC cell, based on square patches, was analytically modeled by an LC circuit [19]; whereas LC modeling did not include substrate losses. In the case of AMC, the equivalent electrical schematic of an AMC cell is a parallel RLC circuit [8] where $R$ corresponds to the losses in the substrate, while $C$ and $L$ represent respectively the capacity between the cells and the inductance created by the height of the substrate (Fig. 6).

A full-wave simulation was carried out to calculate the relative dimensions and the operating bandwidth of the artificial magnetic conductor (AMC). The structure unit cell, excited by a source of an incident plane wave declining from the top of the box, was placed in a boundary conditions box (two faces of Perfect Electric Conductor (PEC) and two others of Perfect Magnetic Conductor (PMC)) to form an infinite periodic structure (Fig. 7).

The distance separating the upper face and the FSS surface should exceed $\lambda/4$ and be deembedded to provide the right TEM incident’s phase reference (Fig. 8).

![Fig. 6 Electric equivalent circuit of a AMC cell](image-url)
2.4 AMC Unit Cell

The characterization of an infinite AMC using CST Microwave Studio® can be obtained using the frequency or time solver. The resonance frequency of the AMC surface was equal to 0° of the reflection coefficient phases, which allowed obtaining the operating bands.

The fundamental structure of the unit cell was manufactured on a dielectric substrate (FR4) with thickness (h=3.2 mm). The square patch of size 17*17 mm² resonated at 2.42 GHz, with 19.2% bandwidth over +90 reflection phase. By introducing the cross-shaped slot in the patch, AMC resonated at additional resonance of 5.8 GHz band. The AMC+90 reflection phase bandwidths for the two required frequency bands (2.33–2.63 and 5.55–5.18 GHz) are represented in Fig. 9.
In the performed experiments, a rigid substrate was used due to its increased thermal and mechanical stability, which would be restricted when placed close to the human body (Fig. 10) (Table 2).

Fig. 9  Simulated reflection coefficient for simple square and Jerusalem cross AMC structures

Fig. 10  a Top view of the fabricated Prototype (AMC backed antenna), b Bottom view of the whole structure

Table 2  AMC unit cell dimensions

| Parameter | Value (mm) |
|-----------|------------|
| L         | 17         |
| H         | 16         |
| K         | 5          |
| W         | 12         |
3 Results and Discussion

3.1 Electrical and Radiation Characteristics of the Designed Antenna

Initially, the optimized antenna without the incorporation of AMC was manufactured and tested in free space. The measured reflection coefficient showed two distinct resonant bands ranging from 2.34 to 2.57 GHz (9.2%), for Wifi/Bluetooth, and from 5.65 to 6.37 GHz (12.4%) for WLAN frequencies, which corresponds well to the simulation results illustrated in Fig. 11.

Figure 11 presents the return loss $S_{11}$ as a function of the frequencies for the two bands at 2.5 and 5.8 GHz, respectively.

Figure 11 demonstrates that the reflection coefficient presents a good agreement for the first band, but with a slight difference for the second band. This result can be explained by the measurement error caused by the tolerance of the soldering and manufacturing of the antenna.

In order to evaluate the radiation performance of the designed antenna, some measurements were carried out in the anechoic chamber. The radiation patterns measured and simulated at 2.5 and 5.8 GHz on the yz (E plane) and xz (H plane) axes were compared with those of the antenna supported by the AMC plane.

Findings presented in Fig. 12 show a good agreement between the simulation and the measurement results.

3.2 Integration of Dual-Band PIFA Antenna and AMC

The unit cell was arranged into a $4 \times 4$ array to form the AMC plane employed as the backplane of the antenna. The size of the entire dual-frequency AMC array is $68 \times 68$ mm$^2$, as shown in Fig. 8. It consists of only eight units, each of which has a size of $17 \times 17$ mm$^2$. The goal of this work is to minimize the coupling of the developed antenna with the human body. Then, cross-shaped slots were introduced into the square patch. Compared with the conventional square unit cell designed on the same substrate, these slots did not only have dual-band behavior, but they also allowed miniaturizing

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**Fig. 11** Simulated and measured $S_{11}$ of the antenna in Free space
the cell by 32%. Furthermore, both AMC plane and the created antenna, positioned at its center, were separated by a 2 mm-thick foam spacer.

As revealed in Fig. 13, due to the manufacturing tolerances of the used model, slight differences between the measurement and simulation results, obtained for the reflection coefficient of the antenna with AMC, were observed. The working range of the antenna with AMC for − 10 dB return loss measurement varied from 2.43 to 2.62 GHz, in Wifi/Bluetooth, and from 5.69 to 5.9 GHz in the WLAN frequency band.

The measurement results of the radiation performance, represented in the following Figures, show the smooth functioning of the AMC on the two frequency bands. Indeed, the radiation pattern measured in the E and H planes was then compared to the radiation pattern of the PIFA antenna supported by the AMC plane in two frequency bands when placed on the human body model (Fig. 14).

Figure 15 shows the gain of the antenna with and without AMC as a function of frequency.

The measured gain of the proposed antenna without AMC was 3.8 dB and 4.1 dB in both frequency bands. Indeed, the use of this AMC plane allowed increasing the maximum gain by almost 1.96 and 1.7 dB for the two frequency bands of 2.45 and 5.8 GHz, respectively.
3.3 Effect of the Antenna on the Human Body

The exposure of the phantom to the radiation produced by PIFA antennas at frequencies equal to 2.4 GHz and 5.8 GHz was modeled with the time solver of the CST MWS electromagnetic module. A three-layer cubic model of human tissue was placed 5 mm below the structure [20]. The thickness of each layer is shown in Fig. 16.

The electrical properties of a 3-layer tissue model of the human body are shown in Table 3.

The following Figures depict the simulation results of the reflection coefficient and the radiation patterns of the antenna with and without the AMC in the presence of the human body model (Fig. 17).

The return loss shows that the antenna without AMC support did not perform well in terms of adaptation and bandwidth. On the contrary, when supported by the AMC plane, its performance was significantly improved in both frequency bands while maintaining its polarization characteristics. Comparing the radiation patterns parameter of the structure only to its radiation patterns parameters when interacting with the model, we observed that the proposed AMC backing allowed protecting the human body as well as improving the performance of the antenna developed for wireless applications. On the other hand, when the designed antenna is supported by the CMA and evaluated on the model, the FBR (Front to Back Ratio) increased from 0.3 dB to 16.5 dB and from 0.2 dB to 12.5 dB in the WIFI/Bluetooth and WLAN band, respectively (Fig. 18).

In order to minimize the absorption of the electromagnetic waves, the SAR value must be lower than the values given by the International Commission for Non-Ionizing Radiation Protection (ICNIRP). On the 1 g and 10 g tissues, the SAR value shall not be greater than 1.6 W/Kg and 2 W/Kg, respectively. It is, therefore, essential to know the levels of the radiation absorbed by the human body. The local SAR was evaluated by determining the electric field in the phantom liquid created by the presence of an antenna near it. The SAR level was calculated and expressed as demonstrated below (Table 4).
Fig. 14 Measurement radiation pattern of the PIFA antenna with and without AMC for two planes (E-plane; H-plane) at: a 2.5 GHz, b 5.8 GHz

Fig. 15 Measured gain of the PIFA antenna with and without AMC
Fig. 16  Simulated prototype on three-layer human tissue cubic model

Table 3  Electrical properties of the human tissue

| Tissue  | Frequency (GHz) | Permittivity (ε_r) | Conductivity [σ (S/m)] |
|---------|-----------------|-------------------|------------------------|
| Skin    | 2.4             | 38.06             | 1.440                  |
|         | 5.8             | 35.11             | 3.72                   |
| Fat     | 2.4             | 5.285             | 0.102                  |
|         | 5.8             | 4.95              | 0.29                   |
| Muscle  | 2.4             | 53.63             | 1.774                  |
|         | 5.8             | 48.48             | 4.96                   |

Fig. 17  Reflection coefficient with and without AMC in interaction with model
The SAR values were simulated based on the IEEE C95.1–2005 standard using an input power of 0.5 W. The table above illustrates the simulated SAR of the created antenna with and without AMC plane. Indeed, due to the existence of the AMC scheme, the SAR was also reduced, from 5.3 W/Kg to 1.45 W/Kg, in the lower frequency band, and from 4.8 W/Kg to 1.1 W/Kg in the upper frequency band.

**Fig. 18** Radiation pattern with and without AMC in interaction with model a 2.45 GHz, b 5.8 GHz

**Table 4** SAR level of the prototype on the human body

| Unit (W/Kg)   | Standard | Antenna without AMC | Antenna with AMC |
|---------------|----------|---------------------|------------------|
| 1 g average   | 1.6      | 4.28                | 3.76             |
| 10 g average  | 2        | 5.34                | 4.83             |
| Standard      | 2.45     | 5.8                 | 1.05             |
| Standard      | 2.45     | 5.8                 | 1.19             |

The SAR values were simulated based on the IEEE C95.1–2005 standard using an input power of 0.5 W. The table above illustrates the simulated SAR of the created antenna with and without AMC plane. Indeed, due to the existence of the AMC scheme, the SAR was also reduced, from 5.3 W/Kg to 1.45 W/Kg, in the lower frequency band, and from 4.8 W/Kg to 1.1 W/Kg in the upper frequency band.
Moreover, until now, no PIFA antenna supported by AMC and designed for wireless local area network applications has been created in the literature. Table 5 compares the antenna designed in this work with those supported by AMC planes.

## 4 Conclusion

In this study, the analysis of electromagnetic absorption in the new design of PIFA antenna with slot was carried out. This modelled antenna was based on a conventional square patch and resulted in a mono-band behavior. Then, by inserting the slot on the resonant cavity of the patch, the second frequency (the dual-band) was obtained. In order to optimize the antenna performance and reduce the effect of the EM fields on the human body, we used a 4*4 AMC plane. The performance of the simulated antenna with and without AMC, placed on a three-layer cubic model of human tissue, was also assessed in this work. Then, the measured gain and radiation pattern of the PIFA antenna without AMC were compared with the performance of the antenna supported by AMC. The experimental results showed that the measurement gain of the created prototype increased by 3.8 dB, in the lower frequency band, and 4.1 dB in the higher frequency band. Therefore, due to the isolation capability of the AMC plane, the SAR was reduced to a safer range (2.0 W/Kg over 10 g tissue) by 72.8% and 75.3% for 2.45 GHz and 5.8 GHz, respectively.

### Authors’ contributions

The ethics approval, the consent to participate and the consent for publication between authors (Yes, compatibility is present).
Availability of data and material  I confirm the transparencies of data and material.

Code availability  Not applicable.

Declarations

Conflict of interest  The authors have no conflicts of interest including financial interest.

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