Effects on the antenna's radiation pattern due to metamaterial-based sub-wavelength insulation

Jorge V. de Almeida, Gláucio L. Siqueira, *Member, IEEE*, Marbey M. Mosso, *Member, IEEE* and Carlos A. F. Sartori, *Senior Member, IEEE*

***Abstract* — A metamaterial-based insulator is proposed for highly compact MIMO-systems. In previous work, the proposed insulator has been demonstrated to reduce efficiently the coupling at PEC boundaries between two very close antennas on a common ground plane. The present study concentrates on the effects of this insulator on the antenna radiation pattern. The chosen operating frequency is 2.4 GHz considering that it is a usual frequency for many indoor wireless applications. The theoretical results are supported by numerical simulations.**

***Index Terms*— Metamaterial, insulator, MIMO systems**

I. Introduction

A MIMO-based communication system uses multiple antennas with low coupling between them. In general, the individual elements are spaced by half wavelength to obtain a good insulation between the antennas, which is not always practical due to spatial limitations of some systems such as smartphones and other communication devices.

Recently, some metamaterials (MTM) were shown to be efficient in insulating patch antennas with the advantage of presenting much smaller, sub-wavelength dimensions [1] [2] [3]. In previous work, their main working principle has been deduced and a MTM-inspired insulator has been proposed [4].

The insulator of Ref [4] introduces an attenuation factor of 6dB between the neighbor antennas with a minimum gap. In this work, the same model is taken. The main goal of this new study is to investigate the influence of the MTM on the parameters of the insulated antenna such as directivity, gain and radiation efficiency. The presented results are supported by numerical simulations, including the radiation pattern.

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II. Proposed Metamaterial Insulator

MTMs are artificial structures with controllable electromagnetic properties such as chirality, permittivity and permeability [5] [6]. The material-like response of a MTM emerges from the collective behavior of its unit cells, that is, the emergent property of the system is not a property of any of its components but a feature of the system as a whole. So, in accordance with the effective medium theory, the dimensions of the MTM's unit cell must be much smaller than its operating wavelength [7].

Accordingly to the theory of MTMs, the MTM unit cell can be made out of other smaller and more fundamental unit cells since the dimensions of the resultant and final cell keep being much smaller than the operating wavelength. So, in order to achieve more complex behaviors of a MTM, superior order cells are sometimes needed.

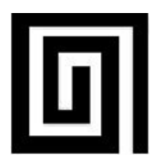

Fig. 1. Periodic structures made out of SR-based unit cells synthesize artificial magnetic conductors.

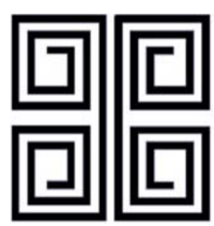

Fig. 2. A second-order unit cell constituted of four out-of-phase SR cells in order to achieve virtually no electric potential in the cell's region.

Starting from a spiral resonator (SR) based unit cell (see Fig. 1), the MTM can be made to act as an artificial reflective material for insulation purpose by introducing a second-order unit cell made out of four out-of-phase SR cells (see Fig. 2). The upper and lower cells were electrically connected to each other in order to minimize their size for a given frequency. Otherwise, the overall dimensions of the cell would be 45% bigger.

As it is well-known, if the winding direction of a coil is reversed its electric potential experiences a phase shift of 180 degrees [8]. Then, the phase discontinuity between the neighbor cells makes the sum of the electric potentials in the new cell to be virtually zero. It implies that no net energy is stored in it as it can be seen in Fig. 3. Once the structure is not absorbing the incoming energy, the conservation law requires it must be transmitting or reflecting it:

$$R + T + A = 1 \quad (1)$$

where R is the reflectance, T is the transmittance and A is the absorbance associated with the insulator's unit cell.

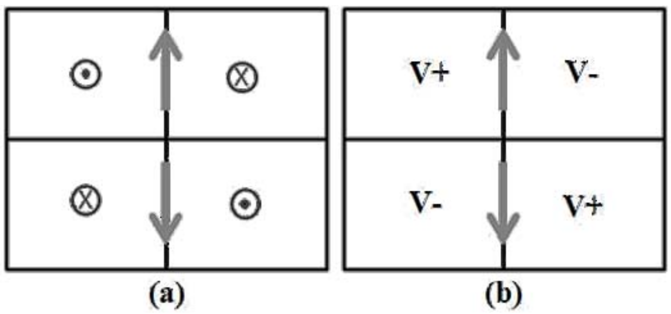

Fig. 3. Representation of (a) the electric field (perpendicular) and the magnetic flux (parallel) as well as (b) the electric potential distribution at the surface of the second-order unit cell.

As it can be seen in Fig. 3, at the right and left sides of the cell the inverted electric potentials behave similarly to an electric field circulation, which is equivalent to a time-variant magnetic flux accordingly to Faraday's law:

$$\oint E\, dl = -\frac{\partial \phi_m(t)}{\partial t} \; [V] \qquad (2)$$

Since the circulations at the top and at the bottom of the resultant cell are inverted, they cancel out each other. So, the tangential magnetic flux at the surface of the second-order cell tends to be zero, which implies from Eq. 2 that the apparent electric field at the cell is also null.

Thus, no real power transposes the interface of the cell as stated by the Poynting's theorem:

$$E = 0 \; and \; H \geq 0 \rightarrow S = E \times H = 0 \qquad (3)$$

For that reason, the transmittance T of the second-order cell must also be zero demonstrating that it behaves as a reflective surface at the PEC boundary of the antennas:

$$R = 1 \qquad (4)$$

which makes the MTM to behave as a reflective surface.

III. THE PROTOTYPE

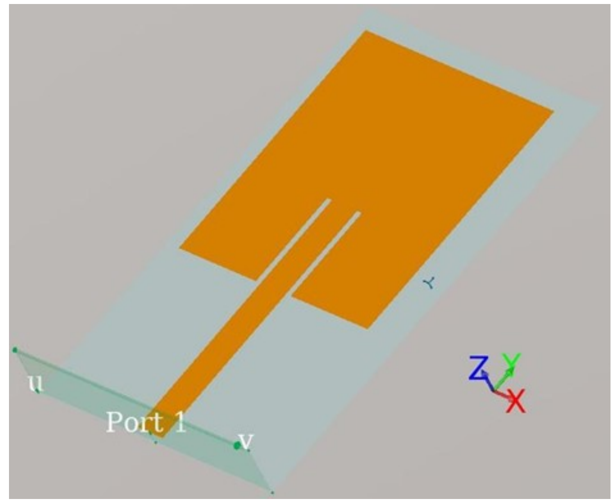

Fig. 4. Numerical simulation of the non-insulated patch antenna.

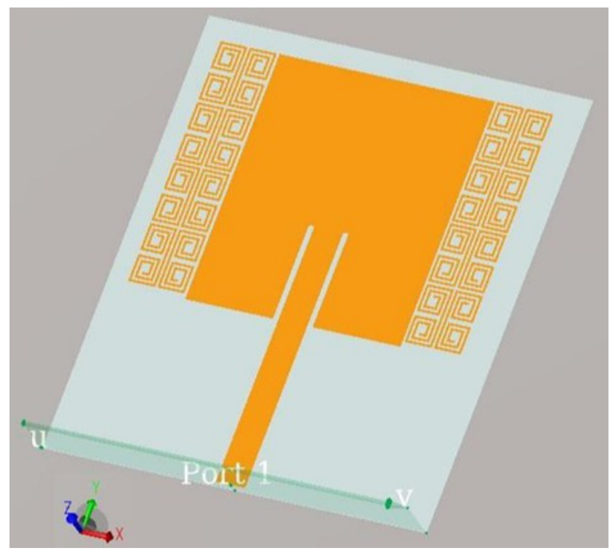

Fig. 5. Numerical simulation of the insulated patch antenna.

The proposed antennas are presented in Fig. 4 and Fig. 5. The employed substrate consists of a 1.6 mm thick FR-4 ($\epsilon = 4.6$). The ground plane on the bottom and the patch antenna and the MTM printed on the top are made of copper. The main dimensions of the MTM second-order unit cells are 6.7mm x 7mm x 35µm. The antennas dimensions are 26mm x 30 mm x 35µm. These dimensions were chosen in order to tune the operating frequency of the system to 2.4 GHz.

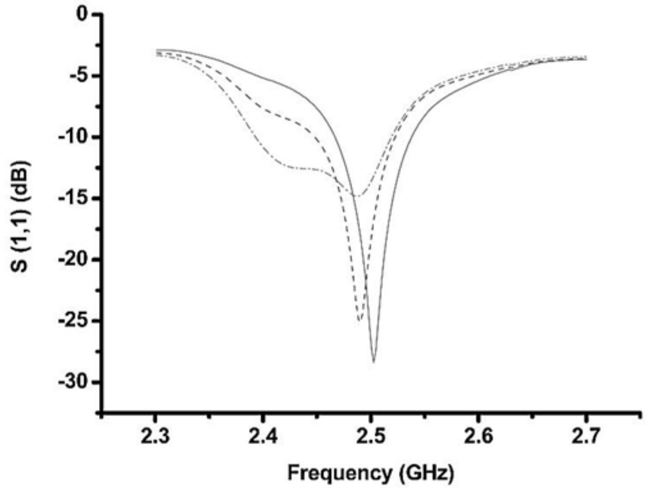

Fig. 6. Return loss of the patch antenna with no insulator (solid line), with an insulator between the antennas (dash line) and with both sides of the antennas insulated (dash dot line).

In Fig. 6 and Fig. 7, the experimental return loss and transmission gain obtained with the proposed antenna and insulator is shown. An attenuation of 10 dB of the transmission gain is obtained when both sides of the antenna are insulated, and an attenuation of 6 dB is obtained when there is just one insulator between the antennas. The operating frequency of the antenna does not vary a lot in frequency when assisted by the MTM (1.2% in the worst case), although its bandwidth is increased at the cost of a less important response in return loss. The effect is more visible when both sides of the antennas are insulated.

Despite the fact the prototypes were successfully implemented, the following studying on their radiation pattern were only simulated and not experimentally confirmed in the present work due to constraints of time.

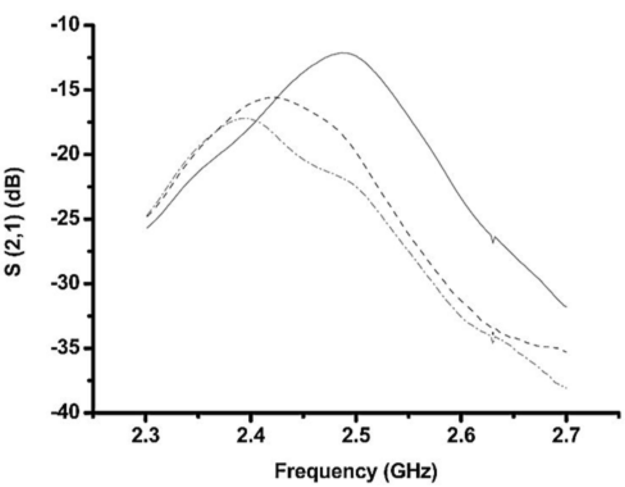

Fig. 7. Transmission gain between the antennas with no insulator (solid line), with an insulator between the antennas (dash line) and with both sides of the antennas insulated (dash dot line).

IV. Results and discussion

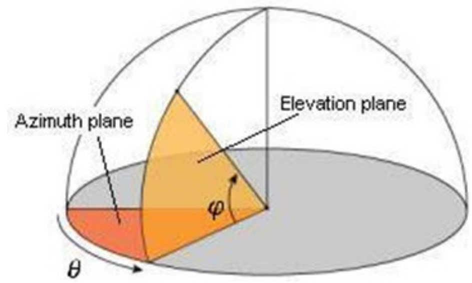

Fig. 8. Schematic of the azimuth and elevation planes.

The results are presented in the polar plane as shown in Fig. 8. The numerical simulations were made using two methods: the Method of Moments (MoM) on Keysight ADS 2015 and Finite Element Method (FEM) on Keysight EMPro 2015. Since ADS is a 2.5 EM simulator, the radiation pattern of the antennas was obtained with EMPro only.

The main parameters used in this work to characterize the antenna in terms of radiation, which is its gain G and its directivity D, are related with each other through are constant called radiation efficiency e_r:

$$e_r = 10 \log \frac{P_{rad}}{P_{in}} \quad [dB] \qquad (5)$$

$$G = e_r + D \quad [dB] \qquad (6)$$

TABLE I
Main results of the simulation of the antennas with MoM

	Non-insulated	Insulated
$f_0\ (GHz)$	2.4	2.37
$e_r\ (dB)$	-3.94	-4.19
$D\ (dBi)$	6.19	6.17
$G\ (dBi)$	2.25	1.98
$P_{rad}\ (mW)$	0.98	0.95
$P_{in}(mW)$	2.5	2.5

TABLE II
Main results of the simulation of the antennas with FEM

	Non-insulated	Insulated
$f_0\ (GHz)$	2.37	2.31
$e_r\ (dB)$	-5.21	-7.55
$D\ (dBi)$	5.62	6.02
$G\ (dBi)$	0.41	-1.53
$P_{rad}\ (mW)$	0.72	0.4
$P_{in}(mW)$	2.5	2.5

TABLE III
BEAMWIDTH AND MAIN DIRECTIONS OF THE RADIATION PATTERN

	Non-insulated	Insulated
$\Delta\theta$ (°)	123.80	100.60
$\Delta\varphi$ (°)	92.27	98.37
θ_{max} (°)	0	0
φ_{max} (°)	5	5

As it can be seen from the results presented in Table I and Table II, the results of the numerical simulations vary significantly from one technique to the other.

The results obtained via MoM indicate that the presence of the insulators does not alter significantly the main characteristics of the antenna, which seems incongruent with our previous work [4]. Despite the fact that it predicts the losses in terms of G and e_r, it is incoherent that D would not be affected by the insulator since it limits the effective angle of the E-field. Also, it does not sound possible that P_{rad} would be only slightly diminished by the MTM, since it stored and dissipated a considerable amount of power.

On the contrary, the results obtained with FEM look much more reasonable. As shown in Table II, P_{rad} is reduced to almost half when the antenna is insulated. Its directivity is enhanced in 0.4 dB, but its gain as well as its efficiency are dramatically reduced in around 2 dB. Thus, it can be said that the results computed based on FEM are more reliable in this case.

These discrepancies between the methods come from the fact that FEM is performed by solving for differential equations (DE) using finite differences and other standard techniques and MoM is performed by solving linear partial differential equations (PDEs), which are formulated as integral equations (IE). This means that FEM solves numerically stable approximations of DEs while MoM takes into account only the boundary condition of the elements of the mesh in order to compute the solution, the reason why it is also known as the boundary element method (BEM).

In other words, the nonlinearities and inhomogeneity of media with complex domains can be well computed using FEM but not using MoM. It is a consequence of the restrictions of the boundary conditions. Since the MTM is essentially nonlinear around its working frequency, FEM is more suitable to evaluate its behavior. Nonetheless, still based on Ref. [4], the MoM estimation of f_0 was closer to the one obtained by the implemented prototype.

In Table III, it is shown the main results concerning the radiation pattern shown in Fig. 9 and 10. It can be seen that the enhancement of D is directly due to the MTM insulation effect in the horizontal plane (azimuth plane). While the effective beamwidth is reduced in 23° in this direction, in the vertical one (elevation plane) it is actually increased in 6°. Other important feature is that the directions of maximum gain is not changed by the MTM.

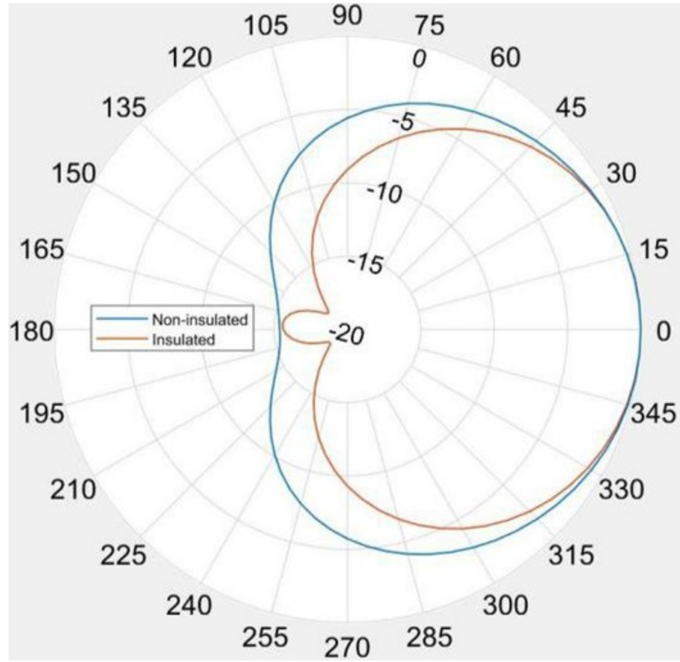

Fig. 9. Radiation pattern of the non-insulated (blue) and insulated (orange) antenna on the azimuth plane.

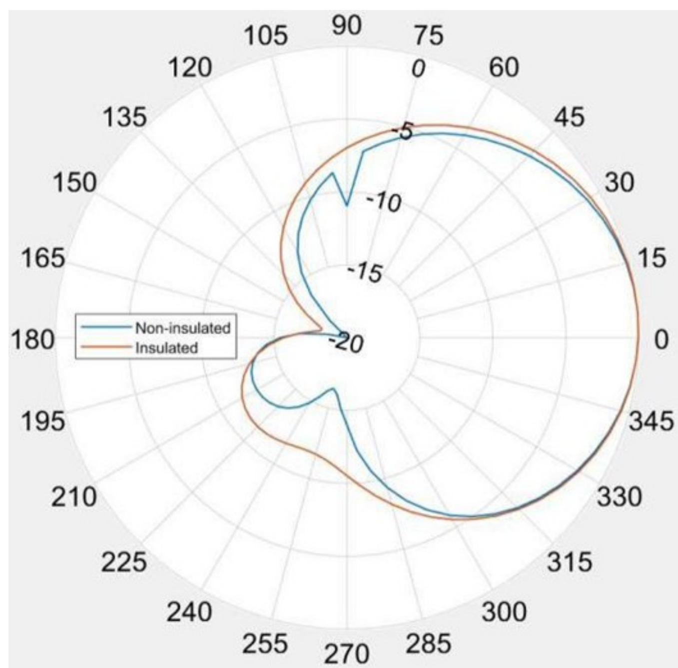

Fig. 10. Radiation pattern of the non-insulated (blue) and insulated (orange) antenna on the elevation plane.

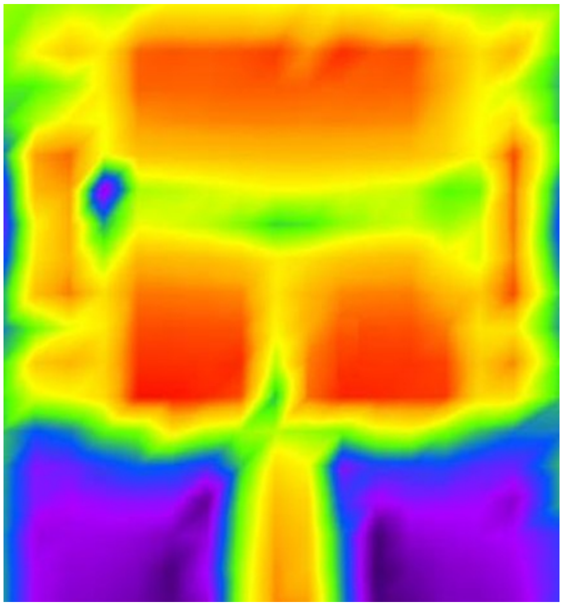

Fig. 11. Electric field intensity on the surface of the insulated antenna.

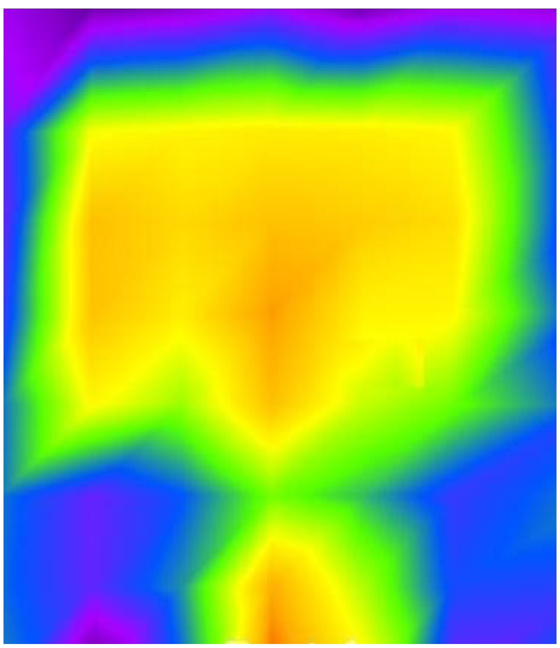

Fig. 12. Magnetic field intensity on the surface of the insulated antenna.

In Fig. 11, it is shown that the intensity of the electric field on the insulator region is quite strong even though most of the electric field is confined into the patch's surface. On the other hand, it can be seen in Fig. 12 that almost no magnetic field is stored around the MTM. It is in agreement with the previous results presented in Ref. [4] which states that main the working principle of the considered insulators is that they behave as artificial magnetic conductors that support magneto-inductive (MI) waves. MI waves are surface waves. Like magnetic currents, they are electric field sources.

Hence, it comes to the conclusion that the insulating structures mostly dissipate power as heat. In order to diminish the significant amount of power that is lost when the antenna is insulated, a less dissipative MTM must be considered.

V. Conclusion

In the presented work, the main effects on the radiation pattern of patch antenna insulated with MTM were studied. As it was shown, gain and efficiency are greatly reduced in the presence of the insulator, although its directivity in the azimuth plane is increased as a direct consequence of the blocking effect at the PEC boundaries. Nonetheless, the maximum radiation angles in both planes are not influenced by the MTM. The loss in efficiency is mainly due to dissipation of power at the MTM level.

As a secondary result, it was shown that MoM is not a very suitable technique in order to deal with the considered second-order MTM since it is strongly nonlinear and inhomogeneous around its operating frequency.

In the future, experimental investigations on the radiation pattern are intended as a mean to validate these numerical results. Besides that, new designs of MTM must be evaluated in order to achieve less costly insulators in terms of power.

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