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# MATERIALS FOR ELECTROMAGNETIC PURPOSE: THE CASE OF A MICROSTRIP PATCH ANTENNA CHARACTERISTICS IMPROVEMENT BY ADDITIONS OF METALS AS SPHERICAL INCLUSIONS INTO THE SUBSTRATE

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## Abstract

*This paper deals with the design of metamaterial (MTM) substrates to be used in electromagnetic devices. In particular, the approach has been considered for different investigations having the scope the realization of antennas on flexible substrates. The importance of the topic resides in the potential of conforming the antenna to/on desirable shapes. Flexibility is well exploitable either in advanced communication systems or in biomedical applications, just to mention some. The proposed MTM is made of metallic spherical inclusions of AISI52100, which are embedded in a polymer host. The paper aims to assess the feasibility of increasing the performance of a microstrip patch antenna, and to decrease its size by using the MTM substrate, which is able to locally control the permittivity of the substrate and to create electromagnetic band-gap regions outside of the patch.*

**Key words**: materials for electromagnetic purpose, metals, spherical inclusions

## 1. Introduction

The proliferation of mobile communications has given rise to a large demand for smaller antennas that operate at relatively low frequencies. Printed antennas are always attractive for these applications since they provide conformity, low manufacturing costs and low profile. Size reduction and bandwidth increase are however difficult to obtain since low-cost, commercially available materials usually only have dielectric constants ranging from 2 to 10. The use of ceramics with high dielectric constants is not a new concept in antenna design [1]. However, bandwidth and gain reductions are inevitable if suitable impedance matching techniques are not also considered. In this research, a way to demonstrate that textured substrates can provide miniaturization with no gain or bandwidth compromise has been pursued. In particular, a textured substrate made of by two materials has been considered, that allowed a patch miniaturization by a factor of 3.3 of one of the most popular geometries, i.e., the (rectangular) microstrip patch antennas (MPA). A schematic illustration of such solution is reported in Fig. 1, where it is possible to appreciate the difference between the initial, unloaded dielectric and the proposed configurations.

Comparisons among patches on different substrates are given to quantify the performance of the textured substrate patch in terms of gain and bandwidth.

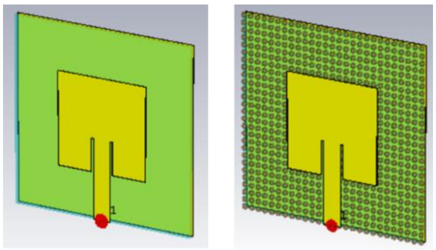


Fig. 1: Schematic representation of MPA with homogeneous substrate (left) and MPA with MTM substrate (right)

In recent year there has been a growing interest in the development of new technologies that enable to engineering synthesis of artificial materials that exhibit properties not available in nature (i.e. negative refraction, band-gap, etc.). These materials are composites, for example, made of elementary inclusions of small size, orderly distributed in a host media. Depending of the length of inter-element spacing and the size of the inclusions, they can be classified in two groups. If the inter-element spacing and the size of the inclusions are of the order of a wavelength they are call “Photonic Crystals”, while if they are much smaller than a wavelength, they are call “Metamaterials” (MTMs). Photonic crystals have been useful in optics for the development of compact optical devices and systems [1]. Current investigations in this area are driven by the possibility to fabricate 2D photonic bandgaps (i.e., photonic crystals able to confine light in two dimensions) for the development of planar integrated optics and photonic circuitry, etc.

The name “MTM” is attributed to Walser [2] who stated that MTMs are “Macroscopic composites having a synthetic, three-dimensional, periodic cellular architectures designed to produce an optimized combination, not available in nature of two or more responses to specific excitation”. Victor Veselago is recognized by the scientific community as the pioneer in the field of MTMs. In 1968, Veselago [3] made a theoretical study of the electrodynamic of a substance with both negative dielectric constant ($\varepsilon$) and magnetic permeability ($\mu$). Following, for approximately 3 decades there have not been further relevant studies on this issue till 1996, when Pendry [4] revealed how the structure made of very thin infinitely long metal wires arranged in a three dimensional (3-D) cubic lattice could have a negative effective dielectric comstant ($\varepsilon_{eff}$) below the plasma frequency in the GigaHertz range. In 1998, Pendry [5] demonstrated the theoretical analysis proposed in [4]. The year after, Pendry [6] introduced the Split Ring Resonator (SRR) and showed that the microstructure built from nonmagnetic conducting sheet exhibit an effective magnetic permeability ($\mu_{eff}$) which can be tuned to values naturally not obtainable. Combining the SRR and the thin wire structures proposed by Pendry, Smith et al. [7] in 2000 fabricated the first MTMs exhibiting a frequency region in the microwave regime with simultaneous negative values of $\mu_{eff}$ and $\varepsilon_{eff}$. Simultaneously, Pendry [8] identified that the lens proposed by Veselago [3] was able to amplify temporary waves, which contain information of small features of the object, which one wants to generate an image from, enabling to create a perfect carbon copy. A perfect lens could have a mayor impact in areas like biology and/or medicine, where it could give a better insight of DNA molecules features and viruses that conventional lenses are not able to capture due to their small size. In computer electronics, they could be helpful for the improvement of lithographic processes that allow reducing the size of processors. Continuing the review of MTM history, in 2001 Shelby et al. [9] demonstrated the negative refraction effect.

Earlier, Smith [7] experimentally verified the feasibility to create double negative MTMs (DNMs). Several homogenization theories have been proposed aiming to analytically characterize composites and mixtures made of two or more materials. The validity of them, usually depends on the shape of the inclusions introduced in the host material and the size of the unit cell ”d” used to extract the effective parameters (i.e., $\varepsilon_{eff}$ and $\mu_{eff}$ ) which have to be much smaller than the size of a wavelength (lattice constant (d) << guided wavelength ($\lambda$)). However, for some special cases, homogenization theories have confirmed to be useful to find a first-degree approximation of the effective parameters of MTMs. The analytical homogenization theories, formulated by Lewin and Maxwell Garnett [10] are two methods, which can be used for the calculation of $\varepsilon_{eff}$. To do so, it is required to know the permittivity of the inclusions and of the host material. Anyway, this analytical principle cannot be used when the inclusions are made of a metal.

On the other hand, MTMs have found extensive applications in antenna engineering. In 1999, Sievenpiper [11] proposed a new type of MTM made of a mushroom like structures having high surface impedance due to the existence of bandgaps. This high impedance surface allows creating Artificial Magnetic Conductor (AMC), i.e., surface with a unitary reflection coefficient of zero phase. Additionally, Sievenpiper explains how this mushroom like MTM can be used in antenna design to eliminate surface currents in patch antennas and create low profile antennas, as illustrated in Fig. 2.

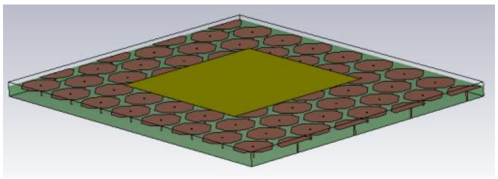


Fig. 2: High impedance surface applied to MPAs to eliminate surface waves

This type of MTM can be used to suppress surface waves in microstrip antennas, improving the characteristics of the radiation pattern especially in array configuration, and/or as ground plane for low-profile antennas since, it reflects electromagnetic waves with a zero phase shift. Other applications of MTMs are as superstrate (i.e., parallel layers of MTM above microstrip antennas with zero index of refraction) that concentrates the antenna radiation increasing the gain and directivity. The huge success of MTM in antenna engineering relies on two factors. On one hand, the potential of MTM is to optimize existing antenna designs and moderate some faults of them by using materials with unconventional responses. On the other hand, the fact that MTMs provide more degrees of freedom to antenna engineers, because their effective properties can be determined not only by the properties of inclusions and host materials, but also by their shape, size, spacing and arrangement.

A periodic medium, frequently considered for the realization of MTMs, can be defined by a regular repetition of a fundamental unit cell through space, where the set of points enclosed by each unit cell is called space lattice (Fig. 3). The fact that periodic material possesses translation symmetry implies that the properties of the MTM have also spatial periodicity. Therefore, by analysing a single space lattice with periodic boundary conditions (PBC) it is possible to predict the behaviour of the entire medium.

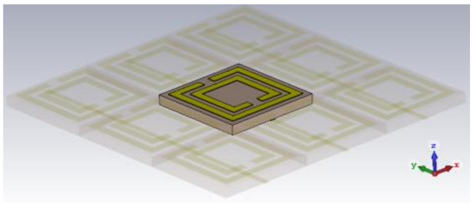
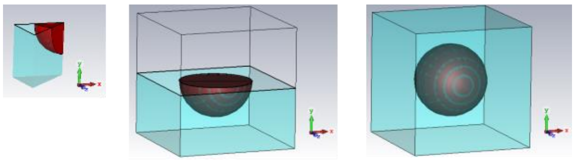


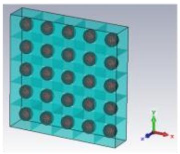
Fig. 3: Space lattice of a periodic arrangement

Moreover, a space lattice can further have rotation, reflection and translation symmetry. Hence, it is possible to identify a volumetric region inside the space/spectral lattice called the Irreducible Brilluin Zone (IBZ) that satisfies the condition, that by applying symmetry operation to the aforementioned volumetric region allows to reconstruct the space lattice and consequently the periodic medium. In Fig. 4a there is an example of the IBZ of a periodic medium made of spherical inclusions in a host medium (Fig. 4d). By applying rotational operation to Fig. 4a it is possible to arrive to Fig. 4b. Then by applying a symmetry operation (mirroring) to Fig. 4b, it is possible to reconstruct the space lattice Fig. 4c. Finally, by applying translation operation to Fig. 4c it is possible to reconstruct the periodic medium Fig. 4d.

Antenna engineering are constantly looking for new ways to minimize antenna profile, reduce antenna size, widening bandwidth, increase gain and control the radiation pattern. This is not a simple task; conventional techniques usually enhance one characteristic while worsening other(s). Additionally, because most antennas behaviour cannot be completely described analytically, most of the optimization techniques used to date are heuristic. Even though they have a theoretical background, they usually require a parametric optimization.



(a) IBZ (b) (c) Space Lattice



(d) Periodic Medium

Fig. 4: Schematic representation of periodic medium made of spherical inclusions in a host medium

If proper boundary conditions are applied, i.e., reducing the analysis to the IBZ, it is possible to extract from the generated (electromagnetic) response the properties of the complete periodic medium, strongly reducing memory, computation time and resources costs.

As mentioned above, since Smith [9] experimentally proved the theoretical work of Veselago, MTMs have driven the attention of antenna designers. The fact that MTMs properties depends on the inclusion shape, size, spacing and materials used for its construction (host material and inclusions materials), means that designers can custom made materials with desired electromagnetic characteristics to fabricate antennas that have a better performance while having more individual control of the antenna characteristics with respect to the those fabricated with conventional materials.

Up to date, one of the most popular antennas is the MPA. This type of antennas is characterized by its low profile, lightweight, low-cost and a simple feeding mechanism that make it suitable among others, for Wifi, UHF and Bluetooth application. However, by using these type of antennas, it is necessary to deal with a series of issues, e.g., low radiation efficiency due to surface currents, medium gain and relatively narrow bandwidth. Conventional techniques to improve MPA performances consist of varying the substrate height and substrate permittivity. Unfortunately, using one of these techniques improves one parameter but deteriorates other(s). Increasing the permittivity improves the bandwidth of the antenna but increases the loss (in case the materials is lossy) and consequently reduces the efficiency. MTM antennas open a way to overcome the conventional techniques as regards performance enhancement limitations in MPAs.

In the following a short review of the principle techniques that have been used to increase the performance of MPAs using MTM is presented. Creating textured substrates enables to increase the bandwidth of the antenna. Xing et al. [12] made use of a non-resonant “I” shape MTM to create a textured substrate and increase the bandwidth of a MPA. First, they optimized the substrate by observing the H field distribution of a patch antenna with homogeneous substrate in a full-wave simulator and by reducing the permittivity in the regions where the H-field had peaks. Then, once the optimization was completed they used the “I” shape MTM to produce the textured substrate. Using this technique, the fractional -10 dB bandwidth of the antenna was broadened from 10.5% to 20.6%.

## 2. Purpose and methodology

Use of flexible substrates has been used for different studies aiming to produce high added-value devices. The topics are significant because of the potential of conforming the substrate to appropriate shapes. Flexibility is well usable in advanced communication systems, i.e., wearable antennas, or in biomedical applications. For example, in [13] a cylindrical shape flexible cloaking structure, reported in Fig. 5, has been developed by a low-cost, easy implemented technique for advanced optical/electromagnetic applications; deposition of Al on flexible polymer substrate and its performance in terms of mechanical and material science points of views have been investigated.

Positioning of a 2D periodic structure around the circumference of the conformal structure has been realized, which provides an artificial impedance surface and guides to incoming plane waves around a solid object, through surface wave coupling. The unit cell is a width modulated microstrip line [14] on a polymeric and flexible substrate, namely Polydimethylsiloxane (PDMS), also known as dimethylpolysiloxane or dimethicone (of thickness h=1.25mm, and relative dielectric constant $\varepsilon_r$=2.3).

Fig. 5: CAD model of the PDMS substrate with the deposited periodic pattern: cylindrical surface

The shape of the microstrip line guarantees a sinusoidal variation of effective dielectric constant $\varepsilon_{eff}$ along the longitudinal direction *u*. The structure supports propagation of surface waves (in the *u*-direction) and the proposed modulation allows the computation of the Dispersion Diagram in a closed form in terms of Mathieu functions, hence the surface waves behaviour is known analytically. Regarding the structure, a thin (in term of wavelength), flexible PDMS substrate has been used, which supports, or in case incorporates, the periodic metallic pattern at a given distance from the surface of the initial object, also avoiding short circuits between the modulated line and metallic cylinder.

From a technological point of view, the metallic pattern can be deposited on the PDMS surface by different coating techniques after printing the desired pattern on, the top of, the conformal layer with photolithographic techniques. The structure has been separately made on thin foil that has been later rolled on the dielectric. The deposition has been performed employing standard methods and exploiting specific issues related to the polymer-metal adhesion. Development of a regular and constant thickness metal layer has been confirmed during the structural and microstructural investigation [15].

Currently, one of the main limitations in the development of new MTMs is the processing of technologies which restraint the size, shape and spacing of inclusions and additionally imposes economic barriers. Consequently, experimental verification of the properties of a huge volume of innovative MTMs are still under development.

In this research, the aim is twofold: (i) firstly, to evaluate the feasibility to increase the performances of the antenna, and (ii) secondly, to reduce the size of the MPA. These goals are obtained by using a new MTM substrate of which permittivity is locally controlled by the density of the inclusions in the substrate. Even more, electromagnetic band-gap regions outside of the path can be generated that in turn avoids surface wave propagation that would contribute to power loss and the performance degradation of the device.

The proposed MTM is made of metallic spherical inclusions of AISI52100 (high-carbon chromium alloy steel: wt% 0.98-1.10% C, 0.25-0.45% Mn, 0.025%(max) P, 0.025%(max) S, 0.15-0.30% Si, 1.30-1.60% Cr, Fe bal.) which is inserted in a polymer, namely in PDMS. Such materials are used because they can be easily synthesized in the laboratory (and later industrially) and their fabrication cost are limited. AISI52100 is used in a wide range of mechanical applications, because it is quite easy to machine and in case one needs characteristics in extreme conditions, it can be annealed to acquire good wear resistance or enhanced tensile and fatigue strength that is however not the case here.

## 3. Results and discussion

In the performed analysis, an effortlessly synthesizable MTM made of spherical inclusions in a host material has been characterized in order to realize a modified substrate that increased the performance of a MPA working at 2.5 GHz, word widely free spectrum. The substrate is made of a textured dielectric region, an EBG region and a homogenous substrate region as illustrated in Fig. 6. Simulations have been carried out by a commercial software [16].

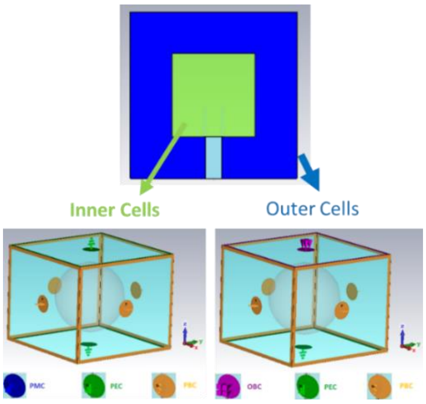


Fig. 6: Top view of the modified substrate. The green region covers the patch and corresponds to the textured dielectric region. The light blue colour covers the feed line and corresponds to the homogeneous substrate region. The dark blue region corresponds to the EBG region

The textured dielectric region is located below the patch to increase the bandwidth and reduce the size of the antenna while the EBG region is located in the outer region of the patch to suppress surface waves and hence increment the gain, directivity and efficiency of the antenna. As well, the homogeneous region is located below the feeding line to fix its characteristic impedance and have a better matching with the antenna. Both the EBG region and the textured dielectric regions are made of the intended MTM. Instead, the homogenous region is made of the host material of the aforementioned MTM.

The unit cell of the MTM used in this research consists of a parallelepiped filled with PDMS with spherical inclusion made of metallic steel material, ANSI52100, with a conductivity of $\sigma = 4.65116279 \times 106$ S/m (Fig. 7). The height of the parallelepiped H was fixed to 2.5 mm, while the width, depth and radius of the sphere ”R” can vary in order to control the permittivity value in the textured dielectric. Moreover, to simplify the parametric study both the width and depth have the same length ”D”.

In this research, two methods were used to characterize the MTM. In order to find the permittivity of a MTM is sufficient to use its unit cell, reported in Fig. 7, while Fig. 8 shows the setup used to retrieve the S-parameters in order to be able to apply the Nicolson Ross Weir Method.

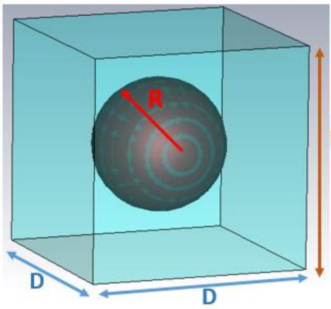


Fig. 7: Unit Cell of the MTM

In the proposed substrate showed in Fig. 7, the unit cells of the considered MTMs are submitted to two types of boundary conditions. The inner cells, i.e., the unit cell under the patch, have PBC in the side and PEC on the top and the button of the substrate, while the outer cell (located in the blue region) presents open boundary condition on the top and the rest of the boundary conditions are as for the inner cells. Nicolson Ross Weir Method is very simple one. Once the S-parameters at the decided frequency are known, i.e., the frequency of operation, by applying the equation reported in [15] it is possible to find $\epsilon_r$ and $\mu_r$. Unfortunately, the both parameter found with this method are not always accurate enough for resonant structures, if the thickness of the MTM layer is larger than $\lambda/4$.

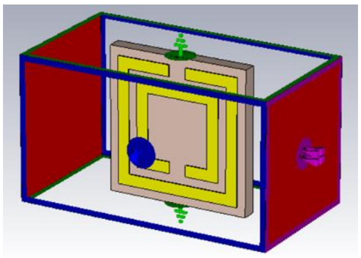


Fig. 8: CAD model for the Nicolson Ross Weir Method setup used to find the determination of the S-parameters

In the present investigation, two studies give details on the influence of the MTM-based substrate on the performance enhancement of the antenna. As a first analysis, the homogeneous substrate below the patch was replaced by a MTM based substrate: all the unit cells have D = 3 mm and the same value of R. As a next step, a parametric study was performed to determine the size reduction of the patch with the variation of the inclusions radius R of the unit cells below the patch from 0.5 mm to 1.1 mm. For all the considered cases, the radiation efficiency of the MTM-based substrate was improved demonstrating the existence of the Electromagnetic Band-gap that prevents the propagation of the surface waves, hence loss of active energy.

An overall view of the substrate with the MPA and its feeding line is reported in Fig. 9. The comparison between the performances of the reference antenna (with no MTM substrate) and proposed solution for different radius of the metallic inclusions of the central part are reported in Tabs. 1 and 2.

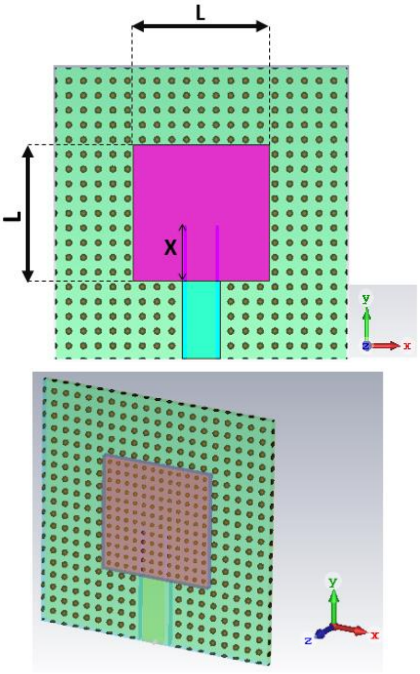
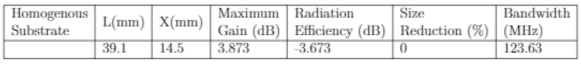


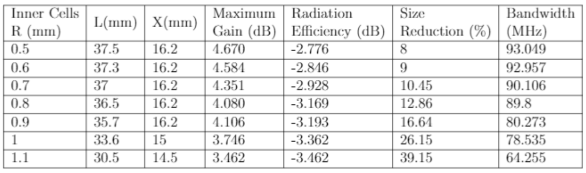
Fig. 9: Overall view of the MPA (top) and MTM substrate (bottom)

Table 1: Characteristics of the original antenna



| Homogenous Substrate | L(mm) | X(mm) | Maximum Gain (dB) | Radiation Efficiency (dB) | Size Reduction (%) | Bandwidth (MHz) |
|---|---|---|---|---|---|---|
|  | 39.1 | 14.5 | 3.873 | -3.673 | 0 | 123.63 |

Table 2: Variation of the size, maximum gain, efficiency and bandwidth of the antenna with respect to the radius R of the spherical inclusion of the inner cells



| Inner Cells R (mm) | L(mm) | X(mm) | Maximum Gain (dB) | Radiation Efficiency (dB) | Size Reduction (%) | Bandwidth (MHz) |
|---|---|---|---|---|---|---|
| 0.5 | 37.5 | 16.2 | 4.670 | -2.776 | 8 | 93.049 |
| 0.6 | 37.3 | 16.2 | 4.584 | -2.846 | 9 | 92.957 |
| 0.7 | 37 | 16.2 | 4.351 | -2.928 | 10.45 | 90.106 |
| 0.8 | 36.5 | 16.2 | 4.080 | -3.169 | 12.86 | 89.8 |
| 0.9 | 35.7 | 16.2 | 4.106 | -3.193 | 16.64 | 80.273 |
| 1 | 33.6 | 15 | 3.746 | -3.362 | 26.15 | 78.535 |
| 1.1 | 30.5 | 14.5 | 3.462 | -3.462 | 39.15 | 64.255 |

## 5. Conclusions

Use of flexible substrates in antenna engineering has been discussed. Improvement of the performance of some MPA in terms of reduced antenna size, increase of the gain, and improvement of the radiation efficiency by substituting the homogeneous substrate with a MTM based substrate was achieved. However, a reduction of the bandwidth has been obtained. Further works to eliminate this unwanted effect are undergoing.

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