Novel Metamaterials for Patch Antennas Applications

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Abstract. In this paper we introduce the incorporation of magneto-electric materials into antenna design and the potential of controlling the behavior of the antenna by means of an external magnetic field. After an intensive study of magneto-electric material properties, a ferrimagnetic compound called Yttrium Iron Garnet (YIG) was found to be the best candidate for the novel antenna design. We provide a metamaterial patch antenna design where a part of the substrate is replaced by the YIG compound. After several design modifications the final model includes a circular-shaped YIG substrate just under the metallic patch and offers sufficient performance in terms of resonance, bandwidth and radiation efficiency. Additionally, in the presence of an external magnetic field the polarization becomes elliptical and the sense of the polarization (left or right) can be controlled through the direction of the magnetic field. That latter characteristic confirms the metamaterial-nature of the antenna.

Keywords: patch antenna, ferrimagnetic compound.

1 Introduction

Patch antennas technology is used for many years now. These antennas are low-profile robust planar structures and can achieve a wide range of radiation patterns. Moreover, they can be easily manufactured and thus they are considered as inexpensive solutions compared with other types of antennas. On the other hand, there are some limitations in patch antenna designs such as low gain, narrow bandwidth of operation and decreased radiation efficiency due to surface-wave losses. Recently, the use of artificially engineered structured materials, known as "metamaterials", has been investigated in order to overcome the above mentioned shortcomings.

Metamaterials refer to a large variety of complex structures that possess exceptional electromagnetic properties not readily available in nature. At microwave frequencies, metamaterials typically consist of periodic arrays of dielectric and/or conducting elements. The term metamaterials is quite general and is used for a wide range of modern concepts such as frequency selective surfaces (FSS), electromag-

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netic band-gap (EBG) materials, left-handed media (LHM), artificial magnetic conductors (AMC).

On the other hand, numerous recent studies in the area of materials science have been devoted in the development of preparation methods, in handling and understanding the physics and chemistry of nanomaterials, nanostructures and metamaterials with modulated physical and chemical properties.

The main goal of this work is to investigate the development of novel metamaterials produced by means of natural mechanisms and their application in patch antennas. After in depth studies, it was found that using a specific material as part of an antenna substrate, one can control the antenna characteristics by properly applying an external magnetic field. More specifically, we aim to design and implement a patch antenna with varying polarization - linear, left circular (LCP) and right circular (RCP) - according to an externally applied magnetic field.

In this paper, the design of a conventional patch antenna is firstly described. This antenna is used as a reference for our studies. Then, a brief description is given of the techniques and the materials that are available to implement the selected designs. Next, the design of the metamaterial-inspired patch antenna and the simulation results are presented. Finally, the paper is completed with the main conclusions of the presented work.

2 Conventional Antenna Design

The potential target of our research is an antenna suitable for satellite communication applications, thus we have selected as operating frequency band the Ku-band. More specifically the conventional patch antenna that will be used to evaluate the proposed metamaterial-inspired patch antenna was decided to operate at 14 GHz. The evaluation process will be based on the comparison of the characteristics and the performance metrics between the conventional (reference) and the metamaterial antenna. The conventional antenna should have a simple design for easy simulation and implementation. For this reason, a simple rectangular patch antenna has been adopted to be the reference conventional patch antenna design. This antenna has been modeled using an EM simulation software package [1]. The detailed design specifications and performance characteristics of the conventional patch antenna are given bellow:

A rectangular patch is used with sides 6.05 mm long, fed by a microstrip line which penetrates inside the patch via a notch in order to achieve the proper matching (Fig. 1 (a)). The ground plane dimensions are 16 x 14 mm and the substrate is Taconic TLY3, 1.524 mm thick dielectric plate with ε_r equal to 2.33. According to the simulation results, a deep resonance (<-25 dB) occurred in the frequency of operation (14 GHz) as can be seen in Fig. 1 (b). The bandwidth (measured at S_{11}<-10 dB) was calculated to be 785 MHz (5.6 %), while the radiation efficiency was around 95 %. The antenna gain on boresight was calculated to be 6.6 dBi. In Fig. 1 (c), the 3D absolute radiation pattern of the antenna is presented to be the anticipated half-plane pattern.

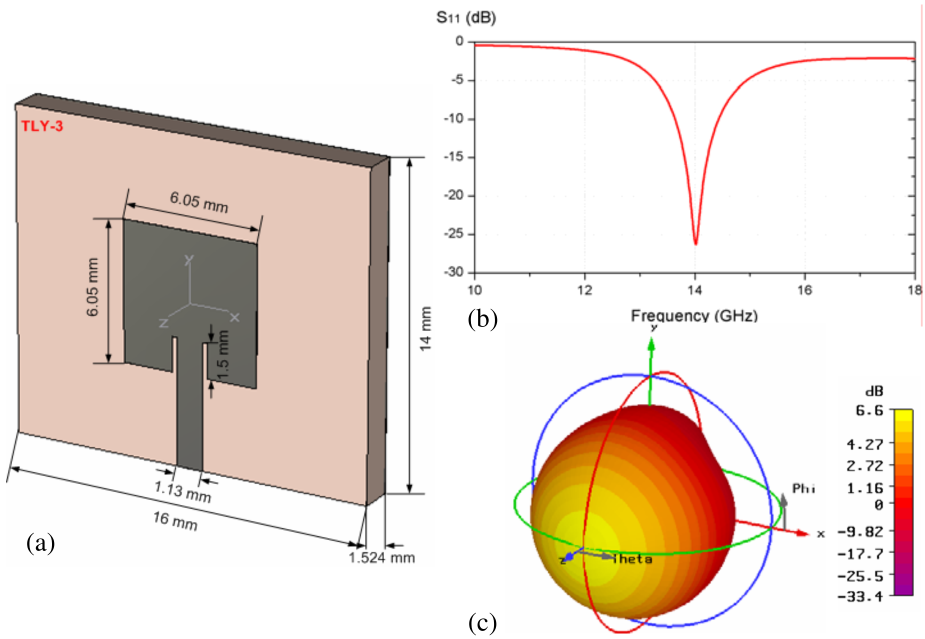


Fig. 1. The conventional patch antenna model (a), its reflection coefficient (b) and radiation diagram (c)

3 Materials with Modulated Properties

Before presenting the specific materials that we propose for implementation in the novel patch antennas and their highly unconventional dielectric, magnetic and crystal properties let us make a brief introduction on the basic underlying physics that could be very helpful to the non-experts.

Ferroelectricity is a term that is used analogously to ferromagnetism, in which a material exhibits a permanent magnetic moment. Thus a ferroelectric material exhibits a spontaneous electric polarization. The electric polarization can be modulated under the application of an external electric field. Thus ferroelectric materials can be used to make capacitors with tunable capacitance an opportunity that could be easily implemented in the design of planar patch antennas possibly enabling the control of the antenna characteristics under the application of an external electric field.

Ferroelectric materials exhibit nonlinear dielectric response and thereto demonstrate a spontaneous polarization in analogy to the spontaneous magnetization of the ferromagnetic materials. Similarly to their ferromagnetic counterparts, ferroelectric materials demonstrate their unconventional dielectric properties only below a certain phase transition temperature the so-called critical temperature.

Going a step farther, *multiferroics* are materials that have coupled dielectric, magnetic and crystal properties. The unusual coupling of these two order parameters enables the modulation of all dielectric and magnetic properties upon variation of a single external parameter that should naturally influence exclusively one of them.

Thus in such materials the dielectric properties may be varied upon application of an external magnetic field or similarly the magnetic properties can be varied upon application of an external electric field.

Such multiferroic materials can be employed as substrate and/or superstrates in patch antennas, possibly offering several novel characteristics that cannot be obtained by conventional design practice. It has been demonstrated both theoretically and experimentally that by using a ferromagnetic substrate we can achieve (a) tunable resonance frequency under the application of a dc magnetic field [2], (b) recurrent and tunable circularly polarized radiation [3]. Accordingly, aiming at controlling the antenna performance under the application of an external parameter such as magnetic or electric field we have focused our effort on these novel materials coming from the class of multiferroics.

The research objective is to investigate theoretically and experimentally the performance advantages of magnetic materials-based antennas over antennas fabricated using conventional substrates. To accomplish that, three different magnetoelectric compounds ($Al_{2-x}Fe_xO_3$, $Ga_{2-x}Fe_xO_3$ and $Y_3Fe_5O_{12}$) have been initially examined as components of the substrate of the novel patch antenna.

4 Metamaterial-Inspired Antenna

The use of ferromagnetic materials as elements of a patch antenna (more appropriate as a substrate) or as constituent elements in fabricating metamaterials, has not been sufficiently studied so far. Electromagnetic metamaterials consist of artificial arrangements of simple unit-cells/building-blocks that when arrayed produce effective media with tailored electromagnetic parameters, that is permittivity and permeability. For instance, such a metamaterial is realized by using periodic arrays of metallic split-ring resonators and wires with size and separation of the order of the radiation wavelength. Besides the success of these types of the metamaterials in improving, in some respect, the microwave devices' operation, significant Ohmic losses are encountered in their metallic parts preventing their use in high frequency applications.

An alternative approach in producing metamaterials that are not based on metallic elements could rely on using non-periodic or periodic arrangements of materials with high dielectric constant, multifunctional materials (magnetoelectric or multiferroic materials) and purely magnetic materials. In this context, we have decided to prepare, characterize, and implement (in patch antennas) these novel materials in simple and self assembled metamaterials form.

The modeling of the dielectric materials is well known and does not display any difficulties. In contrast, magnetic materials exhibit complicated behavior that can be accounted for under the consideration of numerous parameters. Accordingly, the implementation of magnetic properties in the modeling of patch antennas is a quite complicated task. The most important parameter that determines the behavior of magnetic materials in the microwave frequency range is the magnetic permeability tensor. Let us consider a ferromagnetic material under an applied static magnetic induction $B_{dc}=\mu_o H_{dc}$ parallel to the z-axis and an ac-magnetic induction $B_{ac}=\mu_o H_{ac}$. These dc and ac magnetic fields produce a dc- and ac-magnetic moment $M=M_{dc}+M_{ac}$. The equation of motion of the total magnetization is given by the Landau-Lifshitz equation [4]:

$$\frac{d(\mathbf{M}_{dc}+\mathbf{M}_{ac})}{dt}=-\gamma\left[(\mathbf{M}_{dc}+\mathbf{M}_{ac})\times(\mathbf{B}_{dc}+\mathbf{B}_{ac})+\frac{\alpha}{M_{dc}}\mathbf{M}_{dc}\times\frac{d(\mathbf{M}_{dc}+\mathbf{M}_{ac})}{dt}\right] \quad (1)$$

where $\gamma=ge/2m_e$ is the gyromagnetic ratio calculated from the Landé factor g in connection with the charge (e) and mass value (m_e) of an electron. The damping factor α is a dimensionless constant determined by the resonance line width ΔH through the relation $\alpha=\mu_0\gamma\Delta H/2\omega$. By solving this differential equation we can calculate the permeability tensor for the limiting case $H_{ac} << H_{dc}$. A simple expression for the permeability tensor used in practice is given from the expression:

$$\mu_{ij}=\mu_0\begin{pmatrix}\mu_1(\omega) & \mu_2(\omega) & 0\\ -\mu_2(\omega) & \mu_1(\omega) & 0\\ 0 & 0 & 1\end{pmatrix} \quad (2)$$

with:

$$\mu_1=1+[\omega_m(\omega_0+i\omega\alpha)]/\left[(\omega_0+i\omega\alpha)^2-\omega^2\right]$$
$$\mu_2=i\omega\omega_m/\left[(\omega_0+i\omega\alpha)^2-\omega^2\right]$$

where $\omega_m=\gamma\mu_0 M_{dc}$ (here it is supposed that the external magnetic field saturates the magnetic material that is $M_{dc}=M_S$), and $\omega_0=\gamma\mu_0 H_{dc}$. The g, M_S and the permeability tensor are materials' parameters, while the external field, H_{dc}, is an external parameter. This plethora of parameters permits adequate flexibility in designing a patch antenna.

We have conducted a systematic and detailed study of some of the parameters of a simple patch antenna where the substrate consists of ferromagnetic/ferrimagnetic material, by varying the amplitude and direction of the external magnetic field (H_{dc}), the amplitude of the saturation moment (M_S), depending on the chemical composition of the material, and the width of the resonance (ΔH).

4.1 Initial Design

A basic characterization by means of magnetization (Superconducting Quantum Interference Device –SQUID–) and ferromagnetic resonance (FMR) measurements of the three candidate magnetoelectric compounds ($Al_{2-x}Fe_xO_3$, $Ga_{2-x}Fe_xO_3$ and $Y_3Fe_5O_{12}$) have been made. The critical temperature of the first two compounds is placed below T=300 K, making them poor candidates for room temperature applications. In contrast the $Y_3Fe_5O_{12}$ compound exhibits a critical temperature of T=550 K thus being appropriate for utilization in patch antennas operating at room temperature conditions. Further in this work the ferrimagnetic $Y_3Fe_5O_{12}$ compound, called Yttrium Iron Garnet (YIG), was used as a substrate in the proposed antenna design.

The initial design of the proposed antenna consists of the ferrimagnetic material that lies just under the radiating copper patch, and of a dielectric substrate around it as schematically presented in Fig. 2. More precisely, a rectangular block made of YIG having the same length and width with the metallic patch was placed at the centre of the antenna model and exactly under the radiating patch, replacing the dielectric (TLY3) substrate. The dielectric and magnetic properties of the YIG compound were determined the first from the literature and the latter by the magnetization and FMR measurements and they have properly set in the simulation software. These parameters are listed in Table 1. An external magnetic field having the maximum value of 5000 Oe was applied to the antenna having a direction towards +z, perpendicular to the substrate surface. According to the simulation results, the resonance frequency of the proposed antenna is 13 GHz while the bandwidth (measured at S11<-10 dB) is 306 MHz (2.35 %). The presence of the magnetic field has changed the antenna polarization from linear to elliptical with sense according to the direction of the applied field (towards +z is left while towards –z is right). The problem is that there is a large amount of losses resulting at low radiation efficiency and gain values comparing to the conventional antenna.

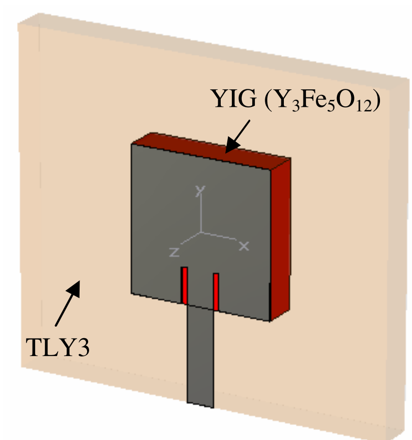


Fig. 2. Initial metamaterial-inspired antenna design

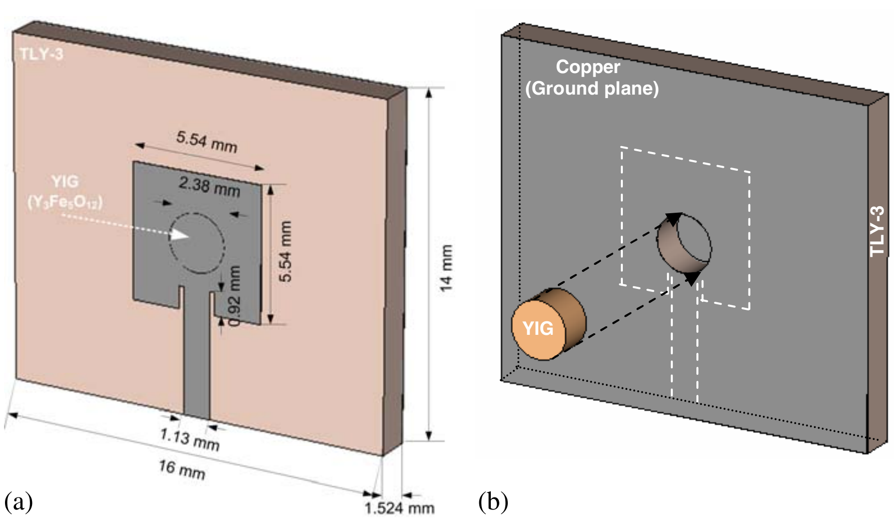
Table 1. Properties of the YIG compound

Dielectric properties		
Relative permittivity	ε_r'	10
Dielectric loss tangent	tanδ	0.0009
Magnetic properties		
Landé factor	*g*	2
Saturation magnetization	4πMs	1700 Gauss
Resonance line width	ΔH	50 Oe

4.2 Final Model

A systematic study of the appropriate position, size and shape of the YIG part has been achieved using suitable simulation models. The aim of the study is the design of an antenna that would have polarization agility, which means it could change its polarization properties according to the value and the direction of an externally applied magnetic field. Additionally, the performance (e.g. radiation efficiency, gain) of the YIG-based patch antenna should be comparable to that of a conventional one. Firstly, rectangular YIG blocks with smaller size were tested in order to achieve higher efficiency and gain. Then, several different positions of the YIG block inside the substrate were investigated in order to find the one offering the highest overall performance. Also, cylindrical YIG blocks were simulated and compared to the rectangular ones. The similar performance of the metamaterial inspired antenna for the two substrate types in combination with the easier manufacturing of cylindrical YIG blocks, lead us towards the adoption of the cylindrical design to be the final patch antenna model.

The final design adopts a cylindrical YIG block, which has been placed at the centre of the dielectric substrate, underneath the rectangular patch [5]. The overall dimensions of the metallic patch have been slightly reduced to 5.54 x 5.54 (mm), resulting in a 8.5% reduction of patch area dimensions compared to the conventional patch antenna, in order to have resonance at 14 GHz. The dimensions set for the final design of the proposed patch antenna are illustrated in Fig. 3 (a). In Fig. 3 (b) the back side of the antenna model is presented, where it can be clearly seen how the YIG disc is being placed at the centre of the antenna exactly under the radiating patch.



(a) (b)

Fig. 3. Schematic representation of the proposed antenna model: (a) radiating element side view, (b) ground plane side view

5 Results

The reflection coefficient of the proposed antenna in direct comparison with that of the conventional patch is presented in Fig. 4. The bandwidth of the proposed antenna is 772 MHz (5.5 %) that is quite similar to that of the conventional one.

As mentioned above, the main characteristic of the proposed antenna is that the presence of an external magnetic field changes the polarization properties of the antenna. In this model, an external field of 5000 Oe has been applied towards the +z direction of the antenna coordination system, perpendicular to the substrate surface.

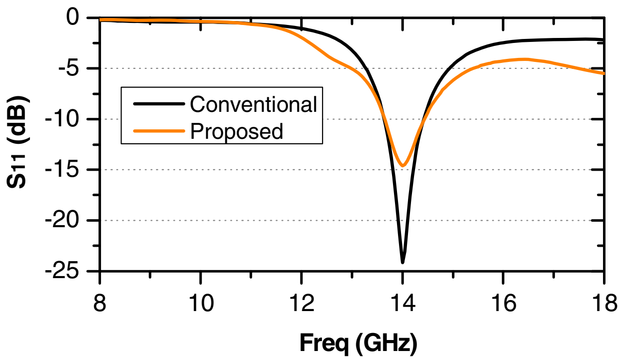


Fig. 4. The S_{11} parameter of the conventional and proposed antenna

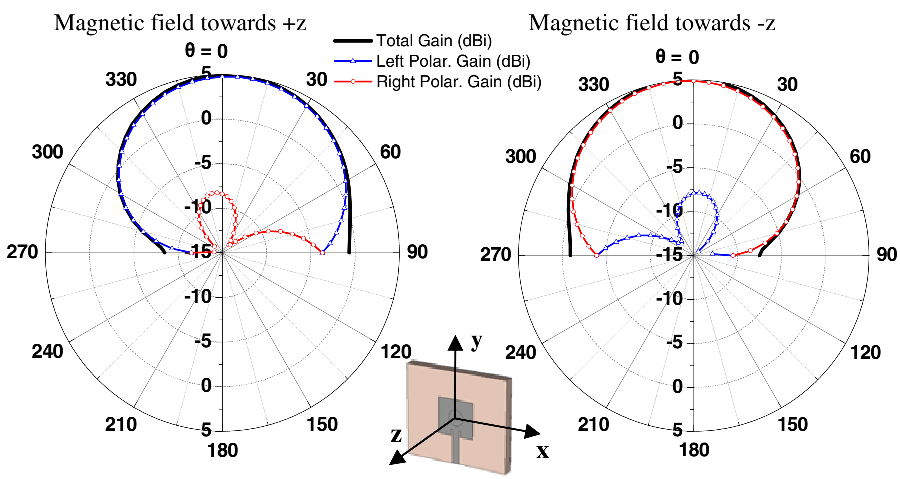


Fig. 5. Gain patterns in the xz plane indicating the change of the polarization sense

By applying this external dc magnetic field the polarization changes from linear (vertical) to left-handed elliptical. Alternatively, the same external field applied towards –z direction changes the polarization to right-handed elliptical one. As can be seen in Fig. 5, when the magnetic field is applied towards +z, the left polarized gain is very close to the total gain at the xz plane (nearly 0.4 dB difference at the boresight direction), while the right polarized gain is significantly smaller (almost -8 dBi). Similar conclusions can be extracted when the magnetic field is applied towards –z direction where now the right polarized gain is the dominant one and it is very close to the total gain.

Concerning radiation efficiency and polarization properties, Table 2 provides a concentrated view of the simulated results of the conventional patch and the proposed antenna. It is noted that the radiation efficiency of the YIG-based antenna is lower than that of the conventional, due to the relatively high permittivity of the YIG part that causes additional losses, but still with sufficient value (higher than 70 %).

Table 2. Comparison of the main antenna characteristics

	Conventional	Metamaterial inspired
Bandwidth (MHz)	785	772
Gain (dBi)	6.6	5.2
Erad (%)	95.3	71.4
Polarization	Vertical	Elliptical
Axial Ratio (dB)	200	4.1

Concerning polarization it has to be mentioned that it is almost circular since the axial ratio is 4.1 dB. All the above-mentioned characteristics of the YIG-based patch antenna are taken considering an external dc magnetic field of 5000 Oe applied perpendicular to its surface.

6 Conclusions

In this paper we introduced the utilization of a ferrimagnetic compound, namely Yttrium Iron Garnet (YIG) as a substrate in patch antennas in an effort to change and control the polarization under the application of an external dc magnetic field. We clearly demonstrated that the sense of the antenna polarization is strongly influenced by the YIG substrate since it changes at will in respect to the direction of the external magnetic field.

Further steps of the work include construction of the antenna and measurements of its antenna characteristics. At a first phase we will use a permanent magnet in order to prove the polarization agility of the proposed antenna and on a second step to investigate ways of altering the polarization of the induced external magnetic field (e.g. with the use of an electromagnet setup).

One of our main concerns is the potential application of the proposed antenna. A possible use of the proposed metamaterial inspired antenna could be as an array element. It could offer polarization diversity changing its polarization from left to right hand elliptical and vice versa according to communication needs.

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