Patch antennas with new artificial magnetic layers

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Abstract—A new type of high-impedance surfaces (HIS) has been introduced by C.R. Simovski et al. recently. In this paper, we propose to use such layers as artificial magnetic materials in the design of patch antennas. The new HIS is simulated and patch antennas partially filled by these composite layers are measured in order to test how much the antenna dimensions can be reduced. In order to experimentally investigate the frequency behavior of the material, different sizes of the patches are designed and tested with the same material layer. Also the height of the patch is changed in order to find the best possible position for minimizing the antenna size. This composite layer of an artificial magnetic material has made the antenna smaller while keeping the bandwidth characteristics of the antenna about the same. About 40\% of size reduction has been achieved.

Index Terms—artificial magnetic material, patch antenna, antenna miniaturization, high-impedance surface.

I. INTRODUCTION

HIGH impedance surfaces for microwave frequency antennas and other devices have been recently introduced and actively investigated. These surfaces are mostly thought to be applied for reducing surface waves, for controlling the plane-wave reflection phase, and as artificial magnetic conductors \cite{1}, \cite{2}.

High-impedance surfaces are thin composite layers (as a rule backed by a metal plane), whose surface impedance has a parallel resonance at a certain frequency or at several frequencies. Within the resonant band the surface of the layer behaves as a magnetic wall for normally incident plane waves. That is why the HIS are often called artificial magnetic conductors (AMC). In practical cases, the thickness of an AMC layer at resonance is much smaller than a quarter of the wavelength. It means that the reflection coefficient of a plane wave from the structure can be close to +1 at a very small distance from the ground plane. This means that the electromagnetic interaction of a horizontal electric current with an AMC can be constructive even for very small distances from the current to the ground plane. This is why AMC are prospective for designing low profile antennas \cite{1}, \cite{3}, \cite{4}, \cite{5}.

Infinite (practically very high) surface impedance means that the tangential magnetic field component is very weak at the surface of the wall. Tangential electric field can be strong at this surface. The reflection properties of a HIS depend on the frequency, and the HIS resonant band can be defined as a frequency range at which the phase change of the reflected electric field is within certain limits (usually from $-\pi/2$ to $+\pi/2$). A HIS conventionally possesses a rather narrow band of AMC operation.

In general, these structures support surface waves, however there is an important difference with the case of a simple metal-backed dielectric layer: there are stop bands for surface waves. Therefore, the same structures interacting with plane waves as HIS operate as EBG (electromagnetic band gap) structures with respect to the surface waves. Sometimes they are called as 2D PBG (photonic band gap) structures which is not a proper term at microwaves. Besides the high-frequency band gaps whose band structure is related with the spatial periodicity of the AMC layer, there can be one or two low-frequency ones, related with the resonance of the surface impedance which can also hold in the regime of the surface wave.

While the AMC are useful to design low-profile antennas \cite{1}, \cite{3}, \cite{4}, \cite{5}, artificial material fillings are useful in the design of small antennas, especially magnetic materials can be utilized as a mean to reduce the antenna size \cite{6}, \cite{7}, \cite{8}.

According to a simple theoretical model of a small patch antenna as a resonator, the resonant frequency and impedance bandwidth $BW$ of a small antenna depend on the relative permittivity and permeability of the loading material as

$$F_r \sim \frac{1}{\sqrt{\varepsilon_r \mu_r}}, \quad BW \sim \frac{\sqrt{\mu_r}}{\sqrt{\varepsilon_r}} \sup (1)$$

Here $\sim$ means the proportionality. In practice, these expressions are not very accurate, and the result of loading depends on the antenna type, but still the tendency predicted by $\sup$ holds.

There has been some work on the effects of magneto-dielectric substrates on the bandwidth of microstrip antennas \cite{6}, \cite{7}, \cite{8}, but these results are contradictory. Papers \cite{6} and \cite{8} conclude that the best filling is a magnetic material with large $\mu$, although the authors of \cite{7} conclude that the best filling is a material with both $\epsilon \gg \varepsilon_0$ and $\mu \gg \mu_0$. Nevertheless, the usefulness of magnetic filling is evident from the known literature.

In paper \cite{9} a material with a finite isotropic permeability was considered as a loading material. Natural magnetic materials at frequencies higher than $100\textendash 500$ MHz are ferrimagnetic crystals (for example, hexaferrites). These ferrites are not very attractive for applications in small antennas since they are lossy, heavy, and expensive. Probably because of this, antennas with ferrite or ferromagnetic filling have been analyzed mainly from the point of view of electrical control of their resonant frequency and radiation pattern, see, e.g., \cite{10}.
realizations of artificial magnetics at 0.5 – 3 GHz can be based on the resonant principle: Artificial magnetic materials can be formed by small particles with a resonant magnetic susceptibility. These should resonate at a frequency which is close to the resonant frequency of an unloaded antenna. Such artificial magnetic materials are practically known in the frequency range 4 – 15 GHz (the structures formed by the so-called split-ring resonators). Such loadings have been successfully tested with patch antennas in [11]: A 0.075λ size patch antenna with the bandwidth of 1.5% has been reported in that paper.

In certain frequency regions, high-impedance surfaces behave as layers of effective magnetic materials, and can be used as magnetic fillings in the antenna design. AMC are not similar to natural isotropic magnetics. These cannot be properly described in terms of magnetic permeability. Formally, one can introduce an effective permeability, but it will strongly depend on the incident plane wave polarization and the angle of incidence. This dependence is a spatial dispersion effect. However, this effect does not forbid one to use such composite layers as a magnetic filling material. Recently, these artificial layers have been used to reduce the size of antennas [12] and filters [13].

The main idea of the present paper is to use an artificial material which would possess the properties of both AMC and magneto-dielectric composite [14] within a rather wide resonance band. In this paper, the new HIS [14] playing also the role of an artificial magnetic material (AMM) is tested under a patch antenna. The choice of this material can be explained in terms of the angular stability of the resonant frequency. The known AMC introduced in papers [1], [2], [15] have the resonance depending on the angle of incidence θ and wave polarization (TE or TM). Therefore the interaction of such AMC with currents on a real antenna cannot be completely constructive. For example, let the working frequency of the patch antenna correspond to the resonance of the conventional AMC illuminated by a normally incident plane wave. Then the narrow part of the angular spectrum of radiation centered at θ = 0 will interact with the AMC as if it were a magnetic wall. For the other part of the angular spectrum the conventional AMC is not a magnetic wall, since its resonant frequency will be different [16], [17], [18]. In the AMC used here this shortcoming is absent as it was shown in [14]. Notice, that in paper [19] another full-angle AMC has been suggested and studied. This is a self-resonant grid on a simple metal-backed dielectric layer. However, our choice of the artificial magnetic material suggested in [14] has additional advantages. First, in this AMM there are vertical conductors (vias). We expect that the TM-polarized surface waves are suppressed in this structure at low frequencies due to the presence of vias in the same way as in mushroom structures [1], [2]. Second, the resonance of the structure [14] takes place at lower frequencies (compared to the structure period) than the resonance of the AMC described in [19]. Both these advantages are important for patch antennas. The second one is important for the antenna miniaturization. The first one is crucial when one uses an array of patches and the problem of mutual interaction appears.

The behavior of the AMM is investigated at different distances from the patch antenna with different configurations. Also a simple comparison method is introduced in order to find the effective (averaged) permeability value of the layer. Results from IE3D/FDTD simulations are shown and compared with the measurement results.

II. THE NEW HIGH IMPEDANCE SURFACE AS AN ARTIFICIAL MAGNETIC MATERIAL

The structure introduced in [14] is shown in Fig. 1. This AMM can be considered as a 2D grid of bulk unit cells with the horizontal period D. Every cell contains two orthogonal loops of length d, so that the upper interface represents an array of metal crosses on the surface of a dielectric layer. Every cross (whose ends are connected to metal vias) together with vias and patches form two orthogonal loops (the loop length d is the same as the length of a cross side). So, the effective vertical loop is formed by two vias perforating the dielectric layer and a horizontal strip lying on the dielectric interface. The loading capacitors are formed by metal patches and the ground plane. The patch array is separated from the ground plane by a thin dielectric layer. The standard printed-board circuit (PBC) can be used to prepare both patch array (which is located on one side of a PBC) and the array of crosses (located on the other one) if the thin layer has no metallization (teflon film). The analysis of the structure impinged by a plane wave becomes easier with the help of the image theory. Every real loop complemented by its mirror image is a symmetrically loaded rectangular loop with sizes...
\[ S = d \times P, \] where \( P = 2(h + \Delta) \) (see Fig. 4). The electric field is zero at the loop center (at the ground plane \( z = 0 \)). Therefore, the electric polarization of the loop is negligible and it can be considered as a horizontal magnetic dipole excited by an external magnetic field. Following the image method, consider an array of loaded rectangular loops illuminated by two plane waves from both sides of the array. Let the plane wave be polarized so that \( E = E_0 \) and the magnetic field is directed along the \( y \)-axis. Then the loops in the \( yz \) plane are not excited (see Fig. 1). The whole structure behaves as an array of parallel loops lying in the planes \( xz \) within the dielectric layer excited by two plane waves coming from \( z = \infty \) and \( z = -\infty \). Since there is no electric dipole polarization of loops, the electric polarization of the whole structure is practically that of the dielectric layer. The reflected field is then the sum of the field produced by the single dielectric layer of thickness \( P \) (excited by two waves impinging the layer from the top and the bottom) and the field produced by the magnetic moments of loops. The magnetization of loops is resonant due to the presence of capacitive loads, and the magnetic response at the resonance is comparatively strong due to high inductance of the loops. Loops are made from thin electric conductors and their inductance is much higher than the effective inductance of the conventional AMC (which is practically determined by the thickness of the dielectric layer). This factor is responsible for rather low frequency of the resonance and for a wider bandwidth (in parallel \( LC \)-circuits the higher is the inductance the larger is the resonant band).

An analytical model of this structure and a comparison with the results of numerical simulations (obtained with the HFSS package) are presented in a recent paper by C. Simovski and A. Sochava [20].

The geometry of the structure that we use in this paper is different from the structure proposed in [14], although the operational principle is the same. This new structure is shown in Fig. 3 where square horizontal loops replace the conducting crosses of the structure [14]. For simplicity, let us consider the normal incidence of a wave whose electric field is polarized along one side of the square horizontal loop. Then the two vertical \( C \)-loaded loops (formed by two sides of the horizontal loop, four vias connected to them and four capacitances between patches and the ground plane) will be excited in every unit cell of the structure. A horizontal loop as such is not excited by the external magnetic field since this magnetic field is tangential. The electric connection of the two vertical loops does not change the operation and the theory developed in [14] basically remains valid.

To realize the material a two sided TLY-5 film with the thickness of 0.127 mm and the dielectric constant \( \epsilon_r = 2.2 - j0.001 \) has been used. This film separates small patches from the ground plane. Horizontal parts of the loops and the patches are printed on the opposite sides of a printed circuit board layer with the dielectric constant \( \epsilon_r = 2.2 - j0.002 \). Horizontal parts of the loops and the patches are connected by via wires (round metal cylinders) as shown in Fig. 3. The whole manufactured structure contains \( 5 \times 5 \) unit cells and has the dimensions of \( 20 \times 20 \times 3 \) mm. This structure is a “brick” from which larger samples of an AMM can be built.

### III. Antenna and the Artificial Magnetic Material

To test the performance of the new artificial magnetic layers with patch antennas we design and study square-patch antennas with different sizes. For measurements, a large ground plane is used and for simulations the ground plane is infinite. This is done in order to exclude possible resonant effects of a finite ground plane. IE3D software as well as an in-house developed FDTD code are used to simulate antennas with and without the material filling. Also, for the sake of comparison, we simulate the same antennas with an infinite dielectric material layer inserted between the ground plane and the patch. The dielectric has the relative permittivity \( \epsilon_r = 2.2 \) and the slab thickness is 3 mm (the same as for the substrate used to manufacture the artificial magnetic layer). The antenna is fed from a side using a microstrip. The new AMM is introduced under the patch gradually in order to save simulation time. In Fig. 4 the configuration with three columns of the material under the patch antenna are shown. AMM blocks are located at the two sides of the antenna symmetrically.

Antennas with the patch dimensions of \( 30 \times 30, 40 \times 40, 50 \times 50, \) and \( 60 \times 60 \) mm have been considered. Since patches of different sizes resonate at different frequencies from 2.5 GHz to 4.5 GHz, we could test the effectiveness of the material.
Fig. 4. A patch antenna partially filled with an artificial material. Three columns of the new AMM at each side of the antenna patch are inserted. The first column is placed just under the side of the patch where the currents are strong. The distance between the patch and the ground plane is \( t = 4 \), \( 5 \), and \( 6 \) mm. Different square patches with the sizes \( 30 \times 30 \), \( 40 \times 40 \), \( 50 \times 50 \), and \( 60 \times 60 \) mm have been designed. The height from the ground plane \( t \) and the size of the patch are used as parameters to test the artificial magnetic material.

at different frequencies. The height of the antenna changes the field applied on the material which also changes the response of the material layer.

A. The effect of the patch height

The height of the patch antenna has been varied in order to find the best reduction for the resonance frequency. In these simulations, the \( 50 \times 50 \) mm antenna is chosen and only one column of the material is placed under each side of the patch. The return loss is compared for \( 4 \), \( 5 \), and \( 6 \) mm heights of the patch antenna (see Fig. 5). The results show that the effect of the material is enhanced when the patch is closer to the material layer. Here we of course see also the effect of the relative permittivity of the loading layer. If there would be no magnetic behavior of the material, antenna would be thought as loaded with a dielectric layer with \( \varepsilon_r = 2.2 \) and the thickness 3 mm. In that case the resonant frequency drops from 2.82 to 2.28 GHz for a patch antenna with the patch at 4 mm above the ground plane. But with the magnetic material the resonant frequency drops to 2.14 GHz. Here, with only one column of the artificial material we have a 24\% reduction in the resonant frequency or, in other words, we have a patch antenna with a size of \( 0.357 \lambda \).

B. The effect of the number of columns

When an antenna is totally filled with such complex material, it becomes very difficult to simulate it with IE3D, using the computer power we have. This is because the AMC is made of a lot of small metal strips, patches, and vias. Therefore we gradually fill the volume below the antenna. If we start to fill from the sides of the antenna where the currents and magnetic fields are strong. Here we investigate the effect when the antenna is partially filled. The number of columns is increased and the effect in return loss is shown in Fig. 6 for the \( 50 \times 50 \) mm patch. In this example the antenna patch is at 6 mm above the ground plane. The same exercise has been repeated with the patch at 4 mm above the ground plane. The results are listed in Table II.

C. The effect of the patch size

In order to see the effect of the new HIS at different frequencies, different-size antennas are simulated with and without the material. Resonant frequencies of antennas with an infinite dielectric material layer placed under the patch antenna with the 3 mm height and \( \varepsilon_r = 2.2 \) are also shown for comparison. There is a 1 mm distance between the material layer and the antenna ground plane. First, only one column is placed under \( 30 \times 30 \), \( 40 \times 40 \), \( 50 \times 50 \), and \( 60 \times 60 \) mm patch antennas with the height of 4 mm, then for \( 30 \times 30 \) mm, \( 40 \times 40 \), and \( 50 \times 50 \) mm patch antennas three columns are placed. In Fig. 7 return loss of patch antenna is shown with and without materials. Also in Table II we show the reduction in the resonant frequencies with a dielectric material and when the AMM is inserted. The results clearly show that the magnetic properties of this material sample are stronger at
TABLE I
Resonant frequencies of the 50 × 50 mm antenna with and without AMM for the patch heights 4 and 6 mm. The antenna resonant frequencies are also shown when there is an infinite dielectric material slab under the antenna patch with the 3 mm thickness and $\varepsilon_r = 2.2$.

| $t$ (mm) | Res. freq. (GHz) | Reduction % |
|----------|------------------|-------------|
| No material | 2.82 | 0.00 |
| No AMM $\varepsilon_r = 2.2$ | 2.28 | 19.15 |
| 1 column | 2.14 | 24.11 |
| 2 columns | 2.00 | 20.08 |
| 3 columns | 1.89 | 32.98 |

| $t$ (mm) | Res. freq. (GHz) | Reduction % |
|----------|------------------|-------------|
| No material | 2.75 | 0.00 |
| No AMM $\varepsilon_r = 2.2$ | 2.45 | 10.91 |
| 1 column | 2.32 | 15.64 |
| 2 columns | 2.16 | 21.45 |
| 3 columns | 2.06 | 25.09 |

TABLE II
Resonant frequencies of different-sized patches and reduction in the resonant frequencies compared to a patch antenna where there is only a dielectric material with $\varepsilon_r = 2.2$, one column of the artificial material, and three columns of the material at both sides of the patch.

| Patch size (mm) | Reduction % $\varepsilon_r = 2.2$ | Reduction % 3 columns |
|----------------|---------------------------------|-----------------------|
| 50             | 10                              | 19                    |
| 40             | 17                              | 32                    |
| 30             | 17                              | 40                    |

higher frequencies (near 4.5 GHz) than at 3 and 2 GHz. On the other hand, we see that the resonance is quite broadband, as the effect is rather strong even far from the resonance of the AMM.

D. Current distribution and the radiation pattern

The current distribution and the radiation pattern of the antenna are shown for the 30 × 30 mm patch antenna with the patch at 4 mm above the ground plane. The material has been placed in three columns. The antenna resonates at 2.7 GHz. It is clearly seen that the current distribution on the patch has an effect on the material and the current is rotating on the loop part of the material. The calculated radiation pattern is shown in Fig. 9. The gain of the antenna is 5.3 dBi. The shape of the pattern is similar to that of a usual patch antenna, so we can conclude that the AMM material is working as expected.

IV. Estimation of the equivalent effective permeability

As has been already noted, the artificial magnetic layers built as HIS surfaces cannot be properly described in terms of magnetic permeability, since that would strongly depend on the incident plane wave polarization and on the angle of incidence. However, it is possible to introduce an equivalent effective averaged permeability for this particular application, comparing the performance of the actual antenna with an artificial layer and calculated results for the same antenna filled by a uniform and isotropic magnetic material.

This has been done using IE3D simulations. First, we simulate antenna with different sizes of the patch filled by an infinite slab of an isotropic magneto-dielectric material (thickness 3 mm). The material parameters are changed from $\varepsilon_r = 2.2$, $\mu_r = 1$ to $\varepsilon_r = 2.2$, $\mu_r = 4$. Then the same antennas are filled by the AMM are simulated. Resonant frequencies of these results are recorded and graphs are drawn for the calculated frequency shifts. Comparing the resonant

Fig. 7. The effect of the AMM on the resonant frequencies of 30 × 30, 40 × 40, 50 × 50, and 60 × 60 mm patch antennas is shown. There is only one column of AMM used. Antenna patches are all at 4 mm above the ground plane.

Fig. 8. Vector current distribution of the 30 × 30 mm patch antenna with three columns of AMM. The scale is going from red (maximum) to dark blue (minimum, −40 dB).

Fig. 9. Radiation pattern of the 30 × 30 mm antenna with three columns of AMM at 2.7 GHz. The maximum gain is 5.28 dBi.
Fig. 10. Comparison of the response of antennas filled by the artificial magnetic material and by uniform isotropic magneto-dielectrics.

TABLE III

CALCULATED EFFECTIVE RELATIVE PERMEABILITY VALUES OF THE AMM FOR ONE AND THREE COLUMNS AS FUNCTIONS OF THE FREQUENCY.

| Patch size (mm) | Calc. $\mu_r$, one column | Calc. $\mu_r$, three columns |
|----------------|---------------------------|----------------------------|
| 60             | 1.136                     |                            |
| 50             | 1.233                     | 1.725                      |
| 40             | 1.295                     | 1.79                       |
| 30             | 1.575                     | 2.43                       |

frequencies, the equivalent permeabilities are identified. These equivalent permeability values are underestimating the actual permeability values of the AMM since AMM is not uniformly filling the volume and it is not isotropic. The field applied to the AMM is not uniform, therefore different parts of the AMM sample are excited differently. But this comparison gives a clear and easy way of understanding the effective permeability of the material and could be used as a helping design tool in the future.

In Fig. 11 one can see the return loss of the $50 \times 50$ mm patch at 4 mm above the ground plane with a 3 mm material layer with different $\mu_r$ values. In that figure, the results for the same antenna with three columns of AMM are also shown. For example, for three columns it is clearly seen that the equivalent averaged relative permeability value is between 1.5 and 2. With this method the effective material permeability value is estimated as $\mu_r = 1.7$ at the resonant frequency of the $50 \times 50$ mm patch and 2.43 for the resonant frequency of the $30 \times 30$ mm patch.

In Fig. 12 the averaged effective material permeability is shown as a function of the frequency. The frequency values are the values when the infinite material layer has $\varepsilon_r = 2.2$, $\mu_r = 1$. When the AMM is introduced, the resonant frequency drops. From this difference the effective relative permeability values are calculated. This procedure is done for one and three columns of the material and the results are shown also in Table III.

V. COMPARISON BETWEEN MEASUREMENTS AND SIMULATIONS USING FDTD AND IE3D

An antenna with the patch size $40 \times 40$ mm has been built. The patch is first positioned at 6 mm above the ground plane, then at 4 mm above the ground plane. It is filled with the artificial material layer of the dimensions $40 \times 40 \times 3$ mm (Fig. 12). The antenna in Fig. 12 has also been simulated with a 3D FDTD code. In FDTD, the particles are constructed from joint thin wires and small plates of approximately same size as in measurements (within limits of finite cell sizes).

As can be seen from Fig. 13, the results are similar even though there are differences in the resonant frequencies. Of course in simulations we have an infinite ground plane, and only three columns of the artificial material partially fill the antenna volume in the case of IE3D simulations. On the other hand, in measurements we have had a large but finite ground plane, and the material sample is of the same transverse dimensions as the patch.

VI. CONCLUSIONS

A new artificial magnetic material layer has been tested in order to shrink patch antenna dimensions. In simulations a $0.34\lambda$ antenna and in practice a $0.38\lambda$ antenna have been realized, with the 6-dB bandwidth of 4.35%. The antenna bandwidth of these reduced-size antennas is practically of the same order as for usual air-filled patch antennas with the patch size $0.5\lambda$, that resonate at the same frequency. Thus, we have demonstrated in practice a technique to miniaturize patch antennas with the use of a certain high-impedance surface.
Fig. 13. Comparison of simulated and measured results.

(working as an artificial magnetic material layer) without worsening the bandwidth.

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