Miniaturised antennas using artificial magnetic materials with fractal Hilbert inclusions

L. Yousefi and O.M. Ramahi

Artificial magnetic materials based on fractal Hilbert curves are used as a substrate to increase effective permeability, thus leading to antenna size miniaturisation. A miniaturised patch antenna with miniaturisation factor of 5.3, and impedance bandwidth of 2.11% is designed, numerically tested, fabricated, and measured.

Introduction: One of the most important applications of artificial magnetic materials is implementing miniaturised planar structures, specially miniaturised microstrip antennas [1]. The size of a microstrip antenna, the same as most traditional planar circuits, is proportional to the wavelength in the substrate. The wavelength in the substrate can be reduced by using a substrate with either a high relative permittivity ε_r or a high relative permeability μ_r. However, since the wave impedance in the substrate is proportional to the ratio of $\sqrt{\mu_r/\varepsilon_r}$, when a material with only high permittivity or permeability is used, there will be a high impedance mismatch between the air and the substrate. This mismatch will result in trapping of the electromagnetic energy in the substrate leading to low radiation efficiency for the miniaturised antenna. To solve this problem, a magneto-dielectric material with moderate values for ε_r and μ_r can be used to achieve a high miniaturisation factor expressed by $\sqrt{\mu_r\varepsilon_r}$ while keeping the wave impedance close to that of the air leading to the less impedance mismatch.

It was shown in [2] that the impedance bandwidth of a probe-fed patch antenna over a magneto-dielectric substrate with thickness h can be expressed as:

$$BW = \frac{96\sqrt{\frac{\mu_r}{\varepsilon_r}}h}{\sqrt{2}[4+17\sqrt{\mu_r\varepsilon_r}]\lambda_0} \quad (1)$$

where λ_0 is the wavelength in the air. According to this formula, for a specific miniaturisation factor of $\sqrt{\mu_r\varepsilon_r}$, as μ_r increases, the bandwidth increases as well. Therefore, using magneto-dielectrics as a substrate miniaturises the patch antenna while enhancing its bandwidth. Since natural magneto-dielectric materials are impractical to use in the microwave frequency regime, artificial magnetic materials are designed to provide desirable permeability, and permittivity at different frequency ranges [3–8].

In this Letter the performance of a recently developed artificial magnetic material based on fractal Hilbert curves [7, 8] for the application of antenna miniaturisation is numerically and experimentally investigated. First, a fast numerical setup is discussed to use for simulation of miniaturised antennas with artificial magnetic materials as substrate. Then, measurement results of a fabricated miniaturised patch antenna using fractal Hilbert inclusions are reported, and compared with numerical simulation results.

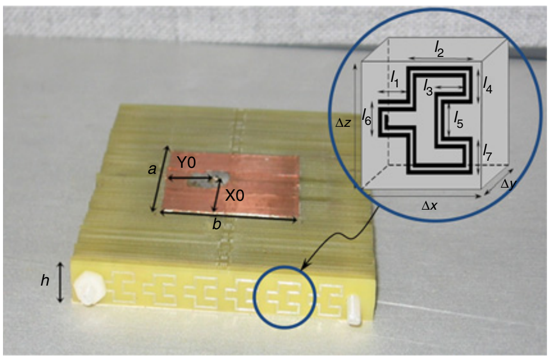

Fig. 1 *Fabricated miniaturised antenna*
$a = 3.3$ cm, $b = 4.6$ cm, $X0 = 1.7$ cm, $Y0 = 1.4$ cm, $h = 1.1$ cm

Miniaturised antenna: Here we use the fractal Hilbert inclusions introduced first in [7, 8] as the building blocks of our engineered substrate. Using this material as the substrate, a miniaturised coaxial probe-fed antenna, shown in Fig. 1, is designed and fabricated to operate at the frequency of 615 MHz. For more information about the unit cell of this material and its dimensions, see Fig. 3 in [6]. The three-dimensional engineering substrate is fabricated by stacking the strips containing the inclusions. The antenna is then placed over the engineered substrate using copper tape. To achieve higher accuracy in the fabrication process, the antenna can be printed on a thin dielectric and then attached to the top of the engineered substrate. The antenna was fed using an N-type coaxial connector inserted through the engineering substrate. Small segments of the stacked strips corresponding to the location of the feed were cut out to provide enough space for the coaxial probe.

To numerically simulate the structure of Fig. 1, owing to the high aspect ratio between the antenna and inclusion dimensions, large mesh is needed, leading to a time-consuming and practically inefficient simulation (whether time-domain or frequency-domain simulations are used). To make the simulation practical, the engineered substrate is replaced by a homogeneous material with effective permittivity and permeability extracted from the engineered substrate using plane wave analysis [7, 8]. In the simulation, numerically extracted values, shown in Fig. 2, are used. The data shown in Fig. 2 are extracted using a plane wave numerical analysis explained in [7, 8]. The simulation was performed using HFSS, a commercial software based on the finite element method. Notice that since an effective medium was used, simulation does not take into consideration the interaction between the metal inclusions and patch antenna. It will be shown below that, however, the simulation method produces good agreement with measurements, implying that the interaction between the metal inclusions and the antenna is indeed weak enough to ignore.

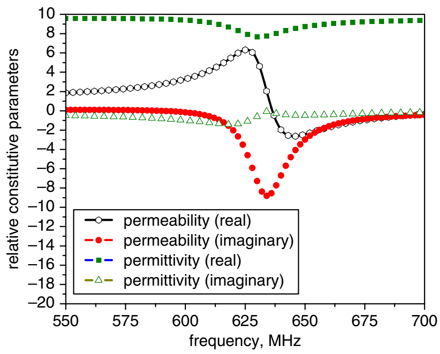

Fig. 2 *Numerically extracted constitutive parameters of artificial magnetic material with unit cell of second-order Hilbert*

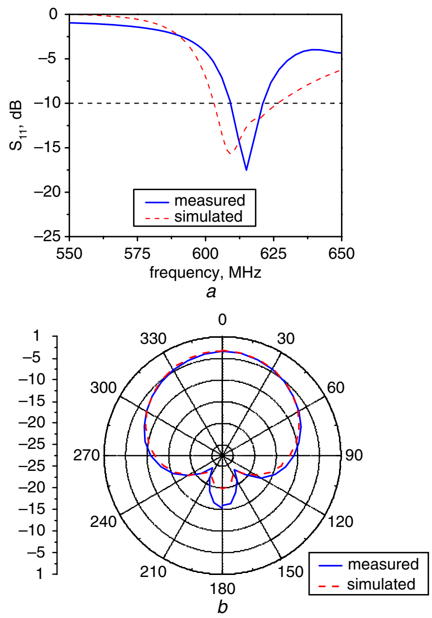

Fig. 3 *Measured results of miniaturised antenna compared with simulation results*

a Return loss
b Gain

According to the extracted constitutive parameters shown in Fig. 2, the fractal artificial substrate results in an effective permeability of $\mu_r = 4.8 - 0.95j$, and effective permittivity of $\varepsilon_r = 8.9 - 1.3j$ at the frequency of 615 MHz. As shown in Fig. 1, the biggest dimension of the antenna, which is in the y-direction, is equal to $b = 4.6$ cm, which is $1/10.6$ of the wavelength at the resonance frequency of 615 MHz. Therefore a miniaturisation factor of 5.3 is achieved using the artificial magnetic substrate. The measured return loss and radiation pattern of the antenna are shown in Fig. 3 and compared with the numerical results. As shown in Fig. 3, strong agreement is observed between simulation and measurement. In fact the miniaturised antenna has a bandwidth ($S_{11} < -10$ dB) of 2.11%, which is more than double that achieved in earlier works on miniaturised antennas using artificial magnetic materials [1]. Fig. 3*b* shows that the miniaturised antenna has a gain of −3.4 dBi at the boresight with a front-to-back ratio of 12.5 dB. The measured gain is comparable with miniaturised antennas reported in earlier works [1] (namely, −3.9 dBi).

Conclusion: The performance of artificial magnetic materials based on fractal Hilbert curves for the application of the miniaturised antenna is investigated. In this investigation, a fast numerical setup is used in which the artificial substrate is substituted with a homogenous substrate with effective constitutive parameters of the artificial structure. A miniaturised patch antenna has been fabricated to radiate over an artificial substrate employing second-order fractal Hilbert inclusions, achieving a miniaturised factor of 5.3. The return loss, and the radiation pattern of the miniaturised antenna, were measured and compared with simulation results. Measurement results exhibit a 2.11% impedance bandwidth and gain of −3.4 dBi. The primary advantage of the new design is achieving wider bandwidth when compared to previous work.

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One or more of the Figures in this Letter are available in colour online.

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