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Exploitation of a novel magneto-dielectric substrate for miniaturization of wearable UHF antennas

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ABSTRACT

A new magneto-dielectric material for wearable antenna applications at 868 MHz is presented. A barium–strontium hexaferrite is synthesized in order to achieve the best compromise between antenna dimensions and performances, exploiting the miniaturization properties offered by relative permeability greater than unity. The electrical properties of the substrate are then experimentally characterized and the corresponding material model is derived and used during the EM-simulation-based design of a patch antenna. The maximum antenna dimension is about $\lambda/20$ with a maximum directivity of 6.4 dBi. Broadband simulations and measurements of the reflection coefficient and of the radiated far-field are finally compared and demonstrate the reliability of the proposed design. A shielding solution by a conductive fabric allows to minimize back radiation and thus to avoid EM interference with human body tissues.

1. Introduction

The most challenging issue in integrated RF systems for pervasive deployment is their miniaturization which may be exploited for easy-to-wear or implantable devices. When miniaturizing the radiating element(s) one has to face the typical limitations of the so-called *electrically small antennas*, namely low radiation efficiency and gain. A commonly exploited solution is the patch antenna mounted on a dielectric substrate. The easiest way to reduce the overall antenna size is adopting dense materials with high relative permittivity ε_r to reduce the guided wavelength λ_g, which the dimension of the antenna strongly depends on. But several drawbacks derive from this choice: the reduction of the field *fringing effect*, which the radiation mechanism is based on, degrades the antenna performance; the reduction of the radiation resistance and, as a consequence, of the antenna impedance. The latters imply lower efficiency and a difficult impedance matching. A narrower bandwidth has to be taken into account as well.

Magneto-dielectric (MD) materials are proposed to strongly reduce antenna size [1–3], with moderate values of relative permittivity and permeability. This allows to keep the material intrinsic impedance within an easy-to-be-matched range and the radiation resistance sufficiently high to guarantee the radiation performance. We propose a direct EM design of planar-type antennas [1,2] exploiting the hexaferrite properties to obtain comparable results at higher frequencies (868 MHz). An edge-shorted antenna is designed for wearable purposes as a miniaturized alternative to the square patch [2]. The tested MD substrate requires easier fabrication than film laminate [3], whose performance strongly depends on the precise size and position of the MD filling material.

2. Synthesis of a magneto-dielectric disc and its EM characterization

For high frequency operation, the permanent part of magnetic bias should be as high as possible, which requires large permanent magnets resulting in relatively large size and high-cost microwave passive components. This issue can be addressed by using hexaferrites, such as $BaFe_{12}O_{19}$ and $SrFe_{12}O_{19}$, which have high effective internal magnetic anisotropy that also contributes to the permanent bias. Such a self-biased material remains magnetized even after removing the external applied magnetic field. Large anisotropic field and low eddy current losses make these magnetic materials ideally suited for microwave applications. In this letter, we describe the study and synthesis of a new hexaferrite material to be arranged as a patch antenna substrate. Owing to the possibility of its manufacturing by ceramic processing, the M-type barium–strontium

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hexaferrite $Ba_{0.75}Sr_{0.25}Fe_{12}O_{19}$ [4] was chosen to be developed for antenna miniaturization. It was produced with the standard *Mixed Oxide* process by calcination at 1000 °C for 24 h to get hexaferrite phase and densification at 1100 °C for 5 h. Disks of 40 mm-diameter were obtained by die pressing at 3000 kg/cm^2; the sintered disks were grinded and the hole was punched. Metallizations were put on the top and bottom surfaces by screen printing a silver paste, followed by heating at 750 °C. The relative permeability of M-type hexaferrites does not undergo Snoek's law, which can be modified to get a more flexible frequency limit, i.e. a higher Ferro-Magnetic Resonance (FMR) as a large anisotropic field *H* is applied [5]

$$\omega_{res}^{min}\mu_i' = \gamma 4\pi M_S\sqrt{\frac{H_\vartheta}{H_\varphi}} \tag{1}$$

where ω_{res}^{min} is the minimum angular FMR, μ'_i is the initial (static) real part of μ_r, $\gamma \approx 3$ GHz/KOe is the gyromagnetic constant, M_S is the saturation magnetization and H^ϑ and H_φ are the polar components of *H*. It is of primary importance to utilize the MD substrate below the FMR, to avoid strong energy absorption and highly dispersive behavior of μ_r. At microwave frequencies such materials offer not negligible magnetic losses and have a complex crystalline structure which has to be carefully controlled during the synthesis process.

A disk of MD material, with a diameter of 12.7 mm and a thickness of 1.3 mm, was used in permittivity measurements, while a toroid-shaped sample, with an inner diameter of 3.3 mm, an outer diameter of 12.4 mm and a thickness of 1.3 mm allows to carry out permeability measurements. A *Solartron* 1296 *Dielectric Interface* in the band 1 Hz–1 MHz and an *Agilent E*4991*A RF Impedance/Material Analyzer* in the band 1 MHz–3 GHz [6] were used, in order to verify measurements consistency at 1 MHz.

The values of real and imaginary parts of ε_r and μ_r are plotted in Fig. 1: a non-resonant behavior of permeability up to 1 GHz can be inferred. These plots confirm that in the band of interest the magnetic losses cannot be neglected during the antenna design, but are still far from those resulting from the gyromagnetic phenomena. By means of the optimization of the grain synthesis process and of the overall material manufacturing magnetic characteristics can be further improved.

Nevertheless the dielectric losses are within the limits of standard antenna substrates and are one order of magnitude lower than their magnetic counterpart.

Hence, for the antenna design we exploited the measured values of ε_r and μ_r in the band 1 MHz–1 GHz, which were modeled inside the EM simulation tool (CST): a critical point was to fit the ε_r and μ_r material simple models of the tool to the measured ones. From Fig. 1, at 868 MHz the MD material shows $\varepsilon' \approx 12$ and $\mu' \approx 2$, $\varepsilon''/\varepsilon' \approx 0.01$ and $\mu''/\mu' \approx 0.38$; thus a refractive index of 5 is achieved approximately.

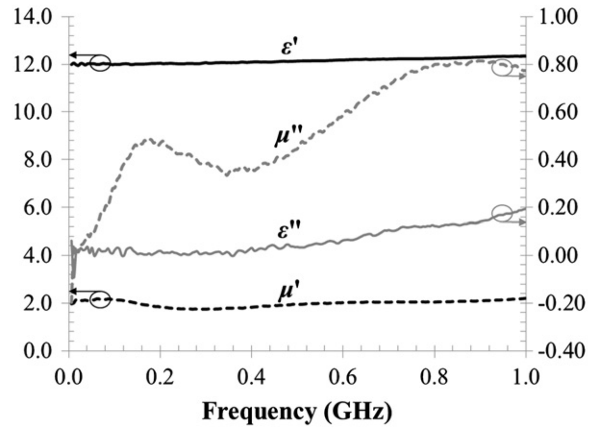

Fig. 1. Real (ε', μ') and imaginary (ε'', μ'') part of ε_r and μ_r up to 1 GHz.

3. Design of a λ/20-reduced-size patch antenna

As a first test of the engineered MD substrate, the design of a planar inverted-F patch antenna is carried out. The chosen operating frequency is 868 MHz, as this is a highly exploited frequency for RFID applications in the UHF band in Europe. We used a disk-shaped sample of MD material for our prototype, thus exploiting the absence of sharp edges for comfortable wearable applications. To further reduce the overall dimensions, a $\lambda_g/4$-patch antenna has been chosen allowing the deployment of a disk of only 33 mm-diameter. The halving of the standard $\lambda_g/2$-patch length has been obtained by means of a curved shorting-plate [7] mounted on the top of the substrate: this turned out to be an easy-to-make solution to ensure the antenna radiating properties. Furthermore, we have tackled two main problems: 1) the fragility of the ceramic composite when cutting the hole to feed the antenna; 2) the need for maximizing the antenna performance with dense substrate. For these two reasons, a value of 5 mm for the substrate thickness has been chosen to simultaneously address robustness against mechanical stress and good radiation performance. The patch, the shorting-plate and the ground plane are made of a 4 μm-thick silver film, which turned out to be sufficient to prevent from thin-conductor losses. The feeding technique is realized by inserting a micro-coaxial cable (50 Ω) into the via. The final prototype of the antenna is shown in Fig. 2: the metallization dimensions of the patch are $L = 19.15$ mm (length) and $W = 17.65$ mm (width).

In order to exploit the antenna for a wearable application, the device has been mounted on a 254 μm-thick EMC Shielding conductive fabric (with conductivity $\sigma = 1 \times 10^7$ S/m), to provide a ground plane which can be attached to any other desired fabric [8].

4. Near- and far-field antenna performances

The near-field behavior of the antenna determines its impedance, thus strongly affects the reflection coefficient shape in the band of interest. For the present design a very good agreement between simulated and measured values of the magnitude of S_{11}, can be observed in Fig. 3(a), and this also proves the quality of the

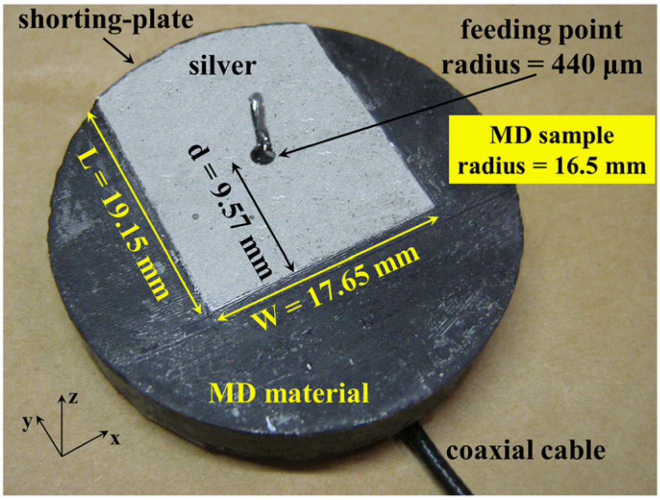

Fig. 2. Wearable patch antenna: detailed view with the micro–coaxial cable.