

Experimental evidence of left handed transmission through arrays of ferromagnetic microwires

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Experimental evidence of left-handed transmission is demonstrated through an array of ferromagnetic microwires. We used amorphous magnetic microwires to take advantage of both electric and magnetic responses locally generating a double negative medium at microwave frequencies, where the ferromagnetic resonance effects take place. The dilution of the responses of the ferromagnetic material provided by the organization of the microstructure in the form of an array provides a means of synthesizing a tailored response to electromagnetic radiation. Finally, transmission characteristics of the analyzed array can be tuned as a function of the applied external magnetic field. © 2009 American Institute of Physics. [DOI: 10.1063/1.3079673]

In the last years, a growing interest has been paid to microstructured devices that can tailor propagation characteristics of electromagnetic (EM) waves by the proper design of their unitary constituents. These artificial media, termed as “metamaterials,” can be the building blocks of a number of unique devices such as negative refraction prisms, super-resolution lenses, or cloaking shells.^{1,2} Because of the small electrical size of the elementary cells forming these devices, an effective medium approach is usually followed to analyze and describe the outstanding features governed by these structures.³ To date, experimental evidence of this type of unusual behaviors, not achievable with natural “materials,” has been basically driven by the development of structures based on microstructured resonators that can provide an artificial magnetic activity. These electrically small structures were developed starting with the split ring resonator⁴ (SRR). Nevertheless, this approach often requires the combination of two elements that can synthesize in a limited frequency range an effective electric permittivity and an effective magnetic permeability that are simultaneously negative (provided they are of small electrical size compared to the electrical wavelength). Hence, wire arrays and current loops are the building blocks of most double-negative metamaterials presently used.

In this context, negative permeability metamaterials based on ferrite rods have been analyzed⁵ and also a number of theoretical studies^{6,7} have been recently proposed in order to design left-handed metamaterials out of ferromagnetic materials. Therefore, conducting ferromagnetic microwires⁸ could provide a double negative medium. Nevertheless, experimental evidence of such a medium, which could allow left-handed propagation, is still missing.

In this letter, we measured and analyzed left-handed propagation behavior on a manufactured prototype, thus conceptually proving that such devices are feasible and can be operated in the microwave range, where the ferromagnetic resonance (FMR) effects take place. As opposed to SRR-based metamaterials, the route using ferromagnetic inclu-

sions permits one to increase the design capabilities with the use of the natural and tunable magnetic response of a ferromagnetic material. The originality of the present work is twofold. First we show experimental evidence of left-handed transmission in a simple microstructure designed only with ferromagnetic microwires. Second, we show that this structure can be tuned by means of an applied external magnetic field, which can increase the operation bandwidth by shifting the resonant response.

Glass-coated amorphous microwires of $\text{Co}_{72.5}\text{Si}_{12.5}\text{B}_{15}$ were prepared as in Ref. 9. The ferromagnetic core of the microwires has a radius of 2–3 μm . FMR phenomena in these samples have been already analyzed in Ref. 10. In brief, the dynamic susceptibility of a ferromagnetic material can be obtained from the Landau–Lifschitz–Gilbert equation of motion of the magnetization,

$$\frac{d\vec{M}}{dt} = -\mu_0\gamma(\vec{M} \times \vec{H}) - \frac{\alpha}{M_s} \left(\vec{M} \times \frac{d\vec{M}}{dt} \right), \quad (1)$$

where $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, α is a damping parameter, M_s the saturation magnetization, $\vec{H} = \vec{H}_0 + \vec{h}_{\text{rf}}$ is the total magnetic field, and $\vec{M} = \vec{M}_s + \vec{m}_{\text{rf}}$ is the magnetization (static and dynamic, respectively). From this equation, the dynamic susceptibility is determined as

$$\chi_{xx}(\omega) = \frac{\mu_0 \gamma M_s [\mu_0 \gamma (H_0 + N_y M_s) - j\omega\alpha]}{-\omega^2 + \omega_{\text{FMR}}^2 - j\omega\alpha \mu_0 \gamma [2H_0 + (N_x + N_y) M_s]}, \quad (2)$$

$$\omega_{\text{FMR}} = \mu_0 \gamma \sqrt{(H_0 + N_x M_s)(H_0 + N_y M_s)}, \quad (3)$$

where $\omega_{\text{FMR}}/2\pi$ is the frequency of FMR, N_x and N_y the dynamic demagnetization factors, and $\vec{H}_0 = \vec{H}_{\text{dc}} + \vec{H}_k$ is the sum of the external dc field and the anisotropy field.¹⁰

In Fig. 1, the real and imaginary parts of the magnetic permeability, $\mu_r = 1 + \chi$, are displayed as a function of the rf frequency of the excitation radiation. This Lorentz-type model for the permeability is defined in particular by the FMR frequency and the ferromagnetic antiresonance frequency (FMAR). The real part of μ_r has a null value (with

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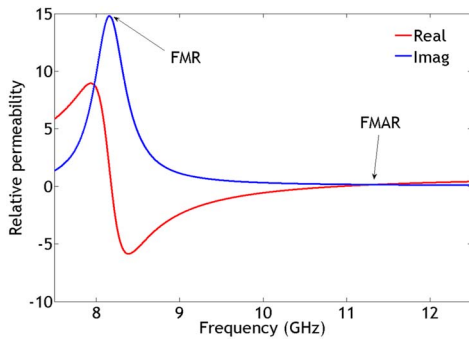


FIG. 1. (Color online) Permeability model based on Eq. (1) for $\mathbf{H}_{dc} = 100$ kA/m. In this model: $\mu_0 M_s = 0.55$ T, $\gamma = 1.76 \times 10^{11}$ T $^{-1}$ s $^{-1}$, $N_x = 1$, $N_y = 0$, and $\alpha = 0.02$.

change of sign) at these two frequencies, and the imaginary part of μ_r has a maximum at the FMR frequency but is very much reduced at the FMAR frequency. This means that between these two characteristic frequencies the real part of μ_r has a negative value. On the other hand, the wire alloy is actually a conductor and has a conductivity $\sigma \sim 6.7 \times 10^5$ S/m. This permits also to take advantage of the electric response of the microwire which is that of a conductor with high conductivity. Both responses, negative permittivity and negative permeability, coexist in a limited frequency band, since FMR does not suppress the negative permittivity behavior of the microwire.^{11–13} Although without magnetic bias the wire is essentially a good conductor, its radius is comparable to the skin depth (δ) at microwave frequencies. Assuming that $\delta = \delta_0 / \sqrt{\mu_r}$, where $\delta(10 \text{ GHz}) \approx 6 \mu\text{m}$, and that μ_r will take high values near the resonance frequency, the wires can be considered as a plane with $N_x = 1$, $N_y = 0$, as depicted in Fig. 1, where according to Eq. (3), $\omega_{\text{FMR}}/2\pi = 8.2$ GHz. This model allows describing qualitatively the following experimental results.

It is well known that an array of metallic wires, see Fig. 2, can be viewed as a “diluted” medium,¹⁴ where the reflectivity characteristics of the metal to EM radiation can be

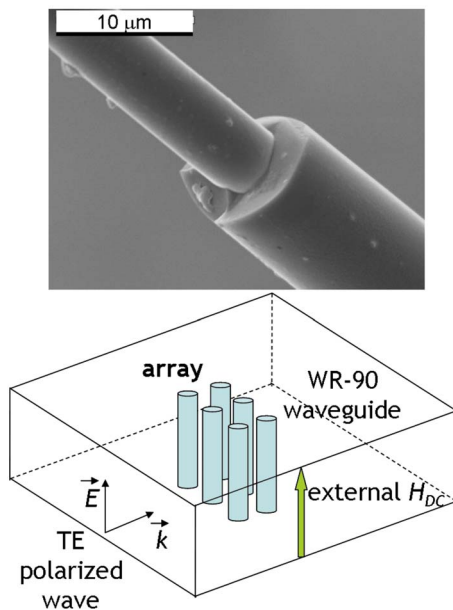


FIG. 2. (Color online) SEM image of a glass-coated microwire (top) and scheme of the measurement setup employed (bottom).

degraded with an effective plasma frequency shifted to much lower frequencies.

The dilution effect will also drive the magnetic response of the ordered wires of the array.⁶ Notably, an effective magnetic permeability can be theoretically calculated for such a medium, with the necessary cautions regarding the electrical size of the inclusions with respect to the electrical wavelength.

In any case, the most relevant feature of the proposed structure is based on the fact that the ferromagnetic microwire, as the single inclusion in the microstructure, locally fulfills the double negative condition, by providing a negative permeability and a negative permittivity.

To confirm the previous theoretical statements, an array prototype and the corresponding experimental test fixture have been setup. The array of microwires has been built by sticking a number of ordered wires on a slab of Rohacell foam ($\epsilon_r \approx 1$) and has been measured under the incident EM radiation propagating in the rectangular waveguide (TE₁₀ mode), see Fig. 2. In practice, the experimental setup consisted of a WR-90 hollow rectangular waveguide for X-band operation filled with the array of wires. The array is oriented so as the electric field \mathbf{e}_{rf} of the TE₁₀ mode is oriented parallel to the axis of the wires and the magnetic field \mathbf{h}_{rf} is oriented perpendicular to the wires. The cylindrical symmetry of the wires is an advantage with regard to the SRR case. An external static magnetic field \mathbf{H}_{dc} is applied through an electromagnet with orientation parallel to the axis of the wires in order to achieve saturation magnetization. This setup is connected to a Rohde & Schwarz network analyzer to measure the S -parameters of the array.

Experimental data have been obtained for multiple samples with different array configurations varying the number of microwires and the lattice period, which was always much smaller than the EM wavelength ($\lambda_g \approx 40$ mm at 10 GHz). All the results are consistent with those shown in Fig. 3, which correspond to a sample made of three microwires in a row placed in the center of the hollow waveguide with a separation of 4 mm. Figure 3 displays the variation in the transmission, reflection, and absorption coefficients as a function of the applied external \mathbf{H}_{dc} field. In the absence of magnetic biasing ($\mathbf{H}_{dc} = 0$), the array of wires behaves as a partially reflecting structure that is more and more transparent with increasing frequency.¹⁵ When a polarization \mathbf{H}_{dc} field is applied, FMR defines the starting frequency at which an increase in transmission is produced. In the same frequency band, the reflectance shows a minimum. Transmittance level is clearly increased over the initial conditions ($\mathbf{H}_{dc} = 0$) and the maximum transmission peak can be tuned by applying different values to \mathbf{H}_{dc} . This rise in the transmission is attributed to a double negative condition obtained, as stated previously, in the frequency range comprised between FMR and FMAR frequencies. Also, Fig. 3 shows the absorption calculated as

$$A = 1 - |S_{11}|^2 - |S_{21}|^2. \quad (4)$$

It is remarkable to note that a minimum absorption is obtained at the frequency of maximum transmission.

Figure 4 shows the transmission through an array of two layers (each with three microwires) centered in the waveguide, with a square lattice period of $p = 4$ mm. Resonant

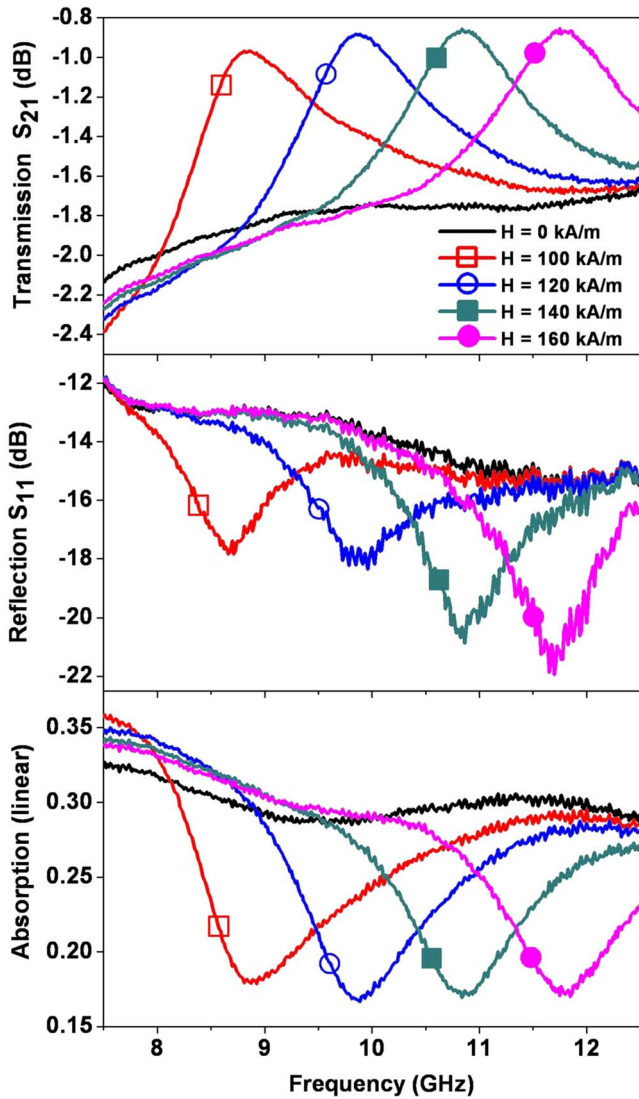


FIG. 3. (Color online) Experimental transmission (top), reflection (center), and absorption (bottom) measured on an array of three microwires in a single layer inside a *WR-90* waveguide, as a function of the applied magnetic field H_{dc} .

frequencies are preserved with increasing number of layers and the dynamics of the transmitted signal is increased as compared to the single layer case.

In conclusion, experimental evidence of left-handed transmission has been demonstrated through an array of ferromagnetic microwires. The frequency of maximum transmission can be tuned with an external applied magnetic field in the microwave range. Devices based on ferromagnetic materials may be implemented to increase the possibilities of designing left-handed metamaterials.

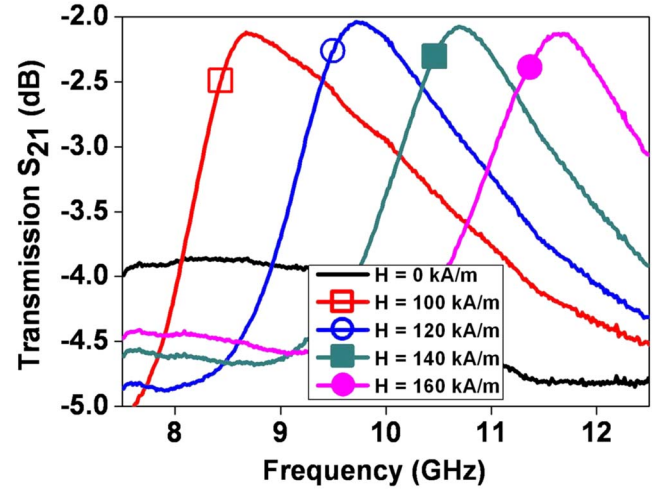


FIG. 4. (Color online) Measured transmission characteristics on an array of two layers of three wires each one, as a function of the applied magnetic field H_{dc} .

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