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RADIATION PHENOMENA IN LEFT-HANDED MATERIALS IMPLEMENTED IN COPLANAR WAVEGUIDE TECHNOLOGY.

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1. Introduction

The study of the so called Metamaterials, i.e. materials with electromagnetic properties not found usually in nature, has found increasing interest in the scientific community. One of the fields where a large amount of effort has been put is in the Left-Handed materials or LHM, characterized by exhibiting a simultaneously a negative value of the dielectric permittivity as well as the magnetic permeability. The extraordinary properties of these materials were already described by Veselago in the late 60´s [1]. From all of them, the verification of backward Cerenkov radiation has lead to a great deal of research, in order to obtain experimental validation [2] as well as performing a mathematical analysis of the phenomenon [3]. In the late 90´s Pendry [4] proposed the so called Split Ring Resonator (SRR), which are particles that enable the implementation in a simple manner of a media with negative magnetic permeability values in a certain frequency band –precisely, between the quasi static resonance frequency and the magnetic plasma frequency. The insertion of these particles in a thin wire media (which exhibits a negative value of ε below the plasma frequency), as described by Smith et al in [5], allows the existence of the left handed media. The results presented in [6] and [7] have demonstrated the possibility and interest of implementing an LHM in coplanar waveguide technology. A set of SRR particles are periodically placed in the bottom side of the CPW, allowing adequate excitation of the SRR particles by the magnetic field, enabling the existence of a frequency band with a negative magnetic permeability value. The negative value of the electric permitivity is obtained by periodically loading the CPW with shunt wires, similar to the metallic thin wire media proposed in [5], which behaves as a plasma below the plasma frequency. In this work, LHM structures in Coplanar Waveguide technology are analyzed in order to verify the presence of reversed Cerenkov radiation. Simulation as well as experimental results are presented, confirming this surprising phenomena.

2. Characterization of CPW-LHM structures.

As stated earlier, the LHM in coplanar waveguide technology is obtained by loading the conventional CPW with SRR particles on the bottom layer, as well as with shunt connected wires between the central conductor strip and the ground planes [6,7]. In order to enhance radiation phenomena, a slightly different version is proposed, exhibiting a non-symmetrical distribution of SRR particles. The layouts of the devices studied in this paper are shown in figure 1, where figure 1(a) shows the LHM structure and figure 1(b) shows the same device but without the shunt wires (and therefore, only exhibiting a negative value of the magnetic permeability). The aim is to verify the inversion of Cerenkov radiation with the aid of both devices. The CPW has been designed to have a 50Ω line impedance (strip width w = 5.4mm, air gap g = 0.3mm) on an *Arlon 250-LX-0193-43-11* substrate (ε_r= 2.43 and substrate height *h*=0.49mm).

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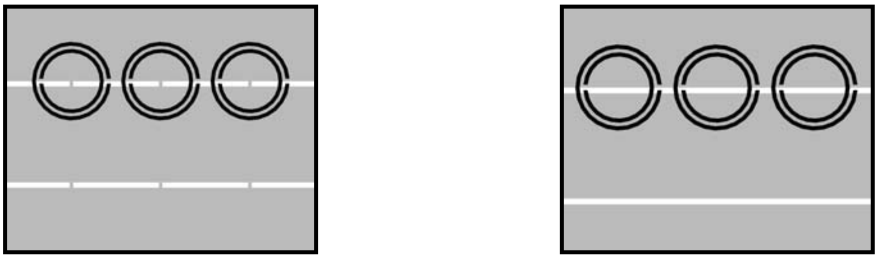


(a) (b)

Fig. 1. Layouts of the fabricated prototypes. (a) CPW LHM device (b) SRR loaded CPW (exhibiting $\mu < 0$)

In order to gain insight in the radiation phenomena exhibited by these devices, the dispersion diagrams have been calculated in both cases. In order to do so, the classical expressions from the transmission matrix parameters of a unit cell [8] have been applied. Figure 2 shows the first Brillouin zone in the dispersion diagram for the structures shown earlier. The radiation cone predicted by Oliner [9] have also been indicated with thin oblique lines. Figure 2(a) allows the verification of the existence of a frequency band where the structure shown in figure 1(a) (i.e., CPW LHM structure) behaves as a left-handed material. This frequency band corresponds to the zone of the dispersion diagram where the slope is negative, indicating that the group and phase velocity are anti-parallel. On the other hand, fig 2(b) shows the dispersion diagram of the structure loaded only with SRR particles, corresponding to the layout in figure 1(b). In this case, there is a frequency band that shows strong rejection, due to the negative values exhibited by the magnetic permeablity. This frequency band is also included in the radiation cone predicted in [9]. This radiation is contained in the first quadrant (between the endfire direction and the broadside direction), as can be inferred from the dispersion diagram.

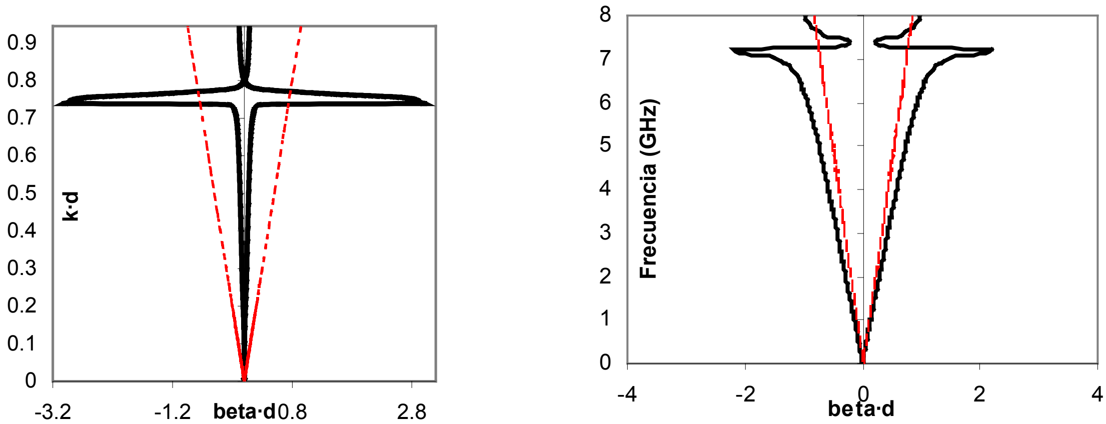
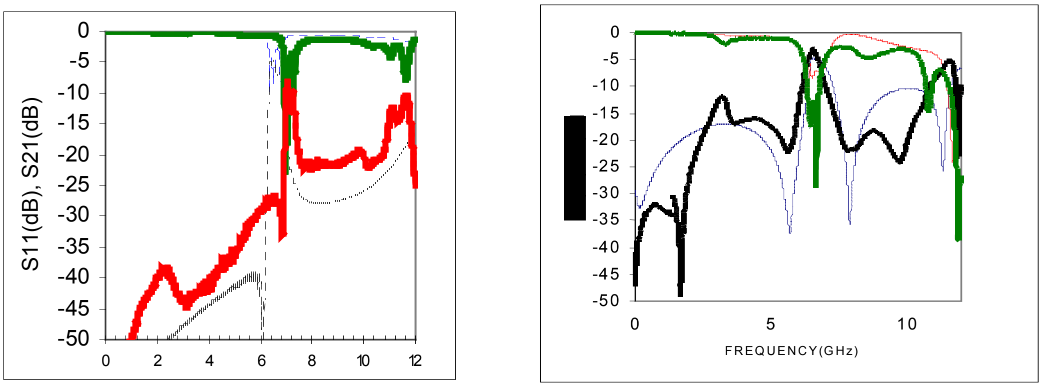


Fig. 2. Dispersion diagram of the proposed structures shown in figure 1(a) and 1(b), respectively. The predicted radiation cone is shown with dotted lines.

3. Simulation and Measurement Results

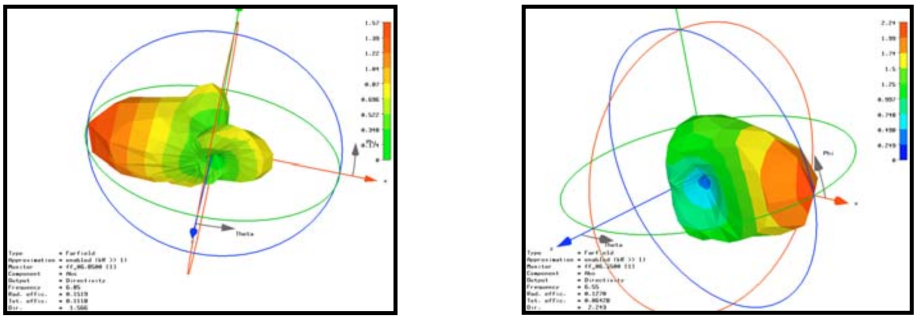
In order to validate the initial predictions obtained with the dispersion diagrams, full wave electromagnetic simulation of the prototypes have been performed, with the aid of MW Studio^{TM}, as well as measurement results from fabricated devices. The circuits have been realized by a photo-chemical etching process and have been measured with the aid of an Agilent 8722 vector network analyzer. Both results are shown in figure 3, where figure 3(a) corresponds to the device depicted in figure 1(a) (i.e., the LHM CPW structure), whereas figure 3(b) shows the results for the device depicted in figure 1(b). The slight differences between simulation and measurement results are due to tolerances in the fabrication process. Both devices have SRR parameters so that the resonant frequency is approximately around 7 GHz. In the LHM case, a passband appears in the vicinity of the quasi static resonance frequency, while in the negative magnetic permeability, a stopband arises around the same frequency. This is consistent with the fact that in the LHM, wave propagation is again possible, due to the simultaneous negative values of the ε as well μ, while in the case of only negative magnetic permeability, high attenuation will be present.



(a) (b)

Fig. 3. Simulation (thick line) vs measurement results (thin line) for prototypes in fig. 1(a) and (b), respectively.

With the aid of the full wave EM simulator, radiation diagrams have been calculated for both prototypes, for the frequency of expected maximum directivity. The 3D results are shown in figure 4. Taking into account that the prototypes are contained in the x-y plane and that feeding is done at the left-most side, inversion of Čerenkov radiation is clearly seen.



(a) (b)

Fig. 4. Simulated radiation diagrams for the prototypes depicted in figure 1(a) y (b) respectively.

These results have been qualitatively verified in the laboratory with the aid of our VNA and a horn antenna tuned in the 5.4GHz to 8.2GHz range, which was conveniently oriented following the polarization of the E-field in the coplanar waveguide, as shown in the photographs in fig 5. Maintaining the orientation in θ shown in fig 5, a manual scan of ϕ (in the 0º to 360º range, in 45º steps), the value of the S21 parameter has been processed for the different angular steps. The results (measured S21 parameter and approximate radiation diagram) are shown in fig 6 for the LHM and in fig 7 for the CPW loaded only with SRR particles, in both cases for the frequency of maximum directivity. As it can be seen on fig 6, the CPW-LHM has a clear tendency to radiate backwards (with a 10 dB gain in the backward direction with respect to the forward direction). In the SRR loaded CPW (shown in fig 7), the Čerenkov radiation produced by the Bloch mode when it enters in the fast wave zone (due to the SRR particles), is, as predicted by the dispersion diagram, in the forward direction.

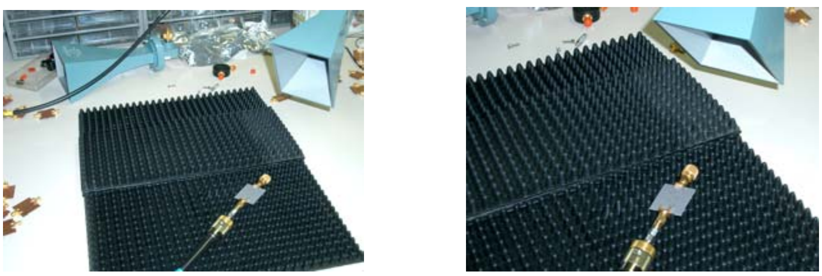
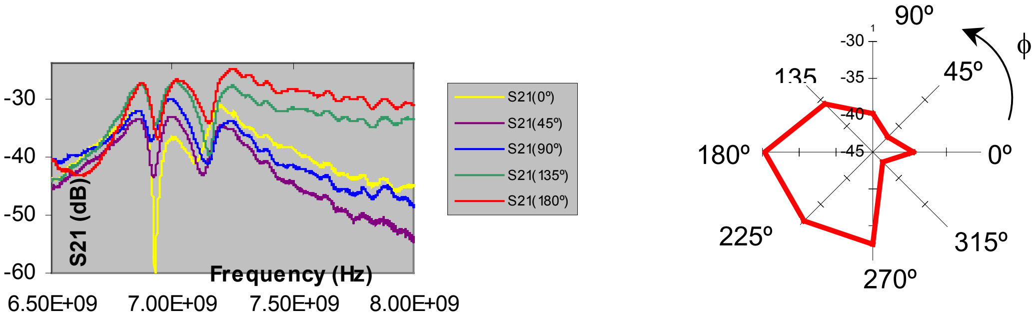
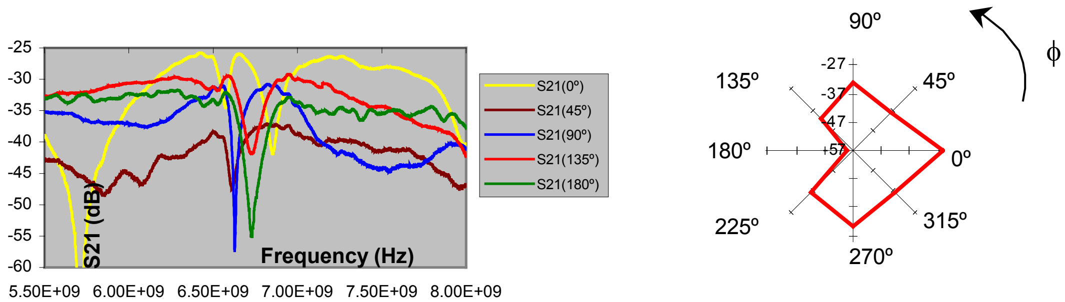


Fig. 5. Radiation measurement setup. The horn antenna is connected to port 2 of our VNA, whereas the DUT is connected to port 1, with a matched load at the output port.



(a) (b)

Fig.6. (a) Measured S21 parameter (CPW-LHM device) in the ϕ=0º-180º range and (b) approximate radiation diagram at 7.4 GHz.



(a) (b)

Fig.7. (a) Measured S21 parameter (CPW-SRR loaded device) in the ϕ=0º-180º range and (b) approximate radiation diagram at 6.7 GHz.

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