Proceedings of ISAP'04, Sendai, JAPAN

METAMATERIAL STRUCTURES IN COPLANAR WAVEGUIDE TECHNOLOGY.

Francisco Falcone[1], Ferran Martín[2], Jordi Bonache[2], Juan Baena[3], Txema Lopetegi[1], Miguel Ángel Gómez Laso[1], Joan García-García[2], Ignacio Gil[2], José Antonio Marcotegui[1,4], Ricardo Marqués[3], and Mario Sorolla[1]

[1]Departamento de Ingeniería Eléctrica y Electrónica. Universidad Pública de Navarra. 31006 Pamplona (Navarra). Spain. E-mail: francisco.falcone@unavarra.es
[2]Departament d'Enginyeria Electrònica. Universitat Autònoma de Barcelona. 08193 BELLATERRA (Barcelona). Spain. E-mail: ferran.martin@uab.es
[3]Departamento de Electrónica y Eletromagnetismo. Facultad de Física - Universidad de Sevilla. Av. Reina Mercedes s/n. 41012 Sevilla (Spain). E-mail: marques@us.es
[4]CONATEL, Polígono Plazaola F, 31195, Aizoáin, Navarra, (Spain) E-mail: marcoteg@conatel.biz

1. Introduction.

In the late 60´s Veselago [1] studied the properties of materials that had simultaneously negative values of electric permittivity as well as magnetic permeability. Such materials exhibited very interesting properties, such as antiparallel phase and group velocities, reversal of Cerenkov radiation and negative index of refraction. Since in this case, vectors E (electric field), H(magnetic field) and k (wavevector) form a left-handed triad, this type of media was termed Left-Handed media (LHM). These properties, though, could not be verified, since this type of media was not readily available in nature (negative electric permittivity was observed in plasmas and negative magnetic permeability was seen in antiferromagnets, but not both phenomena simultaneously).

This limitation was overcome when in the late 90´s a novel particle called de Split Ring Resonator [1] (SRR) was proposed. A schematic is shown in figure 1, where it can be seen that the SRR consists in a pair of concentric metallic rings, separated by an air gap. A small slit is performed in each one of the rings, greatly increasing the capacitve load. When excited by a time varying magnetic field that is perpendicular to the plane that contains the SRR, the particle resembles an L-C resonator at the so called quasi-static resonance frequency. In a certain frequency range, the SRR exhibits a strong magnetic response, leading to a negative value of the magnetic permeability. Since C has been greatly increased, the resonance frequency is reduced, so that it is much smaller than the operational wavelength. This way, a set of SRR can be analyzed by means of effective medium theory. In combination with an array of thin wires (which resembles a plasma below the plasma frequency, i.e., a medium with an effective electric permittivity which is negative up to the plasma frequency), the first experimental validation of a Left-Handed madium [3] was obtained.

The LHM proposed earlier does not allow easy integration in conventional planar circuits. Therefore, alternative implementations have been proposed, many of them based on an equivalent transmission line approach [4,5]. In this work, a novel type of metamaterial structures based on the application of SRR particles in conventional coplanar waveguide technology is presented. Simulation as well as measurement results are presented, showing their potential application in development of devices.

2. Negative Magnetic Permeability CPW medium

The first structure that is proposed is a negative magnetic permeability media in a conventional coplanar waveguide. This can be achieved by loading the CPW with SRR particles adequately placed along the host transmission line, i.e., when the magnetic field has normal incidence on the plane that contains the SRR particle [6]. In a CPW, H-field lines close along the central conductor strip and both ground planes, since the sources are the electric currents flowing along the conductors. At the center of the air gaps that separate the central conductor strip from the ground planes, H-filed lines are normal to the air-dielectric interface. Therefore, SRR particles can be placed underneath the air slots between the central conductor strip and the ground planes, on the bottom side of the CPW (where no metallization layers are present). This approach allows to maintain the properties of the host CPW transmission line practically unperturbed, e.g., the line impedance. Since the SRR particles prove to be electromagnetically "invisible" at frequencies outside the quasi-static resonance frequency range, not modifying the host transmission line will allow to have low insertion losses at frequencies outside the SRR operating frequencies.

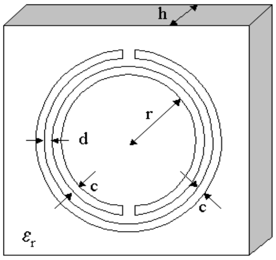

Figure 1: Schematic of a Split Ring Resonator (SRR) particle. The quasi-static resonance frequency is given by the mean radius of the rings, the metallic strip width and the air gap width between rings.

Tuning of the quasi-static resonance frequency is achieved by modifying the values of L and C. This is possible by varying the mean radius of the rings, the width of the metallic strips as well as the air gaps, as described in [7]. Taking into the calculation procedure in [7], a CPW is loaded with SRR particles with outer radius of 2.2mm, air gap of 0.2mm and metallic strips of width 0.2mm, which allows for a quasi-static resonance frequency of approximately 7.7 GHz, on an Aarlon substrate (relative dielectric constant of 2.43 and height 0.49mm). The host CPW has a central strip width of 5.4mm and air gaps of 0.3mm, leading to a line impedance 0f 50 ohm while allowing the introduction of the SRR particles. The lattice period between adjacent rings is chosen to be 5mm, in order to be well below the guided wavelength value, trying to resemble a continuous medium (therefore operating in a sub-lambda fashion). Full wave electromagnetic simulation has been performed with the aid MW Studio^{TM} and is compared with measurement results in figure 2. The prototype was fabricated by means of a chemical photo etching procedure and the measurements were performed with an Agilent^{TM} 8722 vector network analyzer.

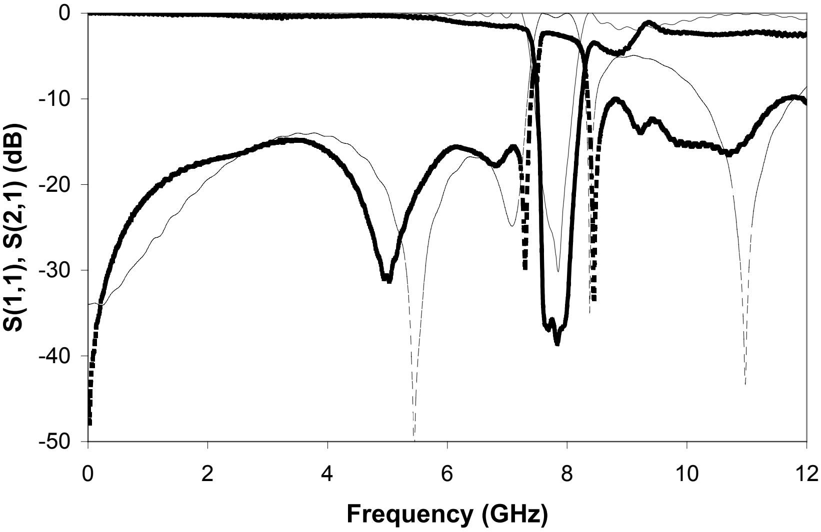

Figure 2: Simulation vs Measurement results for a CPW loaded with SRR particles. A rejected frequency band is observed around the quasi-static frequency. Outside the operating frequency of the SRR particles, insertion losses are ver low, due to matching from the host transmission line.

The rejection bandwidth of the SRR-loaded CPW is given by the frequency range between the quasi-static frequency and the magnetic plasma frequency (the frequency where the magnetic permeability has again a positive value). The rejected frequency band follows a resonant behavior. Therefore, a narrow band response is achieved. In order to increase the rejection bandwidth, a modified version of the SRR loaded CPW has been investigated. It consists in a CPW that is loaded with a set of multiple tuned SRR particles, i.e., a set of rings that have a slight variation in the mean radius, one from another. By doing so, the quasi-static resonance frequencies are displaced. If such displacement is slight (corresponding to small variations in the radius values), the final results is a wider rejection bandwidth. In order to verify this initial assumption, a CPW SRR loaded with multiple tuned SRR particles has been designed, simulated and measured. The result is presented in Figure 3. The device is composed by a host CPW equal to the one described previously and a set of 5 pairs of SRR particles, with a mean radius increase of 0.05mm from one pair to the next, starting from a value of 2.2mm. As it can be seen, the bandwidth is increased from 400 MHz in the single tuned case to approximately 600 MHz in the multiple tuned. Once again, insertion losses are small in the frequencies outside the operating region of the SRR particle.

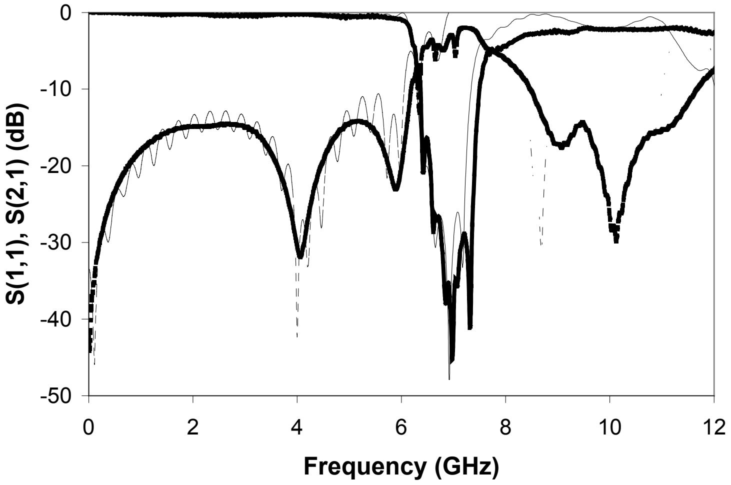

Figure 3: Simulation vs Measurement results in a multiple tuned SRR loaded CPW.

3. Left-Handed Material in CPW

As it was shown in the previous section, SRR can be employed in order to synthesize a CPW with an effective negative magnetic permeability value in a certain frequency range. If it is combined with a structure that has a negative electric permittivity value, then a Left-Handed material can be obtained. In analogy to the experiment described in [3], the CPW can be loaded with a set of shunt connected wires that go from the central conductor strip to both ground planes. This is equivalent to loading the CPW with shunt-connected inductors, which will exhibit a high-pass frequency response. If the cut-off frequency is higher than the quasi-static resonance frequency, then both the electric permittivity and the magnetic permeability are negative in the frequency range between the quasi-static frequency and magnetic plasma frequency, obtaining LHM behavior.

Full wave simulation as well as measurement results for a CPW loaded with SRR particles as well as shunt connected wires is shown in figure 4. In this case, a passband appears where previously a rejected band was present. This is logical, since in this case, propagation is not possible when either the electric permittivity or the magnetic permeability is negative (evanescent propagation is enabled). But when both values are negative, propagation is once again is allowed. The passband is approximately 400 MHz wide, in agreement with the SRR loaded CPW shown previously. The insertion losses are of approximately 3 dB, showing one of the best experimental results of LHM propagation obtained. As to the size, the lattice period is again of 5mm, leading to a very compact device. These results envisage the application of metamaterial structures for the miniaturization of filters and antennas in planar circuit technology. [8,9]

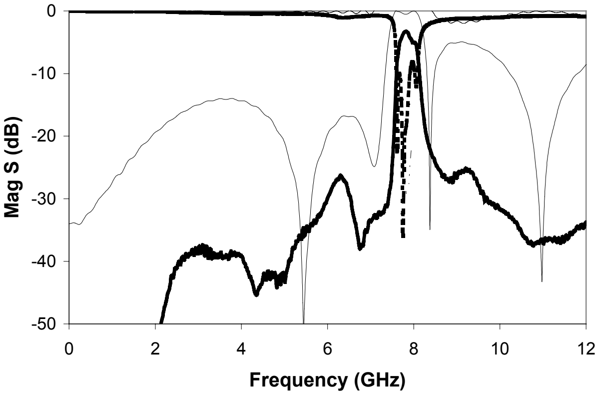

Figure 4: Simulation vs Measurement results for the LHM-CPW prototype. In this case, a passband is observed in the quasi-static resonance frequency range. Insertion losses in order of 3 dB are present in the measured case.

References

[1] V.G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ", *Sov. Phys. Usp*. 10, 509 (1968).

[2] J.B. Pendry, A.J. Holden, D.J. Robbins and W.J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microw. Theory Tech.,* vol. 47, no. 11, pp. 2075-2084, November 1999.

[3] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.*, vol. 84, pp. 4184-4187, May 2000.

[4] C. Caloz, C-C. Chang and T. Itoh, "Full wave verification of the fundamental properties of left-handed materials in waveguide configurations," *Journal Appl. Phys*., vol. 90, no. 11, pp. 5483-5486, December 2001.

[5] A. Grbic and G.V. Eleftheriades, "Experimental verification of backward wave radiation from a negative refractive index metamaterial," *Journal Appl. Phys*., vol. 92, no. 10, pp. 5930-5935, November 2002.

[6] F. Martín, J. Bonache, F. Falcone, M. Sorolla and R. Marqués, "Split Ring resonator-based left-handed coplanar waveguide," *Appl. Phys. Letters*, vol. 83, no. 22, pp. 4652-4654. December 2003

[7] R. Marqués, F. Mesa, J. Martel and F. Medina "Comparative analysis of edge- and broadside- coupled split ring resonators for metamaterial design. Theory and Experiments," *IEEE Trans on Antennas and Propagation*, vol. 51, no. 10, pp. 2572 – 2581, October 2003.

[8] F. Martín, , F. Falcone, J. Bonache, R. Marqués and M. Sorolla, "Miniaturized Coplanar Waveguide stop band filters based on multiple tuned split ring resonators," *IEEE Microwave and Wireless Components Letters*, vol. 13, no. 12, December 2003 .

[9] The application of these structures for circuits and antennas in planar technology is patent pending