INVESTIGATION ON MICROWAVE SIGNAL PROPAGATION THROUGH SOME LEFT-HANDED STRUCTURES

M. G. Banciu *, A. Ioachim*, N. Militaru, G. Lojewski****

*National Institute of Materials Physics, Bucharest-Magurele, Romania
E-mail: gbanciu@infim.ro

**University POLITEHNICA of Bucharest, Bucharest, Romania
E-mail : george.lojewski@munde.pub.ro

Abstract–*Some aspects of microwave propagation through left-handed materials are investigated in this paper. The strong distortion of a Gaussian TEM pulse through a material with negative refraction index is studied in the time domain. Moreover, a method of extracting the constitutive parameters of a material by using the scattering parameters of a sample two-port is developed. This method is then applied to some left-handed microstrip structures.*

Keywords: *left-handed materials, time domain pulse propagation, constitutive parameters.*

1. INTRODUCTION

Recent researches showed that interaction of the electromagnetic waves with artificial structured materials having electromagnetic parameters such as electrical permittivity, magnetic permeability, refraction index taking negative values, leads to exotic phenomena as negative Doppler shift, reversed Cerenkov effect, growing of the evanescent waves or the negative refraction, etc. [1-3]. The super-lens made of such artificial material focus both the propagating and evanescent components of the electromagnetic waves and enables sharper, subwavelength size imaging [4]. The anti-parallelism of phase and group velocities is another interesting physical phenomenon of such structured materials.

One of the practical applications of these features allows the control of the signal phase and of the dispersion characteristics in telecommunications systems.

2. PULSE PROPAGATION

Let us consider the propagation of a TEM Gaussian pulse through a 20 mm thick material sample placed in a free-space region. The time-domain simulations were carried out using a home-made FDTD software. When the sample is of a conventional material with positive relative electric permittivity ε_r and relative magnetic permeability μ_r, the transmitted and reflected signals are sums of undistorted multiple delayed replicas of the Gaussian pulse, as shown in Fig. 1.

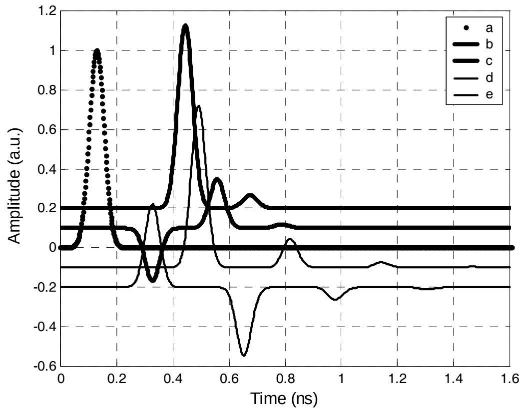

Fig. 1. Pulse propagation through a conventional material: a) input Gaussian pulse; b) output signal for ε_r = 3 and μ_r = 1; c) reflected signal for ε_r = 3 and μ_r = 1; d) output signal for ε_r = 1 and μ_r = 6; e) reflected signal for ε_r = 1 and μ_r = 6.

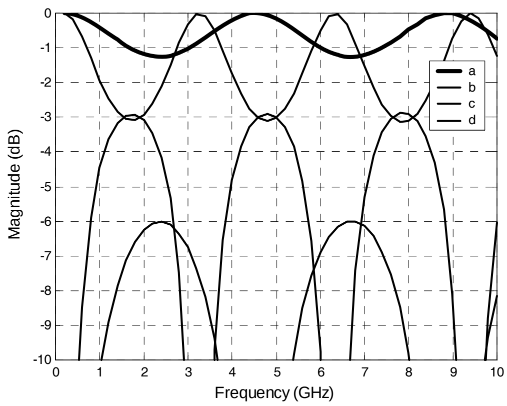

Fig. 2. Magnitude of scattering parameters of a two-port with conventional material: a)$|S_{21}|$ for ε_r = 3 and μ_r = 1; b) $|S_{11}|$ for ε_r = 3 and μ_r = 1; c) $|S_{21}|$ for ε_r = 1 and μ_r = 6; d) $|S_{11}|$ for ε_r = 1 and μ_r = 6.

When ε_r = 3 and μ_r = 1 the first reflected pulse has a negative sign, compared to the initial pulse.

On the contrary, for $\varepsilon_r = 1$ and $\mu_r = 6$, the first reflected pulse has the same sign as the initial pulse.

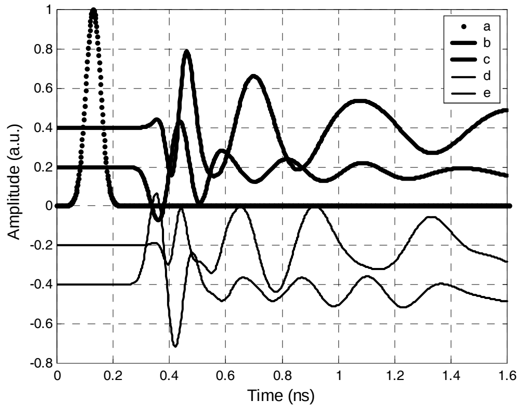

Fig. 3. Pulse propagation through a CRLH material: a) incident Gaussian pulse; b) output signal $\varepsilon_r = -3$ and $\mu_r = -1$; c) reflected signal for $\varepsilon_r = -3$ and $\mu_r = -1$; d) output signal $\varepsilon_r = -1$ and $\mu_r = -6$; e) reflected signal for $\varepsilon_r = -1$ and $\mu_r = -6$.

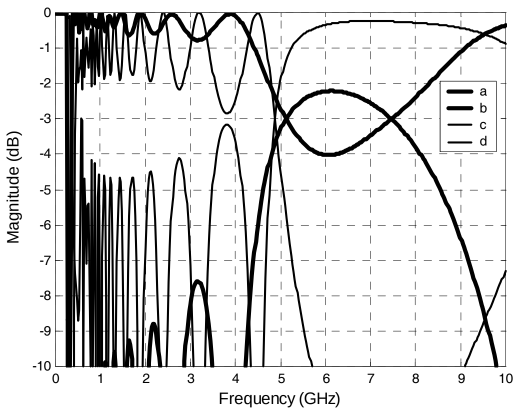

Fig. 4. Magnitude of scattering parameters of a two-port with CRLH material: a)$|S_{21}|$ for $\varepsilon_r = -3$ and $\mu_r = -1$; b) $|S_{11}|$ for $\varepsilon_r = -3$ and $\mu_r = -1$; c) $|S_{21}|$ for $\varepsilon_r = -1$ and $\mu_r = -6$; d) $|S_{11}|$ for $\varepsilon_r = -1$ and $\mu_r = -6$.

It can be observed that after 1.6 ns the amplitude of the transmitted and reflected signals can be neglected.

Unlike in usual media, the Gaussian pulse is strongly distorted when transmitted and reflected through a composite right/left-handed (CRLH) material with a negative refraction index as shown in Fig. 3. The amplitude of the signal oscillations decreases very slowly in time, in such a way that, after more than 35 ns, they cannot be neglected. The scattering parameters in frequency domain, shown in Fig. 4, exhibit a band-pass followed by a band-stop behavior, which is characteristic to CRLH materials [1-5].

3. CONSTITUTIVE ELECTROMAGNETIC PARAMETERS

In order to obtain the constitutive electromagnetic parameters of an artificial material from the two-port scattering parameters, an effective medium method was developed.

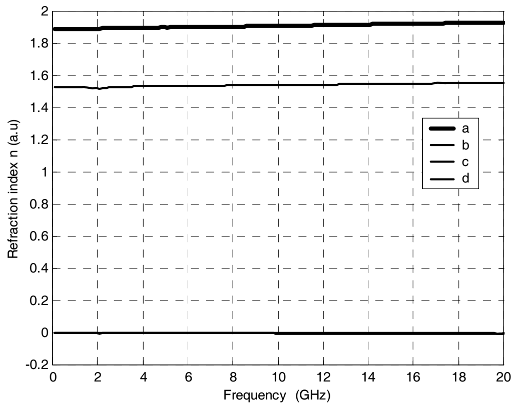

Fig. 5. Equivalent refraction index for microstrip lines of different values of w: a) Re(n) for w=1.3 mm b) Im(n) for w= 1.3 mm; c) Re(n) for w= 0.7 mm d) Im(n) for w= 0.7 mm.

The basic approximation of this theory consists in the fact that cell dimension is smaller than a tenth of the smallest wavelength, in order to consider the material homogeneous. Only the quasi-TEM propagating mode of the microstrip lines is considered. The material sample of length *l* is considered as a two-port, with the scattering parameters:

$$S_{21} = \frac{\tau\left(1-\Gamma^2\right)}{1-\Gamma^2\tau^2} \text{ and } S_{11} = \frac{\Gamma\left(1-\tau^2\right)}{1-\Gamma^2\tau^2}. \tag{1}$$

In (1) the reflection coefficient Γ for a wave passing (from the reference transmission line) into the structure is

$$\Gamma = \frac{Z - Z_C}{Z + Z_C} \tag{2}$$

and τ is the wave propagation factor through the structure,

$$\tau = e^{-\gamma l}. \tag{3}$$

Here γ is the propagation constant, which is related to the effective refraction index n by the relation

$$\gamma = \frac{2\pi f}{c} n, \qquad (4)$$

where f represents the frequency and c is the speed of light in vacuum.

From here can be derived the relation between the effective refraction index and the scattering parameters of the two-port:

$$n = \mp j \frac{c}{2\pi f l} \cosh^{-1} \frac{1 + S_{21}^2 - S_{11}^2}{2 S_{11}}. \qquad (5)$$

As for any passive structure, the sign is chosen in such a way that Im $(n) < 0$.

In order to validate the effective medium method, the equivalent refraction index n was determined in the case of simple microstrip lines. The obtained values of n are in agreement with those resulted from the effective dielectric constant, accordingly to the microstrip line theory.

4. MICROSTRIP CRLH STRUCTURES

Microstrip structures with CRLH behavior were designed on 0.508 mm thick substrate, with a dielectric constant of 3.

The conventional CRLH line [1] shown in Fig. 6 was investigated. The response of this structure in frequency domain was obtained by using an electromagnetic software based on the method of moments [6]. The effective medium method described in the previous section gives the dependence of the refractive index n on the frequency, as shown in Fig. 7. This structure exhibits negative Re(n) values for frequencies up to about ~3.7 GHz. On the other side, for high frequencies Re(n) tends to a positive constant, as for usual microstrip lines, when the dispersion effects are neglected.

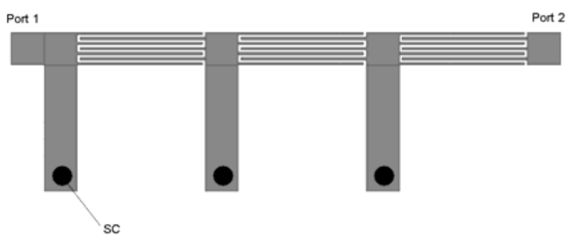

Fig. 6. Microstrip implementation of a CRLH transmission line (SC represents via holes short circuits, ground plane not shown).

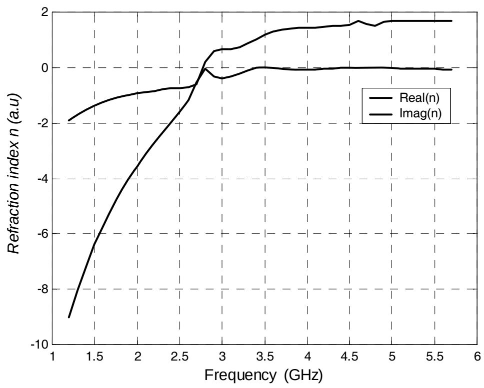

Fig. 7. Equivalent refraction index for the microstrip structure of Fig. 6.

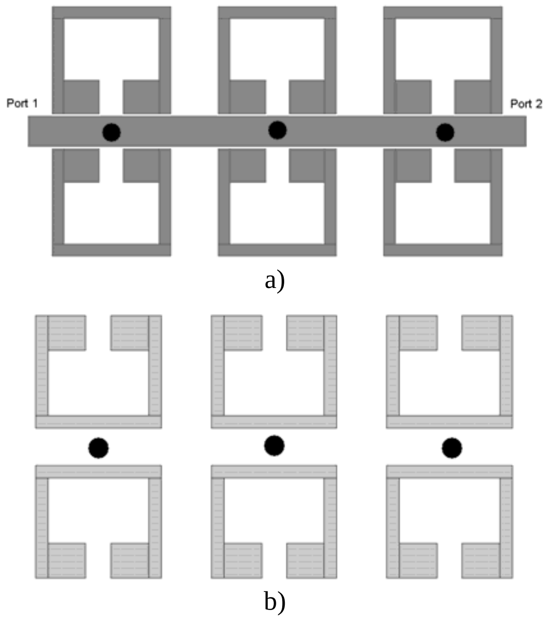

Fig. 8. Proposed microstrip implementation of a left-handed transmission line: (a) top microstrip layer; (b) middle microstrip layer (ground plane not shown).

A new layered CRLH structure based on folded stepped-impedance resonators was proposed (Fig. 8). Two microstrip layers are separated by a dielectric substrate. The vertical via hole short-circuits (SC) is placed between the top microstrip conductor and the ground plane.

In the case of RF field parallel to the periodic via holes, a negative value of the electric permittivity can be obtained. On the other hand, when the magnetic field is parallel to the axis of the resonators, a negative value of magnetic permeability can be achieved.

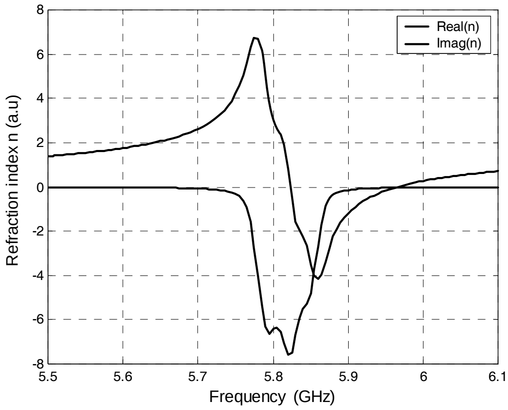

Fig. 9. Equivalent refraction index n for the proposed left-handed microstrip line.

Each folded stepped impedance resonator on the top microstrip layer couples with a corresponding resonator on the middle microstrip layer (Fig. 8). The resonator pairs behave similarly to the split ring resonators leading to a negative magnetic permeability [7, 8].

The dependence of the refractive index *n* on the frequency, shown in Fig. 9, outlines a frequency range near the resonance where the real part of the refractive index is negative.

5. CONCLUSIONS

Investigations in time domain of a TEM Gaussian pulse show significant distortions due to the dispersive characteristics of the left-handed materials. The reflected and transmitted signals decay very slowly in time compared to the signals from a sample of a conventional material. When investigated in frequency domain, the scattering parameters show a pass-band followed by a stop-band behavior, which is characteristic to most of the composite right/left-handed structures.

The developed effective medium theory was applied to multilayer microstrip structures. The proposed CRLH structures exhibit negative values of the refractive index *n* only in a narrow frequency band.

References

[1] C. Caloz, T. Itoh, "Electromagnetic Metamaterials – Transmission Line theory and Microwave Applications", *Hoboken*, New Jersey, 2006.

[2] G.V. Eleftheriades, K.G. Balmain, "Negative Refraction Metamaterials: Fundamental Principles and Application", *Wiley-IEEE Press*, 2005.

[3] N. Engheta, R.W. Ziolkowski, "Metamaterials – Physics and Engineering Explorations", *Wiley-IEEE Press*, New York, 2006.

[4] K. Aydin, E. Ozbay, "Left-handed metamaterial based superlens for subwavelenght imaging of electromagnetic waves", *Appl. Phys.*, **A87**, 2007, pp. 137–141.

[5] S. Simion, G. Sajin, F. Craciunoiu, "Full-wave electromagnetic design an analysis of broadband CRLH couplers", *Proceeding International Semiconductor Conference CAS 2006*, vol. **I**, pp. 123–126.

[6] ***, "*em* User's Manual", *Sonnet Software Inc.*, Sonnet Professional, version 10.52, New York, 2005.

[7] J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Steward, "Magnetism from conductors and enhanced nonlinear phenomena", *IEEE Trans. Microwave Theory Tech.*, vol. **47**(11), 1999, pp. 2075–2084.

[8] R.A. Shelby, D.R. Smith, S.C. Nemat-Nasser, and S. Schultz, "Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial", *App. Phys. Lett.*, vol. **78(**4), 2001, pp. 489–491.