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MODELING AND MEASUREMENT OF A ZEROTH-ORDER RESONATOR AND A COMPOSITE RIGHT-LEFT-HANDED TRANSMISSION LINE IN COPLANAR TECHNOLOGY

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Abstract—This paper presents a coplanar composite right-left handed zeroth-order resonator (CRLH CPW ZOR) and a coplanar composite right-left handed transmission line (CRLH CPW TL). These devices are realized using an elementary cell designed in a coplanar waveguide configuration on alumina substrate. Additional lumped elements are carried out with an interdigital series capacitor and a short-circuited stub inductor as a shunt. The CRLH CPW ZOR is fabricated and analyzed using equivalent circuit modeling and three dimensional finite element method. The proposed devices are fabricated and measured. The resonator has a measured insertion loss of 2.7 dB and a return loss better than 13 dB. The length of the proposed device is only 5.2 mm; this very small size compared with a traditional half wave resonator, shows the interest of this kind of approach.

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1. INTRODUCTION

The concept of materials characterized by a negative permittivity and a negative permeability simultaneously has been studied since several years. These materials are called Left-handed materials (LHMs), according to the orientation of the electromagnetic vectors of the electric with respect to the propagating vector. Originally they were proposed and investigated theoretically by Veselago [1]. Next, an experimental verification showed the negative effective refraction index in a certain frequency band [2]. This concept has been extended to the transmission line domain. An equivalent circuit approach was developed by Caloz and Itoh [3] and Eleftheriades [4] and this approach has lead to the concept of Composite Right Left Handed (CRLH) materials, which fully takes into account the parasitic Right-Handed (RH) effects which cannot be avoided in a practical Left-Handed (LH) structure. Hence, the CRLH concept describes the right and left-handed nature of metamaterials transmission lines [5, 6].

The first zeroth-order resonator (ZOR) was proposed by Sanada et al. [7]; it was realized in microstrip configuration. Based on this unit cell, a practical application was realized for antennas [8]. Compared to the microstrip, coplanar waveguides (CPW) have several advantages for monolithic microwave integrated circuits (ease of shunt and series connections, low radiation, low dispersion and simpler fabrication). In coplanar waveguide configuration, a CRLH transmission line has been implemented for microwave applications using periodic structures loaded with different kinds of series capacitors and shunt inductors [9]. A zeroth-order resonator in CPW technology has been used for realizing a band-pass filter [10], and the demonstration of a tuneable CRLH ZOR on silicon substrate has been developed in [11] using MEMS.

In this paper, we present a composite right-left handed coplanar zeroth-order resonator and a composite right-left handed coplanar transmission line on alumina substrate. Our first aim is to model the basic cell by a simple electrical circuit and to calculate the values of the different elements of the circuit; this is a different approach compared to [10]. As mentioned previously, a purely left handed structure is not possible because of unavoidable RH effects. In order to have the capability to set the properties of our devices and to have the more settings parameters as possible, we have modeled the left-handed elements but also the parasitic elements. Good modeling of the unit cell, then allows realizing different transmission characteristics. As the topic is not new, we have worked on the size and the performances of the two devices. The unit cell we proposed is smaller than in [9]. Transmission characteristics are then analyzed using full wave simulation and equivalent circuit model. Devices are fabricated and measured using a Vector Network Analyzer.

2. THEORY

2.1. A CRLH CPW Unit Cell

Figure 1(a) shows the layout of the proposed CLRH CPW unit cell (black parts are metallic, white ones are slots). It is composed of a series interdigital capacitor (IDC) and 2 symmetric shunt short-circuited stub inductors (SSI).

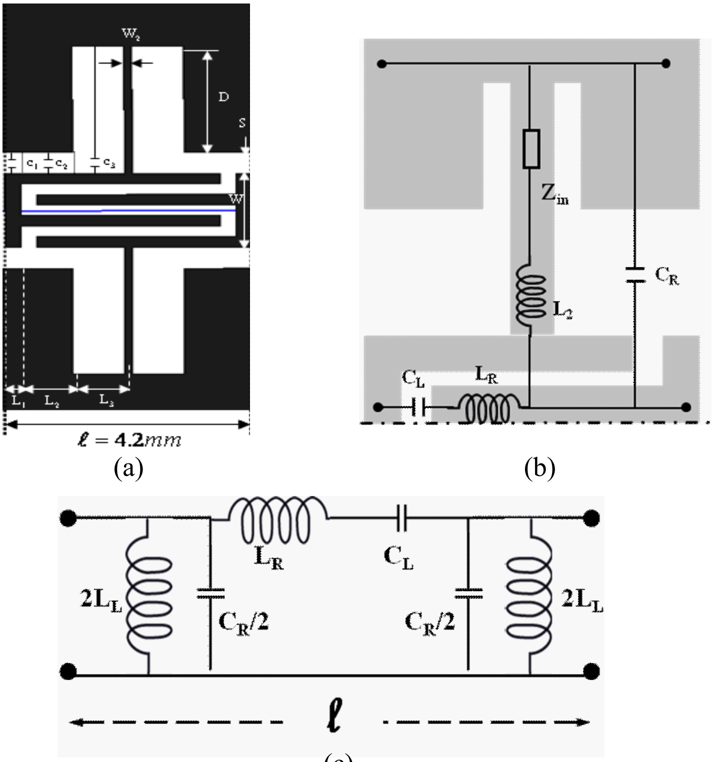
The equivalent circuit of the proposed CRLH CPW unit cell must be made of series capacitor, series inductor, shunt capacitor and shunt inductor. Thus, the model includes the dominant LH characteristic, and the parasitic RH effects. Now let's try to obtain a circuit modeling of this unit cell.

Since the design is symmetric, Figure 1(b) only shows one half of the cell and presents the contribution of the different parts. C_L is the series capacitor of the (IDC); its value is calculated from the method presented in [12]. L_R is the parasitic inductor of the IDC and is approximated using the CPW transmission line theory. Actually, the magnetic field lines do not loop around each finger but around the cross section of the IDC; so the IDC inductance can be considered as the inductance of a line the length of which is equal to the length of the finger. Parallel capacitor C_R is used to model the capacitance between the outermost fingers and the ground planes. This area can be seen as a CPW line with one ground plane only; the value of C_R is calculated from three capacitors (C_1, C_2, C_3), which can be obtained from [13, 14]. The stub can be split in two parts. The first one is represented by the L_2 inductor; the value is calculated using the method described in [15]. The second one is represented by the input impedance of a short-circuited CPW of length D. It can be calculated with the relation:

$$Z_{in} = jZ_{0e}\tan(\beta_0 D)/2 \tag{1}$$

where Z_{oe} is the characteristic impedance of the even mode of the CPW with finite-extent ground planes [16] and β_o is the phase constant of this line.

The simplified equivalent circuit of the complete cell is now shown on Figure 1(c). The shunt inductor L_L is the sum of L_2 and of the inductor calculated from Z_{in}. Factors 2 and 1/2 come from the symmetry of the cell.



(a)

(b)

(c)

Figure 1. (a) Physical configuration of the unit-cell CRLH CPW ($W = 1.4\,\mathrm{mm}$, $W_2 = 0.1\,\mathrm{mm}$, $S = 0.4\,\mathrm{mm}$, $D = 2\,\mathrm{mm}$, $L_1 = 0.2\,\mathrm{mm}$, $L_2 = L_3 = 0.65\,\mathrm{mm}$) & four fingers: width of fingers is equal to gap between fingers (0.2 mm). (b) One half of the unit-cell and its equivalent circuit. (c) Equivalent circuit model of the unit-cell CRLH CPW in symmetric configuration.

2.2. Zeroth Order Resonator

The zeroth-order resonator (ZOR) is one of the interesting applications of planar type left-handed metamaterials. Unlike the conventional transmission line, the CLRH TL can have an infinite wavelength for a non-zero frequency. So the resonant case ($2\ell/\lambda_g = m$ with $m = 0$) is particularly unique and interesting [7]. As a consequence this resonant frequency is independent of the physical length of the resonator.

The resonant condition of the ZOR is based on the cancellation of the propagation constant due to the phase compensation of the sections

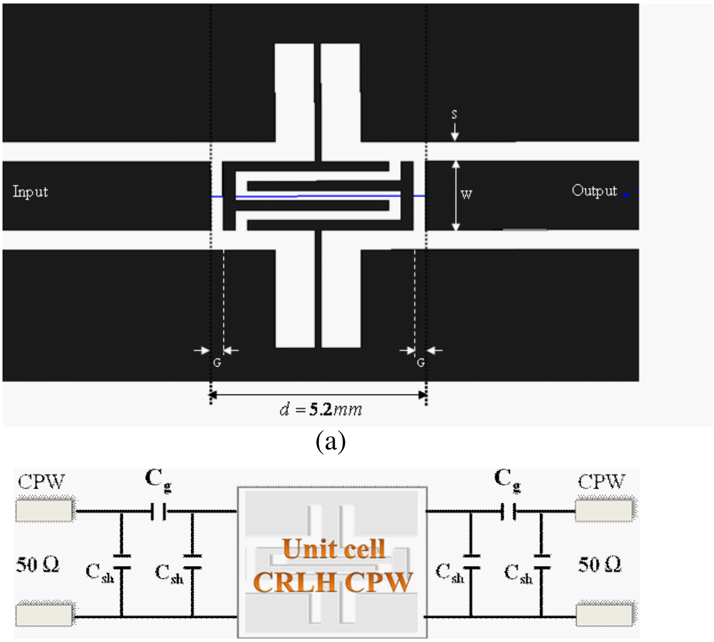
RH and LH TL [7]. The condition of the resonance can be written as

$$\beta\ell = m\pi \quad (m = 0, \pm 1, \pm 2, \ldots) \tag{2}$$

where m is an integer, β is the propagation constant of the CRLH section and ℓ the total length of the section. The resonance of order zero occurs with $m = 0$. Since the length is not equal to zero, the propagation constant must be equal to zero (electric length equal to zero too). This property is characteristic of the zero-order resonance.

We propose to realize a ZOR in CPW technology. Figure 2 illustrates the complete layout of the resonator which is coupled by air gaps. It can be divided into three parts: 50 Ω access lines (one for each side), the CRLH CPW cell and two CPW series gaps as coupling structures.

The coupling air gap is modeled by its π-equivalent circuit. In [15], Dib derived the only available closed form expressions in the literature for C_g and C_{sh} capacitances. We have noticed that each part of the structure must be carefully modeled in order to obtain a predictive analytical model, especially in the resonant frequency band.



(a)

(b)

Figure 2. (a) Geometry of the CRLH CPW ZOR. (b) Equivalent circuit model.

Using our equivalent circuit model, the resonance condition can be obtained starting from the phase constant formula. At zero order resonance one can obtain:

$$L_R C_R \omega^4 - \left(\frac{L_R}{L_L} + \frac{C_R}{C_L}\right)\omega^2 + \frac{1}{C_L L_L} = 0 \tag{3}$$

2.3. CRLH CPW TL

By repetition of the unit cell we can realize a CRLH CPW TL. Analysis of propagation can be derived from the characteristics of the basic cell. Using the equivalent circuit model of Figure 1(c), the dispersion relation of the CRLH TL can be calculated using:

$$\cos(\beta\ell) = 1 - \frac{\omega^2}{2}\left(L_R - \frac{1}{C_L\omega^2}\right)\left(C_R - \frac{1}{L_L\omega^2}\right) \tag{4}$$

The analytical study for the previous dispersion relation shows that the dispersion diagram for our CPW structure has CRLH characteristics. It can be seen from the dispersion diagram (Figure 3) that the dispersion curve represents unbalanced propagation properties. The unbalanced dispersion curve consists of a stopband at lower frequencies below 3 GHz, followed by a left handed passband in the frequency range approximately from 3 up to 6.5 GHz. After that, another stop band appears up to more than 7.9 GHz, and finally a right handed passband at higher frequencies is observed.

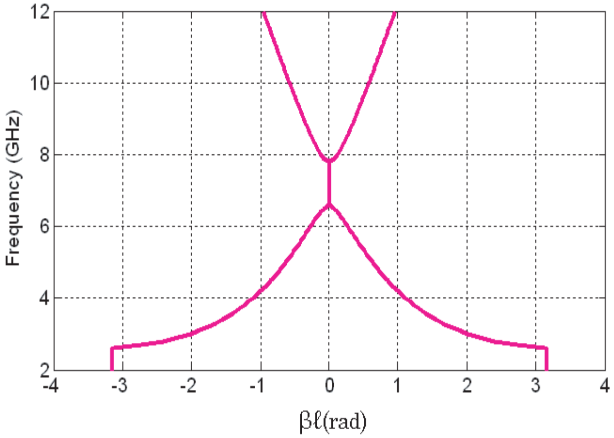


Figure 3. The calculated dispersion diagram of the CRLH CPW. The parameters used are $L_R = 0.93\,\mathrm{nH}$, $L_L = 1.04\,\mathrm{nH}$, $C_R = 0.39\,\mathrm{pF}$ and $C_L = 0.64\,\mathrm{pF}$.

(a) (b)

Figure 4. (a) Picture of the CRLH CPW TL. (b) Picture of the CRLH CPW ZOR.

3. FABRICATION

The proposed CRLH CPW ZOR resonator and CRLH CPW TL are fabricated on alumina substrate ($\varepsilon_r \approx 10$, thickness $h = 635\,\mu\text{m}$). For practical application, our CRLH CPW TL is realized with five cells. The conductors are made of copper and are elaborated by sputtering followed by lift-off process. The thickness of metallization is approximately equal to $5\,\mu\text{m}$. The CRLH CPW TL is presented on Figure 4(a), and the CRLH CPW ZOR on Figure 4(b). Measurements are made using a coplanar probe tester. In order to be compatible with the size of the probes, access lines ($50\,\Omega$) have been tapered to connect to the central devices (see Figure 4).

4. NUMERICALS AND MESUREMENTS RESULTS

First, to verify the validity of the circuit model of the CRLH CPW ZOR, full wave simulation (finite element method) and measurements are performed. The equivalent circuit model is also simulated using a microwave circuit simulator.

All approaches are then compared. The evolutions of the transmission and reflection parameters with the frequency are presented in Figure 5 and Figure 6 respectively. All results are in good agreement. The small variation between the measured resonant frequency, 3D simulated and analytical value calculated from (2) is due to the approximation done in the analytical model were losses are neglected.

At the resonant frequency, the measured device has an insertion loss of the 2.7 dB and a return loss better than 13 dB.

In the case of the composite right-left-handed transmission line, the transmission and the reflection parameters are plotted in Figure 7 and Figure 8 respectively. A good agreement can be observed between simulation and measurement. Analyzing the results, it is obvious that the line has two different transmission bands. The first band lies between 3.55 to 4.35 GHz where the measured insertion loss is better than 3 dB. In this band, the wave is left-handed, the phase constant decreases and the wavelength increases with respect to the frequency. In the second transmission band (between 7.65 to 9.60 GHz), the measured insertion loss is about 5 dB. The measured phase allows us to conclude that wave is right handed.

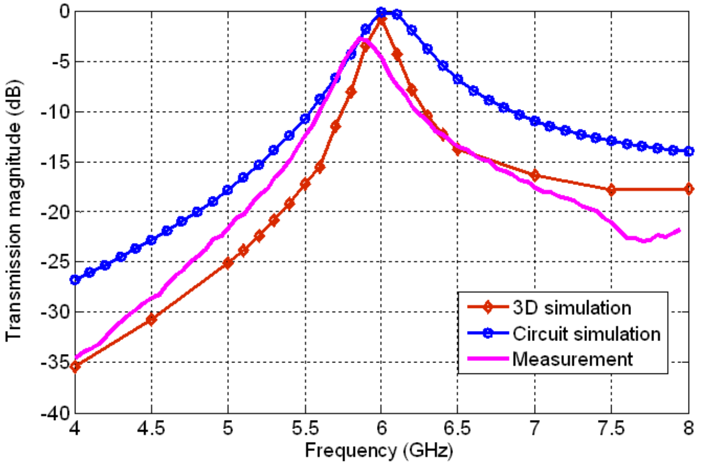


Figure 5. S transmission parameters of the CRLH CPW ZOR on the alumina substrate.

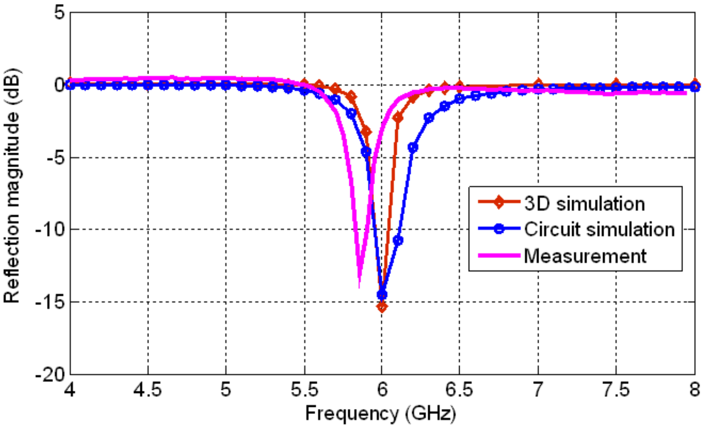


Figure 6. S reflection parameters of the CRLH CPW ZOR on the alumina substrate.

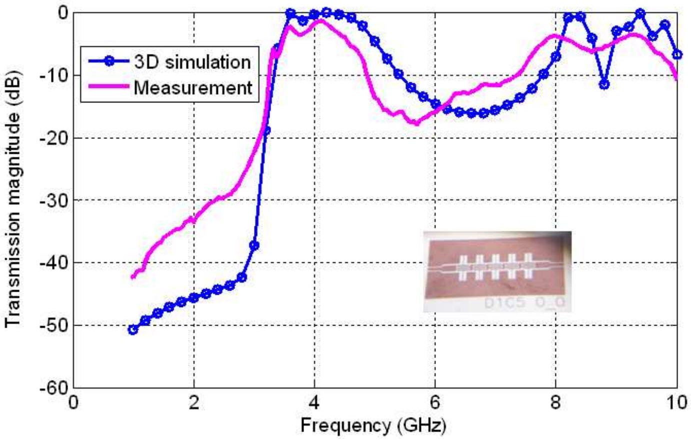


Figure 7. Transmission parameters of the CRLH CPW TL (five cells).

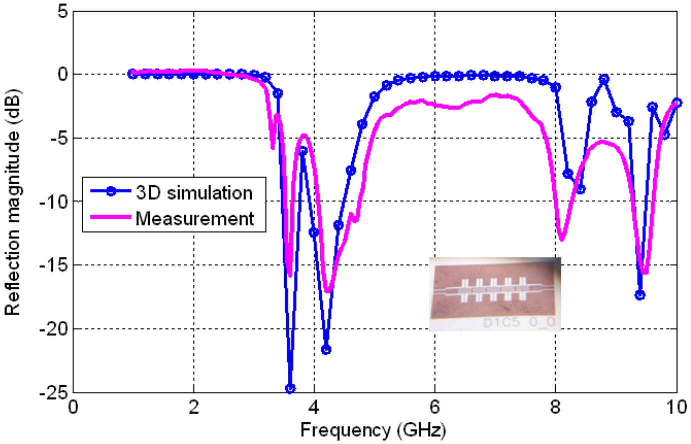


Figure 8. Reflection coefficients of the CRLH CPW TL (five cells).

It can be observed that the analytical analysis correctly predicts stop bands and passbands. However the limit frequencies of the bands are not completely accurate, due to approximations done in the analytical study.

5. CONCLUSION

Based on the unit cell with have proposed, a CRLH CPW transmission line with five elementary cells on alumina substrate has been realized. Measurements clearly show left-handed behavior between 3.5 and 4.5 GHz. Measured insertion loss is less than results presented in [9]. With a single cell, a CRLH CPW ZOR has been numerically studied, realized and verified experimentally. Insertion loss of 2.7 dB has been measured. The resonator we have proposed allows a reduction of 79% of its size compared to the conventional half-wavelength CPW resonator at 5.85 GHz, and its measured quality factor is 108.

A different approach from [10] has been used to model the problem. The unit cell was modeled by an electrical circuit and results show a very good agreement with measured data. The simplified circuit model gives predictive results, proving that this modeling is powerful for engineering. Modeling is valid but losses must now be included to complete the model and to allow optimization of insertion loss. Then more distant objective can be to add tuneability using materials like ferroelectrics or magnetic materials.

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