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Improving MM-Wave Left-Handed Transmission Line Antenna by Stub Matching

Sajin Gheorghe Ioan(1), Mocanu Iulia Andreea(2), Carp Mihaela(1)
(1) National Research Institute for Micro technologies, IMT Bucharest, Microwave Laboratory, Erou Iancu Nicolae Street 126A (32B), 077190 Bucharest, Romania
(2) Polytechnic University Bucharest, Faculty of Electronics, Telecommunications and Information's Engineering, B-dul Iuliu Maniu 1-3, 061071, Bucharest, Romania

Abstract*—The paper presents a method to improve the return loss (RL) of a CoPlanar Waveguide (CPW) Composite Right/Left-Handed (CRLH) zeroth-order resonance (ZOR) mm-wave antenna. When measured, the radiating structure has a complex impedance and has to be matched to the characteristic circuit impedance $Z_0 = 50\ \Omega$. The working frequency is $f = 40$ GHz and the initial RL value without matching was $/S_{11}/ = 16.21$ dB. In order to match the structure, there is needed to compensate the reactive part of the complex impedance with a short-ended parallel reactive stub of length L_m, implemented at a suitable distance d_m from the radiating structure. With the matching circuit introduced, the return loss at the feeding line became $/S_{11}/ = 43.50$ dB, drastically improved, which demonstrates the effectiveness of the matching process. The antenna gain improve from $G_i = 2.017$ dBi in the unmatched condition to the $G_i = 2.76$ dBi and the radiation pattern in the transverse antenna plane remain almost unchanged, excepting a prominent secondary lobe for the matched antenna due to the influence of the radiation from the matching stub.

***Index Terms*—Left handed ZOR antenna, CoPalanar Waveguide, impedance matching**

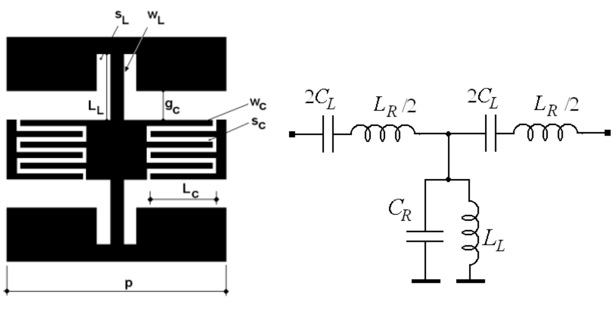
I. INTRODUCTION

The Composite Right/Left-Handed (CRLH) artificial transmission line was introduced in 2002 as an application of the metamaterial concept in the microwave and mm-wave frequency domain [1]. The domain was, further, developed in [2]. The CRLH is an artificial TL obtained by combining the RH behavior of the classical TL with the LH behavior of a complementary line modeled by series connected capacitors and parallel connected grounded inductors. Such a line acts as left handed transmission lines (LH-TL) at frequencies where the guided wavelength is larger than the cell size and as right handed transmission lines (RH-TL) at high frequencies, where the guided wavelength is smaller than the cell size. This particular frequency characteristic of the CRLH TL has been exploited in the development of many types of devices such as coupled-line directional couplers, filters and resonators and various types of antennas. Concerning CRLH antennas, a complete description of the most practical such devices was done in [3]. A lot of constructions on various substrates, with different functional properties and with a lot of potential applications were designed, processed and measured, some of the more recent being [4] ... [8]. It is known that matching a radiating structure is essential for the proper functioning of the microwave and mm-waves antennas, a high level of reflection loss being fatal for the antenna efficiency. In this respect, a method of measuring the impedance of the radiating section of a CRLH antenna and for matching it to the circuit characteristic impedance Z0 = 50 Ω was developed using short-circuit transmission line stubs [9], [10]. In this paper we measure, analyze and compare the functional parameters (RL, resonating frequency, and gain and radiation characteristic pattern) of both unmatched and matched CRLH antennas. The purpose of this study was to see to what extent these parameters were improved in order to allow antenna using in some mm-wave integrated circuit application.

II. MATCHING METAMATERIAL ANTENNA

A. Antenna layout

The studied antenna is a ZOR CPW construction, made of an array of three CRLH cells, each one having a symetrical T circuit topology. Each cell is made of two series connected interdigital capacitors and two parallel connected short-ended CPW transmission lines as inductive stubs. The layout and the equivalent circuit of such CRLH cell is presented in Fig.1 (a) and (b). Here, $2C_L$ and $L_R/2$ are the equivalent capacitance and the equivalent inductance of the series capacitor, while C_R and L_L are the equivalent parallel capacitance and the equivalent parallel inductance, respectively, of the two CPW transmission lines.



(a) **(b)**

Fig.1. Layout of the CPW CRLH elementary cell used in antenna construction (a) and its equivalent circuit (b).

In order to obtain a ZOR antenna, an open circuit series of the three CRLH cells was used. Applying the design conditions known in literature [2], [3], we designed a

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balanced CRLH circuit on silicon ($\varepsilon_{r.Si}$ = 11.9) for f_{sh} = 40 GHz with the following geometrical dimensions of the device layout, see Fig.1 (a):

- Interdigital capacitor: w_C = 8 μm; s_C = 7 μm; l_C = 250 μm; g_C = 65 μm; number of digits = 10;
- Inductive short-ended stub: l_L = 212 μm; w_L = 42 μm; s = 10 μm

With these dimensions, the obtained values for the components on silicon were L_R = 0.4 nH, L_L = 0.08 nH, C_R = 200 fF and C_L = 18 fF.

Here, the symbols f_{sh}, L_R, L_L, C_R and C_L are those usually used in the literature [2], [3] for CRLH cell description. The antenna layout and dimensions were presented in [9], Cap.2. A 3450 μm length feeding line (with a CPW configuration computed to match Z_0 = 50 Ω characteristic impedance of the mm-wave circuit), was attached to the antenna structure. This geometry allows connecting the antenna to the mm-wave circuit and, also, allows subsequent mounting of the antenna structures on a dedicated test fixture for measuring the gain and radiation characteristic. The antenna structure was processed on a 500 μm thickness silicon substrate with a rezistivity of 5 kΩcm and having a 1 μm SiO_2 layer ($\varepsilon_{r.SiO2}$ = 3.9) grown by thermal oxidation on its surface. The processing technology was a standard wet etching photolithographic process of a 0.6 μm Au/500 Å Cr metallization evaporated on the SiO_2 layer surface. A photo of a processed CRLH antenna structure is presented in Fig.2. Between planes AA' and BB' there is the radiating CPW CRLH structure and between the planes AA' and CC', is the feeding line.

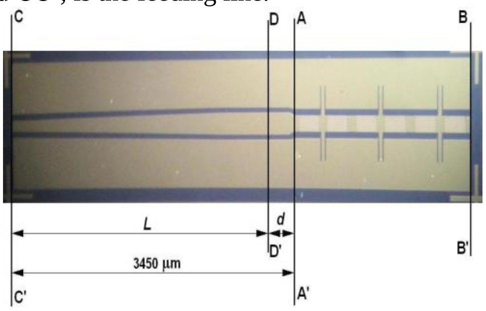
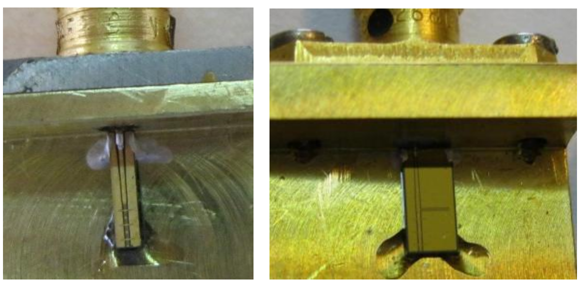


Fig.2. Optical microscopy photo showing the unmatched CRLH antenna



(a) (b)

Fig.3. Unmatched (a) and matched (b) metamaterial antenna structures mounted on test fixtures

After on wafer measurement of the resonant frequency and return loss, the silicon wafer was diced with an abrasive diamond wheel tool, in order to obtain separate antenna chips. These discrete structures were mounted on dedicated test fixtures, as in Fig.3, in order to measure antenna directivity characteristic and gain. The return loss and resonant frequency measured for unmatched device (Fig.2 and Fig.3 (a)) demonstrate a $|S_{11}|$ = 16.21 dB at 39.26 GHz, meaning a VSWR = 1.37 that is a rather modest performance. The challenge was to raise the antenna efficiency by reducing the RL level. A way to obtain this is to properly match the impedance of the CRLH antenna radiator to the characteristic impedance Z_0 = 50 Ω of the mm-wave circuit. The steps used in order to match the antenna radiating section are the following.

B. Deriving the impedance of the radiating structure

The impedance $Z_S = R_S + jX_S$ of the antenna radiating structure at the plane AA', see Fig. 1 (a) was derived using a vector network analyzer (VNA) in combination with a Süss Microtek on-wafer measurement equipment. The applied method was to consider matching stubs on the antenna feeding line, cf. [10]. In Fig.4 (a) it is shown the processed CRLH antenna having applied the on-wafer measurement probe on the feeding line. The measurement runs as follows:

- The probe-tip of the Süss Microtec on-wafer measurement equipment is placed at the AA' plane at the input in the radiating section of the CRLH antenna.
- Then the probe-tip is moved in as small as possible steps in ***d*** direction as in Fig.3. In this time S_{11} is continuously measured.
- As the distance ***d*** increase, the remaining length ***l*** = 3450 μm – ***d*** to the CC' plane, that acts as an open circuit stub, decreases. Simultaneously with this displacement, S_{11} parameter changes its value.
- Finally we find a point on the antenna feeding line at a plane DD' defined by value pair ***d*** and ***L*** where S_{11} reaches a minimum. In this point the impedance Z_S of the CRLH antenna radiating structure defined at plane AA' is matched to the characteristic impedance Z_0 = 50 Ω. The pair made of d and L is retained.
- The position of the probe-tip at the plane DD' is equivalent with an unknown load $Z_S = R_S + jX_S$ fed by a line with the length ***d*** from a generator located at DD' plane on the antenna feeding line. In the same plane DD', but parallel on the antenna access line, there is an open circuit stub with the length ***L***. The equivalent circuit of this arrangement is presented in Fig.3 (b).

In our measurements ***d*** = 150 μm and the stub length ***L*** = 3300 μm. The unknown load $Z_S = R_S + j\times X_S$ of the CRLH cells of antenna radiating structure was computed with the relationship (1) and (2) derived from the transmission line theory:

$$R_S = Z_0 \frac{b}{1+ab}\left[a + \frac{b - a - a^2 b}{b^2 + (1+ab)^2}\right] \qquad (1)$$

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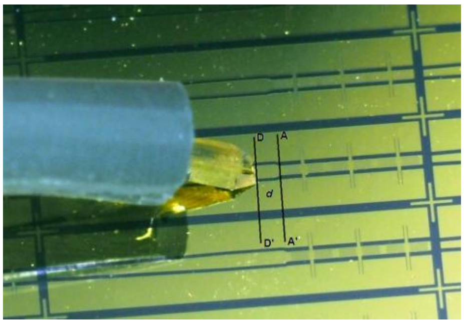
$$X_S = Z_0 \frac{b - a - a^2 b}{b^2 + (1+ab)^2} \qquad (2)$$

Where: a = tan (βd); b = cot (βL); β = 2π/λ.



(a)

Fig.4 (a). Antenna with on-wafer measurement probe-tip contacting the feeding line at distance d from the input in the radiating structure (plane AA')

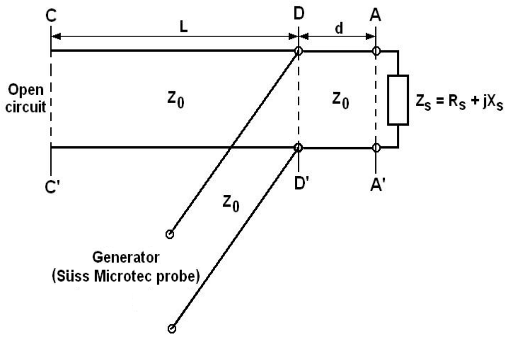


Fig.4 (b). Equivalent circuit of the arrangement in Fig.4 (a).

In all formulas, losses are neglected and the matching stub is considered purely reactive. After measurements and computing, the following data were obtained: ***d*** = 150 µm, ***l*** = 3300 µm, R_S = 48.53 Ω, X_S = -16.96 Ω.

C. Matching CRLH antenna

In order to match the radiating section of the CRLH antenna we will use a short-ended reactive stub, cf. [10]. In this respect, we must compute the distance dm to the point of matching stub implantation and the length Lm of a matching short-ended stub. A short-ended stub is preferred for technological reasons and also to avoid the radiation at the line end. The distance d_m where the short-ended stub is implanted on the feeding line, is computed, cf. [10], using relation (3) deduced from the general theory of transmission lines. The two solutions of (3) correspond to the first two distances dm from the load where the matching stub are possible to be implanted. Usually, the lowest dm value is chosen.

$$d_{m1,2} = \frac{\lambda}{2\pi} \arctan \left[\frac{X_S Z_0 \pm \sqrt{(X_S Z_0)^2 - \left(R_S Z_0 - Z_0^2\right)\left(R_S Z_0 - R_S^2 - X_S^2\right)}}{R_S Z_0 - Z_0^2} \right] \qquad (3)$$

Once the value of d_m was found, formula (4) is used in order to obtain the length of the short ended matching stub, L_m.

$$L_m = \frac{\lambda}{2\pi} \operatorname{arcctg} \frac{aR_S^2 - (X_S + aZ_0)(Z_0 - aX_S)}{R_S^2 + (X_S + aZ_0)^2} \qquad (4)$$

Knowing the previously found CRLH antenna impedance ZS = $R_S + j \times X_S$ and applying formulas (3) and (4), the layout dimensions of the matching problem is found as: d_m = 148 µm, L_m = 1460 µm. A photo showing the modified feeding line layout and the equivalent circuit are shown in Fig.5 (a) and (b) respectively.

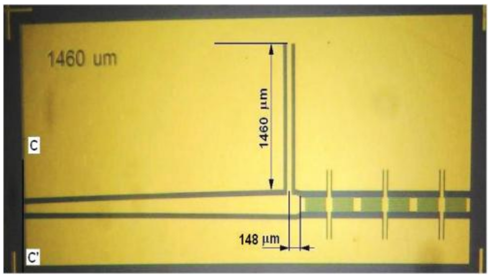


Fig.5 (a). Optical microscopy photo showing the matched CRLH antenna

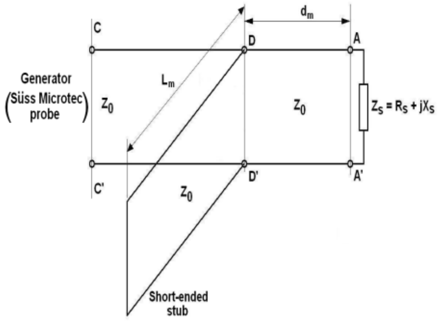


Fig.5 (b). Equivalent circuit of the CRLH antenna modified feeding line layout

As expected, the length Lm of the matching short-ended stub is λ/4 shorter than the previously measured open-circuit stub.

III. MEASUREMENTS OF UNMATCHED AND MATCHED CRLH ANTENNAS

A. Return loss and resonant frequency

The return loss (RL) and resonant frequency measurement on antenna structures at the input of the feeding line at CC' plane – see Fig. 1 (a) were made on-wafer with an Anritsu 37397D vector network analyzer (VNA) combined with a Süss Microtec PM5 on-wafer characterization equipment provided with a ground-signal-ground (GSG) probe-tips with a 150 µm pitch. The graph of the measured RL of the unmatched CRLH antenna in the 35 GHz – 45 GHz frequency range is shown in Fig.6 (a). As it can be seen, for the unmatched CRLH antenna the return loss and resonant frequency are $|S_{11}|$ = 16.21 dB at 39.26 GHz, meaning a

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VSWR = 1.37. The slight shift from the designed frequency (f = 39.26 GHz instead of f = 40 GHz) is due to some over etching of the metal during the technological process.

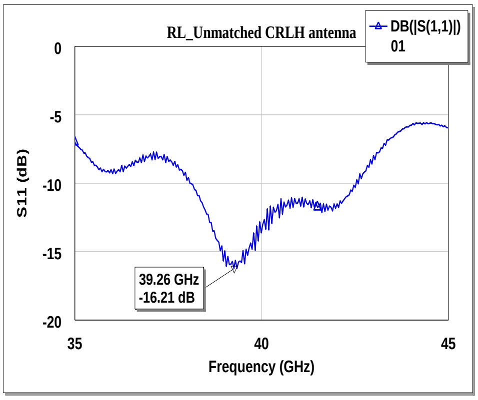

Fig.6 (a). The measured RL for the unmatched CRLH antenna in the 35 GHz ... 45 GHz frequency range

Concerning the matched CRLH antenna, in order to appreciate the effectiveness of the matching process, the RL at the input feeding line CC' was both simulated and measured for a frequency sweep between 35 GHz and 45 GHz. The simulated and measured RL and resonant frequency are presented in Fig.5 (b). The results demonstrates a RL at the CC' input plane $|S_{11}|$ = 43.50 dB at the frequency f = 40.15 GHz, marking a drastic improvement of the antenna matching.

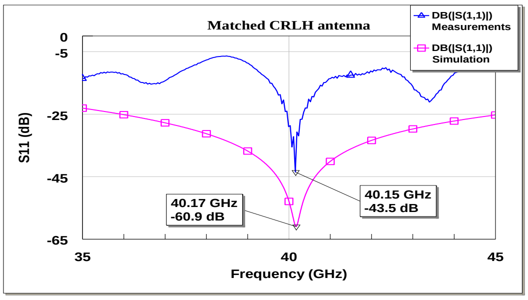

Fig.6 (b). Simulated and measured RL for the CPW CRLH antenna in the 35 GHz ... 45 GHz frequency range after matching with a short-ended stub

B. Radiation characteristic

The radiation pattern measurements were made at the frequency f = 40 GHz, both in transverse and longitudinal planes using a spectrum analyzer Anritsu MS2668C, a frequency generator Agilent E8257D PSG and a Millitech SGH-22 horn antenna as receiving device. The measuring setup allows the CRLH antenna to rotate both in transversal and in longitudinal planes. The received powers at different azimuths were rated to the maximum value. In order to measure the radiation characteristics the silicon wafers supporting both unmatched and matched CRLH antennas were diced and the obtained antenna structures were mounted on dedicated test fixtures as it is shown in Fig.3 (a) and (b).

The radiation characteristic in the transversal plane for the unmatched antenna structure is shown in Fig.7 (a). According to Fig.7 (a), the azimuthally values of the -3 dB transversal beam of the unmatched antenna are between approx. +8^0 and -10^0 meaning a beam width of approx. 18^0. The maximum value of the secondary lobes occurs at an azimuth of approx. -47^0 and have the amplitude of -5.2 dB.

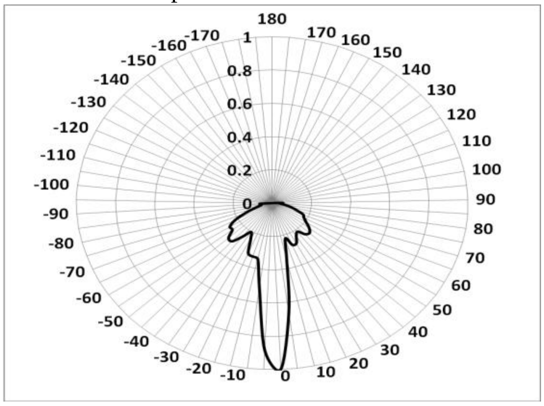

Fig.7 (a). Radiation pattern in transversal plane of the unmatched CRLH antenna

The radiation characteristics in the transversal plane for the matched CRLH antenna is shown in Fig. 7 (b).

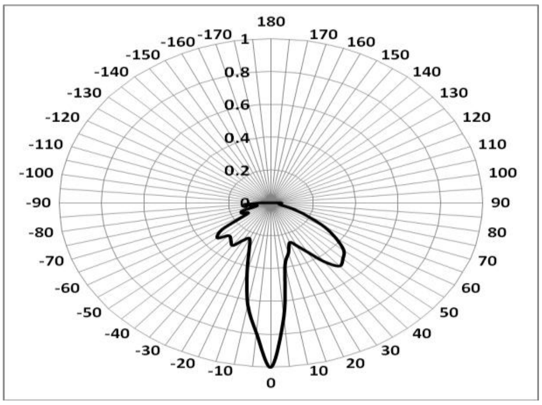

Fig.7 (b). Radiation pattern in transversal plane of the matched CRLH antenna

The -3 dB transversal beam width of the matched antenna is approx. 21^0 between approx. +9^0 and -12^0. It is to note the existence of an asymmetrical high value secondary lobe at an azimuth of approx. +40^0 with a maximum value, also, of approx. -3 dB. The secondary lobes in the negative azimuth domain of the antenna radiation pattern are in the same position and with the same amplitudes as in the case of the unmatched device. This entitled us to consider that the high value of the secondary lobe in the positive azimuth domain is due to the influence of the matching stub. In order to minimize this influence, the layout of matching stub may be designed in a folded form, parallel with the feeding line at a distance that makes coupling to be insignificant. The shape of the radiation characteristic in the longitudinal plane is presented in Fig.8 (a) and (b) for both the unmatched and matched CRLH antennas. The positive values are in the antenna front-end direction. All measured values at different angles were rated

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to the value at the centre of the antenna structure normal to its surface.

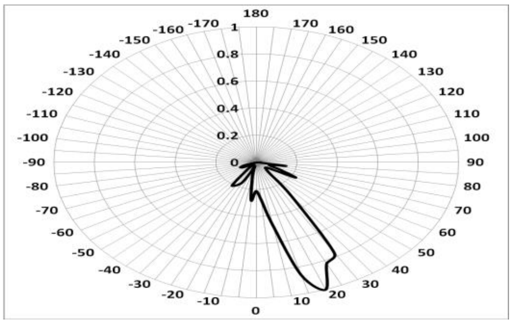

Fig. 8 (a). Radiation pattern in longitudinal plane of the unmatched CRLH antenna

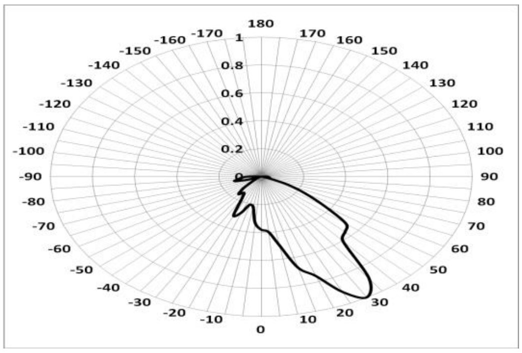

Fig.8 (b). Radiation pattern in longitudinal plane of the matched CRLH antenna

One may see that for the unmatched antenna the maximum radiation occurs in a direction of about 15^0 toward antenna front-end. For the matched device this maximum radiation is, also, in the direction toward antenna front-end but at an angle of approx. 30^0.

C. Gain

The antenna gain was obtained using De Friis relation (1) for two identical antennas:

$$\frac{P_r}{P_t} = G_i^2 \left(\frac{\lambda}{4\pi R}\right)^2 \qquad (5)$$

Where:

- P_t = power transmitted by emitting antenna,
- P_r = power at the receiving antenna,
- G_i = antenna gain with respect to isotropic;
- λ = wavelength,
- R = distance between emitting and receiving antenna (in the same units as the wavelength).

After some manipulations, the formula to express the gain in (dBi) is obtained:

$$G(dBi) = 10\log_{10}\left(\frac{4\pi R}{\lambda}\sqrt{\frac{P_r}{P_t}}\right) \qquad (6)$$

The emitting and the receiving antennas are identical. The gain for both unmatched and matched antennas were evaluated at f = 40 GHz (λ = 7.50 mm), the distance between the two antennas being R = 100 mm. For the unmatched CRLH antenna the measured data were, respectively, power at the emitting antenna: P_t = 0,285 mW and power at the receiving antenna P_r = 2.57E-05 mW. This means a gain for the unmatched CRLH antenna of $G_{i,unmatched}$ = 2.017 dBi. After that, the antenna gain was evaluated following the matching process, using the same measurement conditions, namely λ = 7.50 mm / f = 40 GHz and R = 100 mm. The power level at the emitting antenna was maintained at the value P_t = 0,285 mW and the power measured at the receiving antenna was P_r = 3.62E-05 mW. In these conditions, the matched CRLH antenna gain was $G_{i,matched}$ = 2.76 dBi demonstrating a net improvement following the matching process.

IV. CONCLUSION

The paper presents a matching method of a CRLH antenna to the characteristic impedance of a mm-wave circuit, by inserting a reactive short-ended stub on the antenna feeding line. The length and position of matching stub were obtained as $\boldsymbol{d_m}$ = 148 μm and $\boldsymbol{L_m}$ = 1460 μm. The measured RL was improved from $|S_{11}|$ = 16.21 dB to $|S_{11}|$ = 43.50 dB. The transversal radiation pattern is similar in both cases excepting a prominent secondary lobe for the matched antenna due to the radiation from the matching stub. The -3 dB lobe width is approx. 18^0 for the unmatched device and approx. 21^0 for the matched one. In the longitudinal plane the radiation pattern at f = 40 GHz is bended toward antenna front-end with 15^0 for the unmatched antenna and with 30^0 for the matched one. Following the matching process, the antenna gain was raised from Gi = 2.017 dBi in the unmatched condition to the G_i = 2.76 dBi in the matched condition. Although the method was applied to match a CRLH CPW antenna, it may be also applied to a wide variety of metamaterial devices. It should be noted that the above problems may also be solved using the Smith chart, but the results are less accurate.

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AUTHOR'S PROFILE

Gheorghe Ioan Sajin is M.Sc. in electronics from 1972 and Ph.D. in radiotechnics and radio communications from 1990 at "Politechnica" University of Bucharest (Romania). Now he is with National Research Institute for Micro technologies, IMT Bucharest, Romania and associate professor of "Politehnica" University in Bucharest (since 1991) and of "Valahia" University in Targoviste (since 2002).His work is in the microwave and millimeter wave domain being specialized in microwave propagation in magnetically biased ferrites, technology for microstrip lines configurations for microwave circuits, biological effects of electromagnetic waves and microwave devices for bio-medical applications and left-handed devices for microwaves and mm-waves applications.

He has 20 scientific papers of which 13 papers in ISI ranked technical reviews. Also, he has more than 100 papers indexed in International Data Basis for conference Proceedings. Its scientific production include, also, 16 technical books and book chapters and five patented inventions.

Gheorghe Ioan Sajin is reviewer and scientific referent for more reviews as PIER & JEMWA, International Journal of Physical Sciences, Romanian Journal of Biophysics and member in Advisory Board of Acta Technica Napocensis, Archives on Physiology and Biochemistry and other

He was, also, paper reviewer and scientific referent for the some scientific conferences as: EUROCON 2012, Conference Mediterranean Electro technical Conference, MELECON, 2010 International Conference on Electronics, Computers and Artificial Intelligence ECAI 2009, Asia – Pacific Microwave Conference (APMC) in 2008 and European Medical & Biological Engineering Conference (EMBEC), 2005. He was chairman of 5 sections in international scientific congresses.

Gheorghe Ioan Sajin is member of IEEE MTT society and, also, member of EuMA.