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IMPEDANCE MEASUREMENT OF MILLIMETER WAVE METAMATERIAL ANTENNAS BY TRANSMISSION LINE STUBS

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Abstract—The paper deals with a method to measure the unknown impedance of metamaterial antenna made in Composite Right/Left-Handed (CRLH) Co Planar Wavegiude (CPW) technique for the millimeter wave frequency domain. The method uses a measurement setup made of a high frequency vector network analyzer (VNA) and an on-wafer characterization equipment. The measurement procedure consists in placing the probe-tip of the on-wafer equipment and to move it along the feedline of the antenna radiating structure until the minimum values of the return loss is reached. Using the facilities of the on-wafer equipment (micrometric screws to move the probe-tips) and knowing the geometrical dimensions of the antenna structure, the dimension and the position of an equivalent open-circuit matching stub are obtained. Then, using relationships derived from the transmission lines theory, real and imaginary parts of the unknown antenna impedance are computed.

1. INTRODUCTION

A Composite Right/Left-Handed (CRLH) transmission line (TL), introduced in 2002 [1], consists of series capacitors and shunt inductors associated with their parasitic series inductances and shunt capacitances. CRLH structures act 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.

The planar microstrip and coplanar waveguide CRLH TLs have allowed the development of many novel microwave and mm-wave

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circuit components such as multiband devices, enhanced broadband coupled-line couplers, resonators, reflectors and antennas [2, 3].

Concerning the metamaterial antennas, a lot of constructions on various substrates, with different functional properties and many applications were described, some of the more recent being [4–8]. Much attention has been paid to the electrical characterization of these devices [9–11]. One of the problems to be solved consists in matching the impedance of the CRLH antenna radiating structure to the characteristic impedance Z_0 of the microwave or millimeter wave circuit, where usually $Z_0 = 50\,\Omega$. Due to the specific properties of the metamaterial configuration of these components, the measurement of the CPW CRLH structure impedance is required in order to successfully design, process and use such a device.

Measuring this impedance is necessary in building complex integrated circuits on semiconductor substrate. In these circuits, the antenna itself is integrated along with the other passive and active elements.

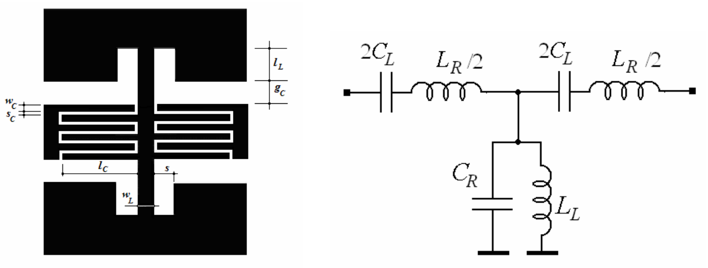
It is known that an insufficient matching of the radiated structure results in power loss through reflexion at the antenna input. This loss can be fatal to the good functioning of microwave and mm waves integrated circuits. Knowing the input impedance in the radiant structure of the antenna allows for taking correcting measures regarding designing and micro-processing of these devices. Avoiding the mentioned losses requires an "in situ" measurement of the already microprocessed CRLH antenna.

The method presented in this paper can be applied particularly to planar circuits in CPW configuration. In addition, the presented method allows using computation programs for calculating the input impedance in the radiating structure. Also, this method can be used to quickly adapt the technological execution masks of the CPW CRLH antennas structures.

2. METAMATERIAL ANTENNA CONSTRUCTION

To illustrate the solving of this problem, the construction of a CPW CRLH zeroth-order resonant antenna was used. The radiant antenna structure consists of an open-ended array of three CRLH cascaded cells, each one having a T-circuit topology. Each cell consists of two CPW interdigital capacitors and two parallel connected short-ended CPW transmission lines as in Figure 1(a).

The equivalent circuit of the CRLH cell is presented in Figure 1(b) where $2C_L$ and $L_R/2$ are the equivalent capacitance and the equivalent inductance of the series capacitor, while C_R and L_L are the



(a) (b)

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

equivalent parallel capacitance and the equivalent parallel inductance, respectively, of the two CPW transmission lines.

Applying the design conditions and mathematical relations given in literature [3] the CRLH circuit was designed to be balanced, with the series resonance frequency equal to the shunt resonance frequency (f_{sh}).

$$f_{sh} = \frac{1}{2\pi\sqrt{L_L C_R}} \tag{1}$$

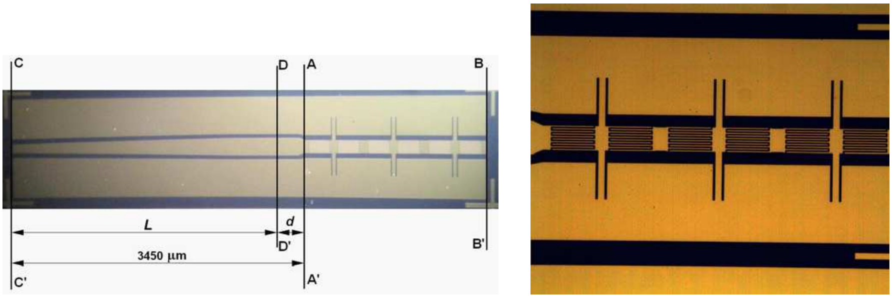
Two metamaterial antenna structures in CPW configuration were used in experiments concerning measurement of the unknown impedance.

The first one, marked as C2L15_150 was made on silicon substrate having the following CRLH cell dimensions (see Figure 1):

- Interdigital capacitors: $w_c = 8\,\mu\text{m}$; $s_c = 7\,\mu\text{m}$; $l_c = 250\,\mu\text{m}$; $g_c = 65\,\mu\text{m}$; number of digits = 10;
- Inductive short-circuit stub: $l_L = 212\,\mu\text{m}$; $w_L = 42\,\mu\text{m}$; $s = 10\,\mu\text{m}$.

The antenna structures were processed on a high resistivity ($5\,\text{k}\Omega\text{cm}$) silicon substrate with $500\,\mu\text{m}$ thickness and permittivity $\varepsilon_{\text{r.Si}} = 11.9$. On this silicon wafer a layer of $1\,\mu\text{m}$ SiO_2 with a permittivity $\varepsilon_{\text{r.SiO2}} = 4.7$ was grown by thermal oxidation. The technological process for the antenna manufacturing consists of a standard wet etching photolithographic process of $0.6\,\mu\text{m}$ Au/500 Å Cr metallization obtained by evaporation on the surface of the silicon wafer. The working frequency of this antenna is 40 GHz.

The second one, marked as C1L7_260, was made on a AlSiMag 614 ceramic substrate with $600\,\mu\text{m}$ thickness and permittivity $\varepsilon_{\text{r.ceramic}} = 9.6$. This second antenna has the same dimensions as the previous one. The working frequency of C1L7_260 antenna is 32 GHz.



(a) (b)

Figure 2. Optical microscopy photo showing (a) the whole CRLH antenna and (b) the device radiating structure.

For both antenna structures, the feedline has 3450 µm of length and the CPW geometry computed to match the 50 Ω characteristic impedance of the measuring system. This geometry allows subsequent mounting of the antenna structures on a dedicated test fixture for measurement of the radiation lobe and of the gain.

An optical microscopy photo of a metamaterial whole processed antenna as well as a detail of the interdigital capacitors and the inductor lines structure is presented in Figures 2(a) and (b).

The constitutive antenna parts (see Figure 2(a)) are (i) the radiating CPW CRLH structure between planes AA' and BB' and (ii) the feedline between planes AA' and CC'. It is noted that the plane AA' defines the input in the antenna radiating structure represented by the first interdigital capacitor of the first CRLH cell.

After on-wafer measurement of the S_{11} parameter, the silicon or ceramic wafer is cut with a diamond abrasive cutting-off wheel tool, thus obtaining separate antenna chips. These discrete structures are mounted on dedicated test fixtures for a subsequent directivity characteristics and antenna gain measurement.

3. MEASURING THE IMPEDANCE OF THE ANTENNA RADIATING STRUCTURE

Finding the impedance $Z_s = R_s + jX_s$ by its real and imaginary parts, R_s and X_s respectively, is made by applying the method of matching stubs on the antenna feedline. In this respect was used a measuring setup composed of a high frequency vector network analyzer (VNA) in combination with an on-wafer characterization equipment. Figure 3 shows one of the processed CRLH antenna structures having applied

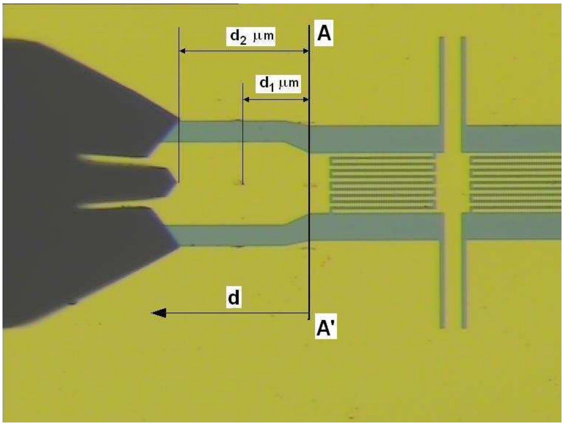


Figure 3. Antenna feedline with on-wafer measurement probe placed at two different distances, d_1 and d_2.

the on-wafer probe-tip to the feedline. In this example, the probe-tip was applied successively at two distances d_1 and d_2 from the plane AA'. The traces of the probe-tip on the antenna gold metallization can be seen.

The measurement procedure runs as follows: the probe-tip of the on-wafer measurement equipment is placed at the AA' plane and then are continuously moved in d direction (see Figure 3) measuring the S_{11} parameter until a minimum S_{11} is obtained at a plane DD' (see Figure 2(a)). This minimum is required in order to make the measurement setup independent from the length of the feedline.

The location of the probe-tip at the plane DD' is equivalent to an unknown load Z_s fed by a line with the length d from a generator located at DD' plane on the antenna access line.

In the same plane DD', parallel on the antenna access line, there is an open circuit stub with length L. Its length comes from the whole length $d + L = 3450\,\mu\text{m}$ of the antenna feedline (see Figure 3) minus the distance d between planes AA' and DD' where the probe-tip are located. The equivalent geometry of this placement of probe-tip is shown in Figure 4.

As the value of d increases, the length L of the open circuit stub decreases, and it is possible to find a point defined by d and L value pair where the return loss S_{11} reaches a minimum. This is the point where the impedance Z_s of the antenna radiating structure is matched to a circuit having the $Z_0 = 50\,\Omega$ characteristic impedance.

In this arrangement, starting from $d = 0\,\mu\text{m}$ at the plane AA' and using the moving possibilities of the on-wafer measuring equipment, the

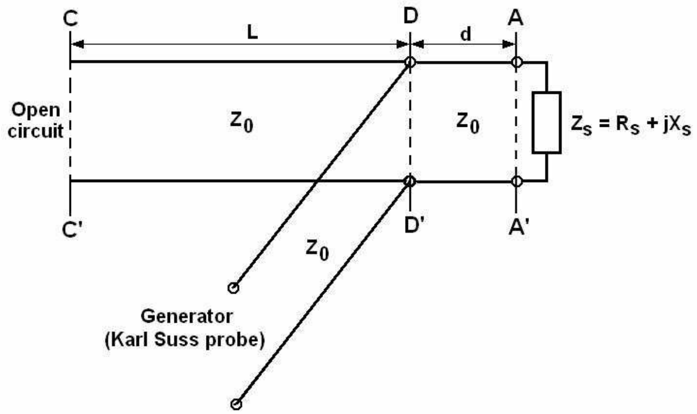
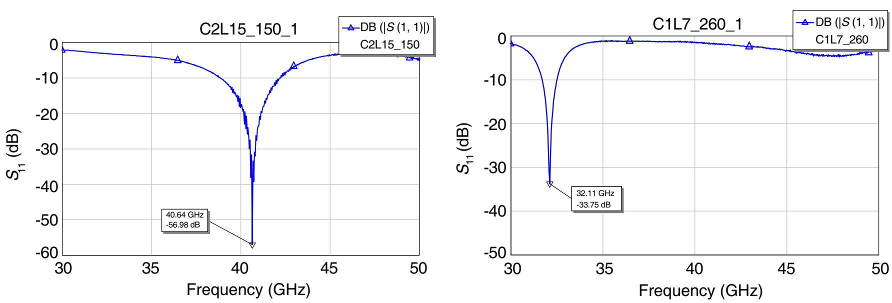


Figure 4. Equivalent geometry of the probe-tip position in Figure 3.



(a) (b)

Figure 5. Return loss measurement of the of CRLH antenna radiating structures made (a) on silicon and (b) on alumina substrate.

probe-tip was moved in d direction in increments of 10 µm (minimum allowed by the probe micrometric screw). Using this technique, measurements of S_{11} on two samples of CPW CRLH antennas were made. Measurement results show the position d and the length L of the open-circuit stub in the point of maximum matching. The measured results for the two CRLH antenna structures previously presented are shown in Figures 5(a) and (b). The frequency sweeping domain was the same: 30 GHz, ..., 50 GHz.

The measurements show that the minimum return loss for the antenna C2L15_150_1 made on silicon is obtained for a distance $d = 150\,\mu\text{m}$ that means a remaining length for the open-circuit stub $L = 3300\,\mu\text{m}$. The obtained matching performance was $S_{11} = -56.98\,\text{dB}$

at a frequency $f = 40.64\,\text{GHz}$. For the antenna C1L7_260_1 made on alumina substrate the minimum return loss is obtained for a distance $d = 260\,\mu\text{m}$ and a open-circuit stub length $L = 3190\,\mu\text{m}$. In this point $S_{11} = -33.75\,\text{dB}$ at a frequency $f = 32.11\,\text{GHz}$.

The computing of the unknown load Z_s represented by the CRLH antenna radiating structure between planes AA' and BB' starts from the well-known formula (2) expressing the input impedance Z_i in a lossless transmission line of characteristic impedance Z_0 with a load impedance Z_s.

$$Z_i = Z_0 \frac{Z_s + jZ_0 \text{tg}\beta x}{Z_0 + jZ_s \text{tg}\beta x} \tag{2}$$

where:

$\beta = 2\pi/\lambda =$ phase constant;

$Z_0 =$ characteristic impedance of the transmission line; usually, $Z_0 = 50\,\Omega$;

$Z_s = R_s + jX_s =$ unknown impedance loading the transmission line;

$Z_i =$ impedance at the input of a transmission line of length x and characteristic impedance Z_0 loaded with Z_s;

$\lambda =$ wavelength.

Starting from (2), formulas (3) and (4) expressing the relations between real and imaginary parts of the load impedance Z_s were derived:

$$R_s = Z_0 \frac{b}{1+ab} \left[a + \frac{b - a - a^2 b}{b^2 + (1+ab)^2} \right] \tag{3}$$

$$X_s = Z_0 \frac{b - a - a^2 b}{b^2 + (1+ab)^2} \tag{4}$$

where

$a = \text{tg}\beta d$;

$b = \text{ctg}\beta L$;

$d =$ the distance of the on-wafer probe-tip location from the beginning of the interdigital capacitor;

$L =$ the length of the parallel adapting stub. In our measurements the parallel adapting stub was an open circuit one.

In all previous formulas, losses are neglected, and the matching stub is purely reactive.

Applying the above procedure, the impedances of the two antenna structures were measured. The results are summarised in Table 1.

Table 1. Computed resistances (R_s) and reactances (X_s) for the CPW CRLH antennas on silicon and alumina substrate.

Antenna	d (μm)	L (μm)	R_s	X_s
	$d + L = 3450$ μm			
C2L15_150	150	3300	48.5326	−16.9639
C1L7_260	260	3190	17.8707	−33.3631

Data in Table 1 show the measured values for the radiating structures of the two metamaterial antenna structures. The complex impedances are $Z_{\mathrm{Si}} \approx 48.53 - j \times 16.96$ for silicon supported antenna and $Z_{\mathrm{ceramic}} \approx 17.87 - j \times 33.36$ for alumina supported antenna. As is normal, in both cases the measured impedances reactive part are negative due to the CRLH line construction with series interdigital capacitors providing left hand behavior.

The input impedance of the radiating part of a CPW CRLH antenna structure may be derived also by using the Smith chart in a reverse manner. But, due to the graphical method characterizing the Smith chart use, the results are less accurate.

4. CONCLUSIONS

A new method to measure the impedance of metamaterial antenna, useful in device matching in a functional circuit, was developed. The method uses a setup made by a very high frequency vector network analyzer and an on-wafer measurement equipment. Starting from the input of the CRLH CPW structure, the probe-tip is moved (continuous or in small steps) to the input of the antenna feedline while measuring the return loss S_{11}. When a minimum of S_{11} is reached, the distance d and the equivalent open circuit stub length L are noted.

Using appropriate formulas, the resistive R_s and reactive X_s parts of the CRLH radiating structure impedance are found. In the example presented in this paper, two metamaterial antennas were measured, the results being shown in Table 1. A mark of results accuracy is the negative values of the reactive parts, a normal result for the capacitive character of the left handed transmission line.

Although it was applied to measure the impedance of a CRLH CPW antenna, the method may be, also, applied to a wide variety of metamaterial devices.

It is noted that solving the above problems may be done also by using the Smith chart in reverse manner, but the results are less accurate.

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