# Silicon Supported Millimeter Wave CRLH Antenna Microprocessed by Laser Ablation

Alina-Cristina BUNEA[1], Florea CRACIUNOIU[1], Marian ZAMFIRESCU[2], Razvan DABU[2], Gheorghe SAJIN[1]

[1]National Institute for Research and Development in Microtechnologies, IMT Bucharest, Str. Erou Iancu Nicolae 126A, 077190 Bucharest, Romania
Phone: +40-21-269 0775
[2]National Institute for Laser, Plasma and Radiation Physics, Atomistilor 409, PO Box MG-36, 077125 Magurele, Bucharest, Romania
Phone: +40-21-457 5066

**Abstract.** The paper presents a zeroth order resonance CRLH CPW antenna on high resistivity silicon substrate for millimetric wave frequency range (28 GHz). As technological approach, the laser ablation was preferred due to better results in device microprocessing compared to classic photolithographic processes. Experimental results show RL < -25 dB / 28.6 GHz, the -3 dB beamwidth of the radiation lobe of approx. 370 and the gain 2.99 dBi / 28.6 GHz. It is, according to the authors' knowledge, the first report concerning the design, fabrication and full characterization of a CRLH antenna on silicon substrate intended to work integrated in a more complex mm-wave circuit.

## 1. Introduction

A possibility to obtain transmission media having metamaterial (MM) characteristics is to develop particular artificial transmission lines. If the artificial transmission line is realized by using cascaded cells of interdigital capacitors and parallel connected short-ended microstrip line inductors, CRLH (Composite Right/Left-Handed) transmission lines are obtained [1]. The CRLH TL cell is the key to a new class of devices such as coupled-line directional couplers [2], filters and resonators, [3]–[5] and various types of antennas [6]–[13]. Concerning the domain of antennas made on the basis of MMs, a lot of contributions were produced, some of the more recent being [10, 11, 12]. For the near future, this kind of circuits should be fabricated on semiconductor substrate due to the need to monolithically integrate a more complex circuit. To integrate these circuits together with other passive or active devices, they must be designed using coplanar waveguide (CPW) configurations. In this paper, the design, fabrication process and measurements of a CRLH TL CPW zeroth-order resonant antenna on silicon substrate for millimeter wave frequency range (28 GHz) are presented.

## 2. Constructive Data and Simulation

A CPW CRLH zeroth-order resonant antenna at the frequency $f$ = 28 GHz was designed, fabricated and electrically characterized. It consisted of three resonant CRLH cells processed on a high resistivity silicon wafer.

The conditions and mathematical relations for the design are presented in literature [1], [13] and will not be presented here. The CRLH circuit was designed to be balanced, with the series resonance frequency equal to the shunt resonance frequency. The components of the elementary CRLH cell used in the antenna construction are presented in Fig. 1.

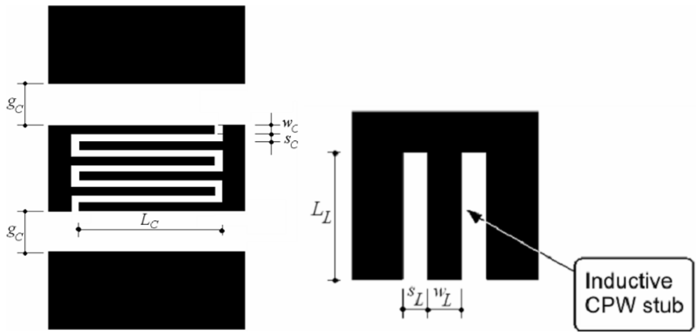



**Fig. 1.** Components of the CRLH elementary cell that is used in antenna construction: interdigital capacitor and inductive CPW stub.

The dimensions obtained for these components are the following: $L_L$ = 212 µm; $w_L$ = 42 µm; $s_L$ =10 µm, for the inductive stub; $L_c$= 250 µm; $w_c$ = 5 µm; $s_c$ = 10 µm; $g_c$ =65 µm and number of digits: 10, for the interdigitated capacitors.

The antenna input is made of an access line with 3400 µm length and the geometry computed to match the 50 µ characteristic impedance of the measuring system. This geometry allows the mounting of the antenna structure on a dedicated test fixture for the measurement of the radiation characteristic and of the gain.

## 3. Technology

The antenna structures were processed on a high resistivity (5 kΩcm) silicon substrate with 500 µm thickness and permittivity $\varepsilon_{r\text{-}Si}$ = 11.9. On this silicon wafer a layer of 1 µm $SiO_2$ with permittivity $\varepsilon r.SiO_2$ = 4.7 was grown through thermal oxidation. A 0.4 µm Au / 500 Å Cr metallization was obtained by evaporation on the surface of the silicon wafer. The processing technology applied to obtain the antenna structure consists of two steps. In the first step, the Au/Cr metallization is removed from the large areas of the structure by standard wet photolithography. In the second step, the fine details of the interdigital capacitor are processed by laser ablation. This two step process is necessary because the removal of metallization from the large areas by laser ablation is a difficult task.

A direct laser writing (DLW) method was used to microprocess the Au/Cr layers deposited on silicon. The samples were laser ablated by tightly focusing a femtosecond laser with 200 fs pulse duration, 775 nm wavelength, tens of nJ pulse energy, and 2-kHz repetition rate. The 2D structures were generated according to a computer controlled algorithm by precisely translating the sample with resolution below 1μm.

The active part of the future antenna structure following the first microprocessing step is presented in Fig.3 (a). The grounded lines forming the inductive stubs and the areas where the interdigital capacitors will be created by laser ablation can be observed. The same area, after the capacitor was microprocessed by laser ablation, is presented in Fig.3 (b).

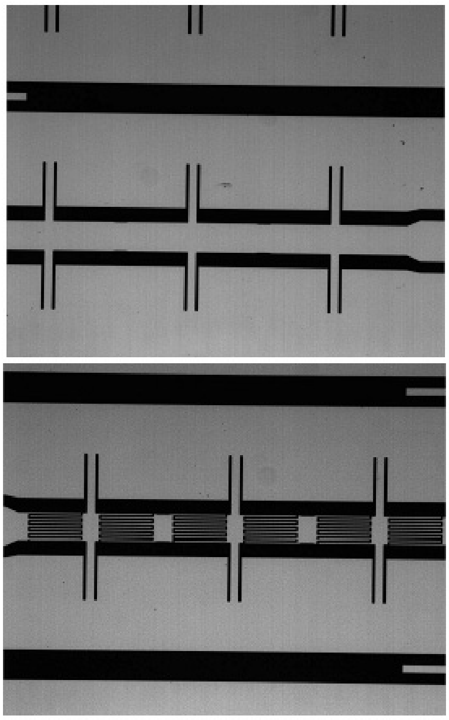


**Fig. 3.** Optical microscopy photos showing the active part of the CRLH antenna after the first step (a) and after the second step (b) of the technological approach.

After on wafer measurements of the S11 parameter, the silicon wafer was cut with a diamond abrasive cutting-off wheel tool, thus obtaining separate antenna chips. These discrete structures were mounted on dedicated test fixtures in order to measure directivity characteristics and antenna gain.

Two such separate CRLH antennas mounted on the test fixtures are presented in Fig. 4.

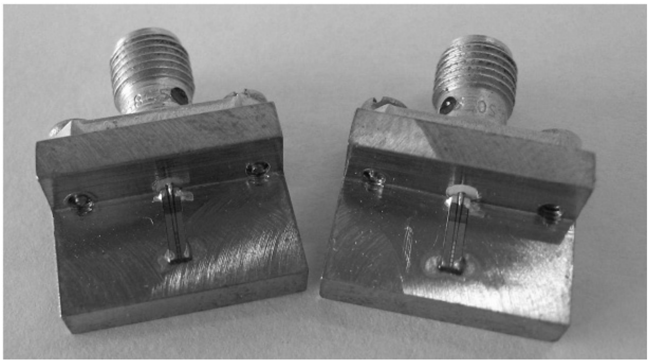


**Fig.4.** Two discrete CRLH antenna structures mounted on the test fixture.

## 4. Measurements and Experimental Results

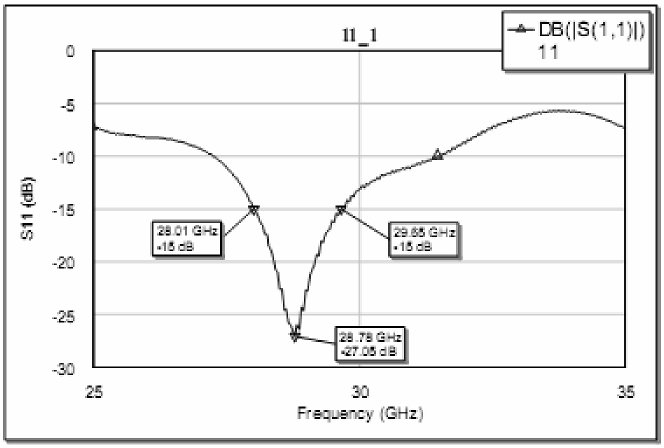
### *A. Return loss*

The $S_{11}$ parameter was measured on wafer using a 37397D vector network analyzer from Anritsu, equipped with PM5 set-up from Süss Microtec. The results for two CRLH antenna samples are presented in Fig.5.

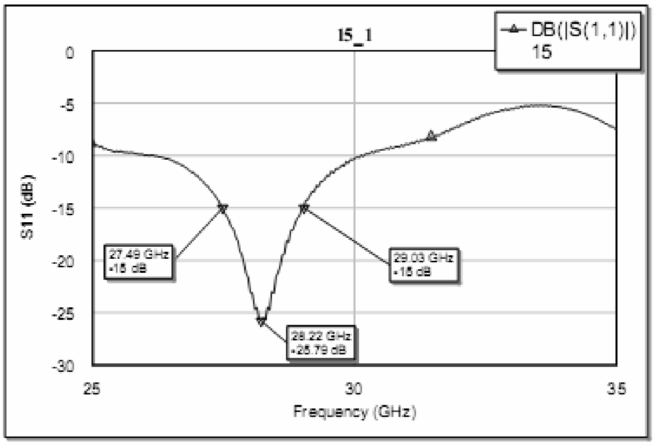
Fig. 5 shows that for two CRLH antenna structures (antenna #1 and antenna #2) the reflection losses (maximum absolute values) are, respectively, -27.05 dB / 28.78 GHz and -25.79 dB / 28.22 GHz. The frequency is slightly higher than the simulated one but the reflection losses are substantially smaller.

In order to obtain the radiation characteristic, the received power was measured for various angles. A CRLH antenna was used as emitting device and a Millitech SGH-28 horn antenna as receiving device connected to the spectrum analyzer. The frequency used was 28.7 GHz where the antenna return losses have a minimum. The measured power at reception was averaged over 50 measurements. The measurements of the radiation pattern were made both in transverse and longitudinal antenna planes.

The measurements were made using a frequency generator Agilent E8257D PSG, a spectrum analyzer Anritsu MS2668C and a measuring setup with the CRLH antenna as emitting device having the possibility to rotate both in transversal and in longitudinal planes.




Antena #1

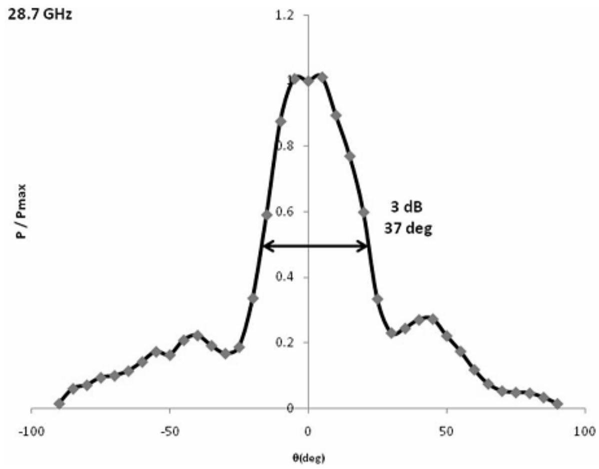



Antena #2

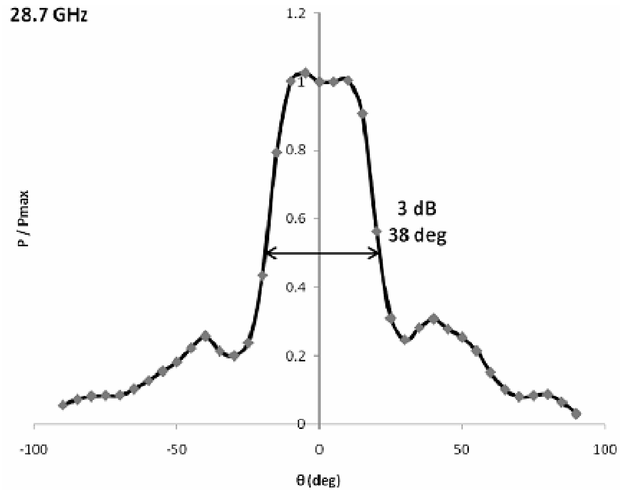
**Fig. 5.** Return loss of CRLH antennas for a frequency sweep between 25 GHz ... 35 GHz

### *B. Radiation characteristic in transversal plane (θ)*

The radiation characteristics in the transversal plane (θ) for two CRLH antenna structures are shown in Fig. 6 where the received powers at different angles were rated to the maximum power value even if it happens at an angle slightly different of $\theta = 0^0$. According to Fig.6, the -3 dB beamwidth of the radiation characteristic extends approx. between +210 ÷ -160 for antenna #1 and approx. between $+20^0$ ... $-18^0$ for antenna #2.




Antena # 1



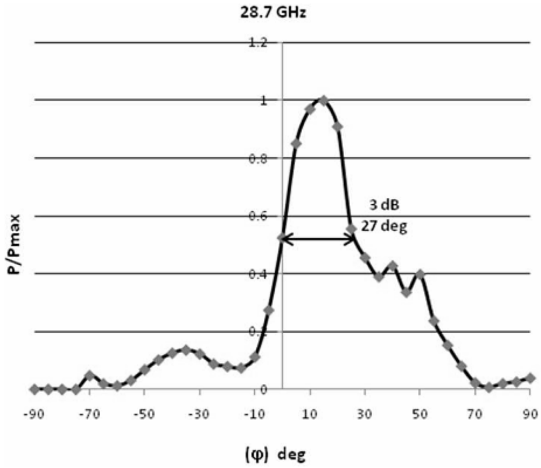

Antena # 2

**Fig. 6.** Radiation characteristic in transversal plane (θ) for two samples of CRLH antenna structures.

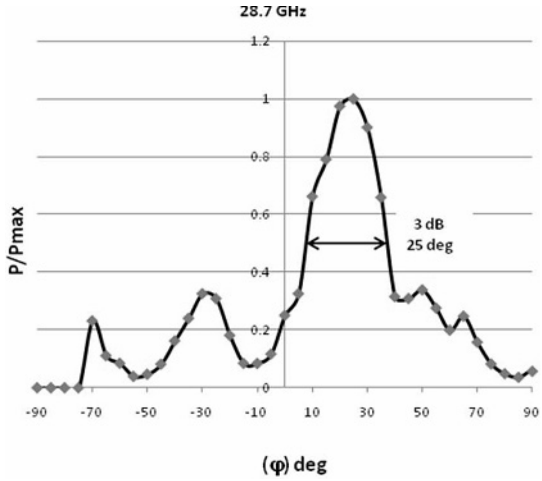
### *C. Radiation characteristic in longitudinal plane (φ)*

In order to complete the characterization of the antenna's radiation capability, measurements were also made in the longitudinal antenna plane (φ). In this respect, the measuring setup was slightly modified and the measuring angle was in forward direction. The frequency was, also, 28.7 GHz and the measurement technique was the same as for the radiation characteristic in the transversal plane (θ) previously presented. The positive direction for the angle (φ) is toward end of the CRLH antenna.

The experimental results are shown in Fig.7 where the radiated powers at different angles in the (φ) plane for the two CRLH antenna samples (antenna #1 and antenna #2) were plotted. The domain of variation of the φ angle was between $-90^0 \div +90^0$. All the received power values were rated to the maximum value in this variation range.




Antena # 1




Antena # 2

**Fig.7.** Radiation characteristic in longitudinal plane (φ) for two samples of CRLH antenna structures.

As shown in Fig.7, the maximum radiated power occurs at an angle φ ≅ +140 for antenna #1 and φ ≅ +240 for antenna #2. The width of the radiation lobe in the longitudinal direction of the antenna is approx. 250 for antenna #1 and approx. 270 for antenna #2.

***D. Antenna gain***

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

$$\frac{P_r}{P_t}=G_i^2\left(\frac{\lambda}{4\pi R}\right)^2 \tag{1}$$

where: $P_t$ = power transmitted by the 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 wavelength). In this situation the emitting and the receiving antennas are identical so that the gains with respect to isotropic of both devices are the same, ($G_i$) The gain in dBi is expressed by:

$$G(dBi)=10\log_{10}\left(\frac{4\pi R}{\lambda}\sqrt{\frac{P_r}{P_t}}\right) \tag{2}$$

The antenna gain was evaluated in the frequency domain 28 GHz ... 29 GHz and the obtained data are the following: λ = 10,7 mm/f = 28 GHz, R = 100 mm, power at the emitting antenna: Pt = 0,45 mW, power at the receiving antenna Pr = 1.29E-04 mW.

The antenna gain was computed with (2) at different frequencies in the 28 GHz ... 29 GHz frequency band. The results show the following gain values G = 2,12 dBi / 28 GHz for and G = 2.62 dBi / 29 GHz with a maximum value G = 2,99 dBi / 28.6 GHz. It was observed that the value of G is approx. constant in the 28 GHz ... 29 GHz frequency band.

## 5. Conclusions

A zeroth-order resonant wave millimeter wave CRLH CPW antenna on silicon substrate was proposed. The silicon substrate and the CPW transmission lines were chosen for the future antenna integration in a more complex monolithically integrated circuit. The antenna was fabricated and the electrical parameters (on-wafer measured return loss, the radiation characteristic and the gain) were measured for two antenna samples obtained in the same technological run.

The measured return-loss: -27.05 dB / 28.78 GHz and -25.79 dB / 28.22 GHz shows a very good matching of the obtained devices. The slightly higher value for the working frequency is due to a technological overetching of the interdigital capacitors metallization. Due to that, the interdigital space increases, the capacity decreases and the working frequency may be higher than designed.

The 3 dB beamwidth of radiation lobe is approx. $37^0$ for one of the CRLH antenna samples and approx. $38^0$ for the other one.

Concerning the gain, the values computed from the measured data give G = 2,12 dBi / 28 GHz and G = 2.62 dBi / 29 GHz with a maximum G = 2,99 dBi / 28.6 GHz.

There is a frequency difference of approx. 0,5 GHz ÷ 0,7 GHz between S11 measurements (see Fig. 5) and adiation characteristic (see Fig. 6 and Fig. 7) and gain measurement. These differences are due to the fact that the $S_{11}$ parameter of the CRLH antenna structures was measured on-wafer and the gain and the radiation characteristic were evaluated with the antenna structures mounted on the test fixture. The mechanics and the antenna structure contacting to the test fixture connector generate this slight frequency displacement.

## References


[1] C. CALOZ, T. ITOH, *Electromagnetic metamaterials: transmission line theory and microwave applications*, John Wiley & Sons, Inc., 2006.

[2] C. Caloz, A. SANADA, T. ITOH, *A novel composite right-/left-handed coupled-line directional coupler with arbitrary coupling level and broad bandwidth*, IEEE Trans. on Microwave Theory and Techniques, **52**(3), pp. 980–992, March 2004.

[3] I. VENDIK, D. KHOLODNYAK, P. KAPITANOVA, K. ZEMLYAKOV, *Multiband tuneable microwave resonators and filters on a combination of right/left-handed transmission line sections*, Proc. of the 3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, METAMATERIALS, pp. 181–183., London, UK, 30th Aug. – 04th Sept. 2009.

[4] Jian-Qiang GONG, Qing-Xin CHU, *Miniaturized Microstrip Bandpass Filter Using Coupled SCRLH Zeroth-Order Resonators*, Proc. of the European Microwave Conference, EuMC, EuMW, pp. 370–373, Rome, Italy, 28 Sept. 02 Oct. 2009.

[5] R.H. GESCHKE, B. JOKANOVIC, P. MEYER, *Compact Triple-Band Resonators Using Multiple Split-Ring Resonators*, Proceedings of the European Microwave Conference, EuMC, EuMW, pp. 366–369, Rome, Italy, 28 Sept. 02 Oct. 2009.

[6] A. SANADA, M. KIMURA, I. AWAI, S. CALOZ, T. ITOH, *A planar zeroth-order resonator antenna using a left-handed transmission line*, Proc. of the 34th European Microwave Conference, pp. 1341–1344, Amsterdam, 2004.

[7] Cheng-Chi YU, *et al.*, *A compact antenna based on metamaterial for WiMAX*, Proc. of Asia-Pacific Microwave Conference, Paper J2-05, Hong Kong, 2008.

[8] Seongmin PYO, *et al.*, *A metamaterial-based symmetrical periodic antenna with effiency enhancement*, Proc. of Asia-Pacific Microwave Conference, Paper A3-49, Hong Kong, 2008.

[9] Chen-Jung LEE, Maha ACHOUR, Ajay GUMMALLA, *Compact metamaterial high isolation MIMO antenna subsystem*, Proc. of Asia-Pacific Microwave Conference, Paper A2-27, Hong Kong, 2008.

[10] Richard W. ZIOLKOWSKI, Peng JIN, Chia-Ching LIN, *Electrically Small Metamaterial-Inspired Antennas: The Next Generation*, Proc. of the 3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, METAMATERIALS, pp. 44–46, London, UK, 30th Aug. – 04th Sept. 2009.

[11] A.A. BASHARIN, N.P. BALABUKHA, *The Radiation of Antennas Based on Metamaterial Waveguides*, Proc. of the 3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, METAMATERIALS, pp. 224–226, London, UK, 30th Aug. – 04th Sept. 2009.
[12] S. EGGERMONT, R. PLATTEBORZE, I. HUYNEN, *Analysis of Radiation in a Metamaterial Leaky Wave Antenna Based on Complementary Split Ring Resonator*, Proc. of the 3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, METAMATERIALS, pp. 102–104., London, UK, 30th Aug. – 04th Sept. 2009.
[13] G. SAJIN, S. SIMION, F. CRACIUNOIU, R. MARCELLI, *Silicon supported microwave zeroth-order resonance antenna on metamaterial approach*, Proceedings of the 2007 Asia-Pacific Microwave Conference, APMC, pp. 221–224., Bangkok, Thailanda, 11–14 Dec.2007.