Femtosecond Laser Fabrication of Metamaterials for High Frequency Microwave Devices

Marian ZAMFIRESCU*, Razvan DABU*, Marius DUMITRU *, George SAJIN**, Florea CRACIUNOIU **

* NILPRP – Bucharest, Atomistilor 409, 077125 Magurele, Romania
E-mail: Marian.Zamfirescu@inflpr.ro
** IMT Bucharest, Str. Erou Iancu Nicolae 126A, 077190 Bucharest, Romania

The laser etching technique is used for configuration of micro-structures. Films of few-hundreds nm of gold deposited on glass or silicon are precisely processed by tightly focusing a femtosecond laser with 150fs pulse duration, 775nm wavelength, and energy of tens of nJ. The laser fluence is hold just above the ablation threshold. Thus, the evaporated film leaves behind structures with thin lateral size of about 1μm. Using this technique, the fabrication of micro-structures is demonstrated. The periodic structures are designed to behave as a left handed metamaterial in the GHz range. The fabricated metamaterials have applications for antenna, filters, couplers in the high frequency bands of microwave spectral range.

DOI: 10.2961/jlmn.2008.01.0002

Keywords: metamaterials, laser ablation, diffraction limit, microwave devices.

1. Introduction

Artificial periodical structures named left-handed metamaterials (LH-MTMs) can be designed and realized for exhibiting fascinating electromagnetic and optical properties such as backward-wave propagation, negative refractive index (NRI), negative refraction, reversal Doppler effect, etc. The fundament of such unusual proprieties, unobserved at the basic materials forming the structure, is the negative permittivity and negative permeability of the MTM obtained at a certain frequency for a special design of the structure. These effects were theoretically predicted by Veselago [1]. Structures behaving simultaneous *negative-*ε and *negative-*μ were the first time realised by Smith *et al* [2], inspired by the theoretical works of Pendry [3,4]. The negative refractive index was obtained in microwave electromagnetic spectra at about 5GHz in plasmonic-type periodic structures formed by metal split-ring resonators (SRR) intercalated with metal thin-wires (TW), with period p much smaller than the wavelength ($p<<\lambda$).

Due to the great potential for microwave, terahertz, up to optical applications, in the last few years the LH-MTMs attract more and more interest for fabrication of new devices such as microwave antenna, modulators, couplers, band-pass filters, superlenses, based on MTMs. The condition of low size periodicity compared with the wavelength, and the technological difficulties encountered in the realization of nanometric structures, restricted the rapid scientific advances to the microwave range. In this range, new designs were proposed to overcome the disadvantage of resonant-type TW-SRR structures, which consequently exhibit high loss and narrow bandwidth.

Transmission line (TL) structures in 1D and 2D configuration, exhibiting low loss and broad bandwidth were designed [5,6,7]. The TLs are usually realised by microstrip techniques and consist in series of interdigital capacitors and shunt stub inductances, with typical size of few millimetres and hundreds of microns of the interdigital width [8]. Such structures exhibit a negative phase velocity medium at frequencies of few GHz. When moving toward the spectral range of hundreds of GHz up to terahertz, a considerable reduction of scale is required, down to tens of microns for the physical size of the unit cell of the MTM, as well as interdigital capacitors with fingers width of few microns have to be considered. Metallic or dielectric structures with such resolution are traditionally done by photolithography: UV sensitive photoresist deposition, UV exposure, photoresist hardening, chemical layers corrosion.

In this work, the photo-lithography techniques are replaced by laser processing for the configuration of the metallic layers microstructures. The laser etching technique has the advantage upon hard materials (glass, ceramic), chemical inert materials (platinum, gold) or anytime an efficient mask material can't be found due to the chemical attack of the mask material while layer corrosion takes place. Of the main importance for this technique is the tight laser focusing (near the diffraction limit or below the diffraction limit), the laser beam control along axes including depth control of the processed layer, the support layer selectivity, and the roughness control of processed surfaces that have to be smooth enough, avoiding debris deposition on neighbouring active areas.

Thin films of gold deposited on silicon or glass are laser processed in order to create periodic structures with resolution down to the diffraction limit. The conditions of the laser etching are studied and the writing parameters of the structures with periodicity of tens of microns are optimised.

2. The model of LC network

The fabricated microstructures are designed in the TL architecture, and can be analysed using the model of LC network composed by series capacitors C_L and shunt inductors L_L. A real TL will exhibit both right-handed (RH) and left-handed (LH) characteristics, due to the additional parasitic capacitances or inductances. The equivalent circuit model for a real TL is shown in the figure 1. The RH characteristic is introduced by series-L/shunt-C (L_R and C_R) as the dual of the series-C/shunt-L. Such structure is widely known as composite right/left-handed transmission line (CRLH-TL) and is characterised by the series and shunt resonance frequencies:

$$\omega_{se} = \frac{1}{\sqrt{L'_R C'_L}} \qquad (1a)$$

$$\omega_{sh} = \frac{1}{\sqrt{L'_L C'_R}} \qquad (2b)$$

where all the prime unities represent per-unit length capacitance and respectively per-unit length inductance.

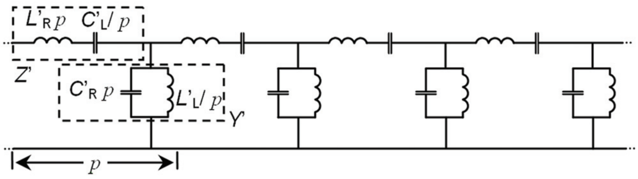

Figure 1. Equivalent circuit model for CRLH-TL structure. ***p*** is the size of a periodic cell.

Permittivity and permeability of the CRLH-TL are defined as:

$$\mu = \mu(\omega) = L'_R - \frac{1}{\omega^2 C'_L} \qquad (2a)$$

$$\varepsilon = \varepsilon(\omega) = C'_R - \frac{1}{\omega^2 L'_L} \qquad (2b)$$

Then, the equivalent refractive index is written in the following form:

$$n = n(\omega) = s(\omega)\sqrt{\left(\omega C'_L - \frac{1}{\omega L'_R}\right)\left(\omega L'_L - \frac{1}{\omega C'_R}\right)} \qquad (3)$$

where $s(\omega)$ is:

$$s(\omega) = \begin{cases} -1 & \text{if } \omega < \min(\omega_{se}, \omega_{sh}) \\ +1 & \text{if } \omega < \min(\omega_{se}, \omega_{sh}) \end{cases} \qquad (4)$$

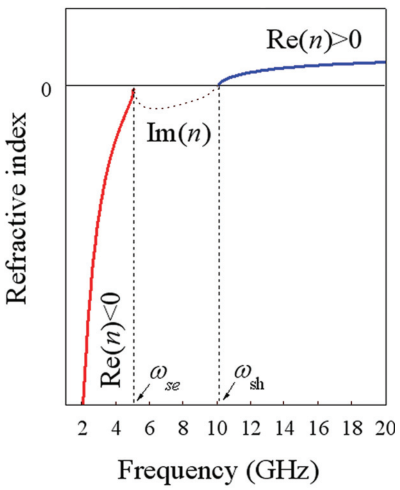

Figure 2. Computed refractive index. The numerical parameters are described in the text.

In the figure 2 is shown the computed refractive index using the Eq. (3), and the parameters L_R = 0.25nH, C_R = 2pF, L_L = 0.5nH, C_L = 1pF, and p = 12mm. In the case of this structure, similar to the one described in the Ref. [8], the backward-wave propagation is obtained at low-frequency band, below 5GHz. This value corresponds to a periodicity of the structure of 12mm. Scaling the structure down to tens of microns, tens to hundreds of GHz could be expected, depending on the capacitance and inductance of the scaled structure. In the following section, we present the technique used to create 1D and 2D CRLH-TL structures with micron lateral size, which potentially can behave as MTMs at high frequncy bands of microwave spectral range.

3. Fabrication technique.

By tightly focusing the laser beam on the surface of a metallic film, a small volume of material can be evaporated. The Abbe's law D =1.22λ/NA, gives a minimum diameter of a focused beam of about D = 1.9 µm. In order to overcome the difraction limit and to obtine stuctures with lateral size less than 1µm, we take advantage of high peak power and short heat diffusion length of ultrashort laser pulses [13].

Due to the very high power density, the interaction of femtosecond laser beams with materials is mainly based on nonlinear optical processes such as multiphoton ionization. The multiphoton absorption process is characterized by a certain laser power density threshold. For a focused beam with a Gaussian intensity profile, the heat affected volume becomes smaller than the focus size when the laser fluence is at or just above the threshold value. Once the plasma of free electrons generated by multiphoton absorption and ionisation reaches a high enough density, irreversible material breakdown and ablation begin. The electrons transfer energy to the ions and the lattice, and the material is heated up to much higher temperatures compared to the long pulses cases. Due to the very short pulse duration, the heat diffusion to the surrounding volume of the material is negligible. A large fraction of the material in the small interaction volume is directly vaporized, going through a melt phase very quickly. For femtosecond pulses, the resulting melt layer thickness will be very small because most of the heated material reaches the vaporization temperature, and there is rapid cooling due to the steep temperature gradient. Practically, a large amount of the absorbed laser energy is carried away by the direct vaporization. As a result, ablation and material removal become very precise, in contrast to the long pulse case, and the ablated area is significantly smaller than the focused beam size.

The equipment used to create the periodic microstructures with submicron resolution is a standard laser micro-processing setup, consisting in a commercial laser system, delivering ultrafast pulses of 150fs duration, 775nm wavelength, and 2kHz repetition rate. The laser pulses are atenuated in the range of tens to hundreds nJ. The laser beam is focused by a 100x microscope objective with 0.5 numerical aperture. The samples are precisely translated and positioned by a XYZ fine translation stage, equipped with stepper motors and piezoelectric actuators which provide a high accuracy displacement in the range of tens of nanometres.

By translating the sample according to a computed design, any 2D structure could be generated. The lateral resolution of the created structure is controlled by adjusting the laser intensity above the threshold of ablation.

Table 1 Ablation threshold versus writing speed

Speed (mm/s)	Ablationn threshold (J/cm^2)	Lateral size of the structure
0.5	2	1000±500nm
0.1	1.5	900±200nm
0.05	1.2	700±100nm
0.01	0.95	700±200nm
0.005	0.65	700±300nm

For a given material, the quality and the resolution of the written structure depends strongly on few parameters such as writing speed, focusing, and laser energy. These have to be attentively determined for each particular sample in order to establish the most appropriate conditions for writing the structure. In the table 1 is presented the minimum laser energy required for ablation of 100nm gold film, for speeds of the translation from 5µm/s up to 0.5mm/s. The minimum lateral size of the obtained traces on the film is also listed, together with an estimation of the width fluctuation.

Due to relatively low laser repetition rate (2kHz), for speeds higher than 1mm/s, spatially separated dots were created on the metal surface corresponding to a single pulse ablation regime. This effect remains visible when the speed is decreased down to 0.5 mm/s, affecting the smoothness of the traces borders. When the writing speed is slowed, the energy threshold for ablation decreases due to the overlapping of the laser pulses, corresponding to the multiple pulse ablation regime [9,10,11]. For speeds as slow as few µm/s, the ablation threshold decreases several times, from $2J/cm^2$ in the single pulse regime to $0.65J/cm^2$ at 5µm/s speed. When the ablation threshold decreases together with the writing speed, the structures are obtained more precisely having smoother borders. At the very slow writing speed, if the laser energy is kept at threshold, any local inhomogeneity of the metallic film could induce fluctuations of the ablation threshold compromising the shape of the trace. At very slow speed, by increasing the energy the depth of the ablated film is more difficult to be controlled. In this case, an intermediate speed of writing is desirable.

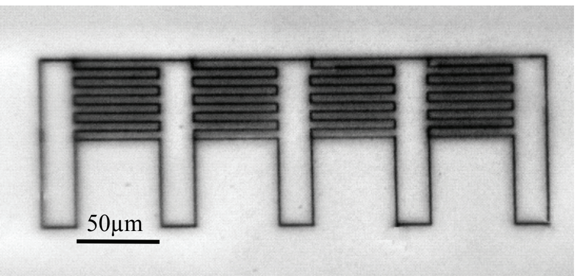

Figure 3. The optical image of a 1D CRLH-TL structure created by laser etching on gold film.

The effect of the unfocused beam was also analyzed. When a displacement of the sample with ±1µm around the focus plane of the microscope objective is considered, the ablation effect is lost. This is related to a very short Raleigh range of the beam when the 100x microscope objective is used. This fact insures that the depth of the ablation can be easily controlled with less than 1µm precision.

4. Fabricated structures

A network of interdigital capacitors and stub inductors was created on gold thin films by tightly focusing the femtosecond laser. The designed structure was obtained by computer controlled displacement of the sample with submicron precision. In figure 3 is shown the optical image of the 1D CRLH-TL structure with the interdigital finger length of lc =50µm, stub inductance length of ls =100µm, and period of the structure p=70µm. The width of one finger is 5µm, N = 5 pairs of fingers and the interdigital width is 1µm. For obtaining this structure, the laser density energy was 1.5 J/cm2, and the translation speed was 0.1mm/s.

As shown in the figure 2, a structure with *p*=12mm and the interdigit width of 0.1mm [8] has the LH response at few GHz. Scaling the structure down to *p*=70µm, we can expect a similar behaviour, but shifted toward tens or hundreds of GHz. The exact value can be obtained only by an accurate numerical calculation which is not the subject of the present paper [12].

A typical microstrip CRTL-TL has the stub inductors shorted to the ground by a via. In our case the construction of a via is not an easy task because of the dimension of the structure and the nature of the substrate. Using open stub is in fact possible, and the only disadvantage is the requirement of a longer strip. Also, via-less configurations using a virtual-ground capacitors can be designed [14].

A more complex structure was demonstrated by the same technique. The 2D CRLH-TL structure in the figure 4 was created with the laser density energy of 1.5 J/cm^2, and the translation speed of 0.05mm/s. The geometrical parameters of the structure are the folowing: the finger length is l_c = 30µm, the inductance width is l_s =30µm, and the digits and interdigit width is 1.5µm.

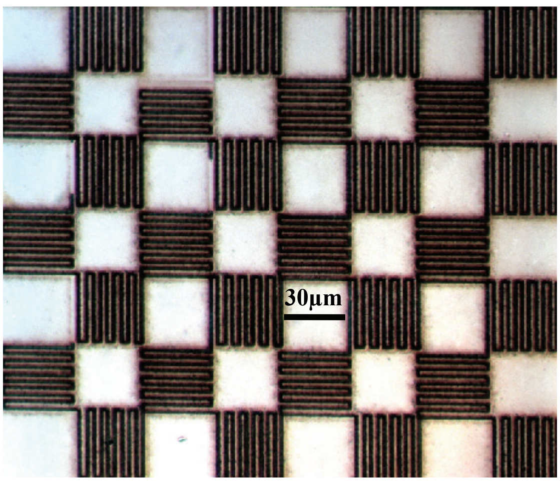

Figure 4. 2D CRLH-TL structure with l_c = 30µm and l_s =30µm, the digits and interdigit width is 1.5µm.

The meaning of the parameters is explained in the text.

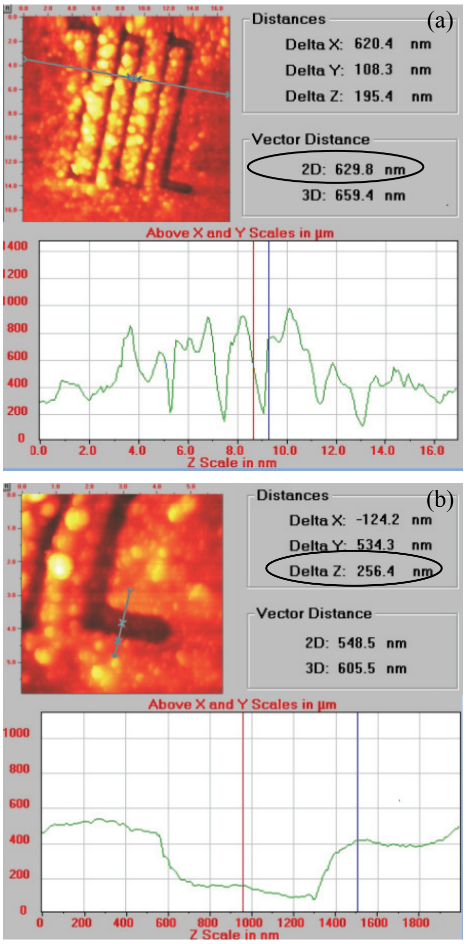

Figure 5. AFM image of a TL structure written in the condition of minimum lateral resolution of 650nm (a). Ablation depth is about 260nm (b).

The AFM image of an interdigital structure, created in the most appropriate conditions required for obtaining the minimum lateral size, is presented in the figure 5. The laser energy density was 1J/cm^2 and the writing speed was 0.02mm/s.From the AMF image we measured the geometry of the structure: the period of the digits is 2µm, the width of the interdigit is about 650nm, and the ablation depth is about 260nm.

The image in the figure 5 is taken immediately after the writing of the structure, without any intermediate treatment of the surface. During the laser etching process in the air, the material expelled from the film can be splashed on the surface of the sample in the form of metallic particles. These particles can be easily removed from the surface by a simple ultrasonic bath of the sample in acetone, for one or two minutes. In the case of very thin fingers, below 1.5µm, this treatment has to be carefully done because the long time ultrasonic cleaning could brake and remove the fingers from the substrate. The SEM images, not presented here, confirm the complete cleaning and the removal of any undesirable particles from the sample surface on the processed area.

5. Conclusions

Metamaterial structures can be easily fabricated on metal films by femtosecond lasers etching. Using the actual setup, structures with resolutions below 1µm were obtained by nonlinear absorption of femtosecond laser radiation in the processed metallic films. The created structures show smooth traces when the most appropriate writing conditions are chosen. Depending on their cell size, the fabricated periodic structures can behave as metamaterials in the microwave spectral region (tens to hundreds GHz). A better resolution, as small as few-hundreds nm, could be reached by laser machining based on harmonics of the fundamental frequency, radially polarised laser beams, or/and shorter pulse duration.

Acknowledgments

The authors would like to acknowledge the Romanian Research Agency for funding through the “Nucleu PN10” program. MZ thanks for the support of Nato SfP RIG program, Project No.RIG 982600.

References

[1] V.G. Vesselago: Soviet Phys. Usp. 10 (1968).
[2] D. R. Smith et al: Phys. Rev. Lett. 84, (2000) 4184.
[3] J. B. Pendry et al: J. Phys. Condens. Matter 10, (1998) 4785.
[4] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart: IEEE Transactions on Microwave Theory and Techniques, 47, (1999) 2075.
[5] A. K. Iyer and G. V. Eleftheriades.: Proc. IEEE-MTT Int’l Symp., vol. 2, Seattle, (2002) p.412.
[6] A. A. Oliner: IEEE-AP-S USNC/URSI National Radio Science Meeting, San Antonio, (2002) p.41.
[7] C. Caloz and T. Itoh: Proc. IEEE-AP-S USNC/URSI National Radio Science Meeting, San Antonio, (2002) p.412.
[8] C. Caloz, T. Itoh: “Electromagnetic metamaterials: transmission line theory and microwave applications”, John Wiley & Sons, (New Jersey, 2006) p.128.
[9] K. Furusawa, K. Takahashi, H. Kumagai, K. Midorikawa, M. Obara: Appl. Phys. A: Mat. Sci. & Proc., 69 (1999) p.S359.
[10] S.E. Kirkwood, A.C. van Popta, Y.Y. Tsui and R. Fedosejevs: Appl. Phys. A: Mat. Sci. & Proc., 81, (2005) p.729.
[11] X.Ni, C.y.Wang, L.Yang, J.Li, L.Chai, W.Jia, R.Zhang, and Z.Zhang: Appl. Surf. Sci. 253 (2006) p.1616.
[12] for an accurate calculation of the response of a TL, the parameters C_L, L_L, C_R, and L_R have to be experimentally extracted.
[13] X. Liu, D. Du, and G. Mourou, IEEE J. Quantum Electron. **33**, 1706 (1997).
[14] A. Sanada, K. Murakami, S. Aso, H. Kubo, and I. Awai: IEEE-MTT Int’l Symp., Fort Worth, TX, (2004) p.301.

(Received: April 24, 2007, Accepted: October 30, 2007)