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Photogalvanic self-pulsing of electro-wetting of LC droplet on LN-crystal

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Abstract. Photogalvanic current photoinduced by CW laser illumination of Fe-doped LN reveals quasi-periodic pulsing due to microplasmas discharges. This transformation of constant external influence into periodic response is interesting as example of self-excited systems, resembling pulsations of biological systems (including heart beats). Microplasmas is also interesting for potential applications in various fields, such as surface treatment, sterilization, water splitting, light sources, micro jets. Self-pulsing regime of microplasmas discharges in microhollow cathode discharges was observed and modeled in plasmas physics. In this paper, we analyze self-pulsing of photogalvanic current visualized by dynamic electrowetting in a simple LC-cell, formed by a nematic LC droplet placed on Fe-doped LN crystal. We have developed model of self-pulsing regime based on nonlinear discharge resistance. Experimental phase-space plot may be used to find parameters of the nonlinear discharge resistance. In the dynamic modeling contributions from both photogalvanic and pyroelectric effect are included. The analysis of dynamic regime reveals that a current pulse (in microsecond range) have asymmetric shape with extremely sharp rise with longer decay time. These self-pulsations are visualized by reflection of laser light from a LC droplet placed on LN-crystal. Reflected interference patterned was modulated by the dynamic electro-wetting effect.

1. Introduction

In description of self-pulsation we will start from the standard photorefractive equations that include pyroelectric contribution [1-4]. For modeling of nonlinear resistance will be used similar approach, that was developed in [5-6]. In this paper, we will expand the theoretical analysis to the high light intensities, where quadratic recombination is pronounced and the photogalvanic coefficient begins depend on the concentration of photo-excited charge carriers. This extension allows us to analyze the maximal photogalvanic voltage and current in practically important experiments when electrical discharges are pronounced.

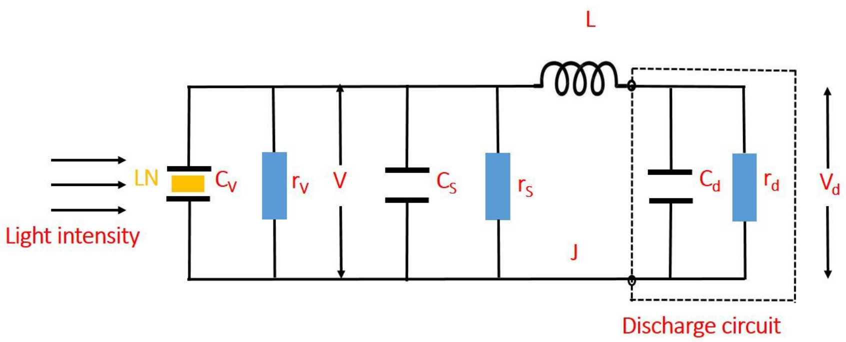


Figure1. Equivalent electric scheme of photogalvanic/pyroelectric crystal: C_v, r_v –capacitance and resistance of the crystal volume. C_s, r_s – effective capacitance and resistance of crystal surface. L – inductance of the effective discharge circuit. V, J, V_d, C_d, r_d - output voltage and current, voltage, capacitance and resistance of the discharge circuit.

We will consider the equivalent electrical scheme of photogalvanic/pyroelectric crystal (Figure 1) and include both the photogalvanic and the pyroelectric contributions to the crystal charging.

We will consider a semiconductor ferroelectric, with donor impurity with concentration *N*, which may be excited by laser illumination, producing electrons with concentration ***n*** in the conduction band and generating photogalvanic current along the crystal polar axis and with acceptors with concentration $\boldsymbol{N_A}$. In quasi-neutrality approximation and neglecting diffusion, equations for photoinduced voltage ***V***, current ***J***, photoinduced temperature change $\boldsymbol{\delta T}$ and concentration of electrons ***n*** can be written as:

$$
\begin{aligned}
&dV/dt = -\frac{V}{(C_v+C_S)}\left(\frac{1}{r_v}+\frac{1}{r_s}\right) - AGIs(N-N_A-n)/(C_v+C_s) - d\delta T/dt\frac{pA}{(C_v+C_s)} + J/(C_v+C_s)\\
&dn/dt = s'I(N-N_A)-(sI+\gamma N_A)n-\gamma n^2\\
&dJ/dt = (V_d - V)/L \qquad (1)\\
&dV_d/dt = -\frac{V_d}{r_d C_d} - J/C_d\\
&d\delta T/dt + \delta T/\tau_T = \alpha_T I
\end{aligned}
$$

Here, $\boldsymbol{C_s}$, $\boldsymbol{r_s}$ are effective capacitance and resistance of crystal surface, $\boldsymbol{C_d}$ is the capacity of the discharge circuit and $\boldsymbol{V_d}$ is the voltage on this capacitor, ***L*** is an effective inductance of the discharge circuit, $\boldsymbol{r_d}$ is effective discharge resistance, $\boldsymbol{\delta T}$ is photoinduced change of temperature, ***p*** is the pyroelectric coefficient, $\boldsymbol{\tau_T}$ is thermal relaxation time, ***ε*** is the effective dielectric constant and ***s'=sF/ω, F*** is the quantum efficiency, and ***ω*** is photon energy, $\boldsymbol{\alpha_T = (\alpha + \alpha h)/(\rho\ C_h)}$ is the effective heat absorption coefficient, $\boldsymbol{\alpha = s(N - N_A - n)}$ is an optical absorption coefficient, $\boldsymbol{\alpha_T}$ is thermal absorption constant due to IR absorption, ***ρ*** is mass density, $\boldsymbol{C_h}$ is heat capacity.

Here ***N***, $\boldsymbol{N_A}$ and ***n*** are concentrations of donors, acceptors and electrons, respectively, μ is mobility of electrons, ***G*** is photogalvanic coefficient, and ***J*** is the total current density, ***s*** is the absorption cross-section of photons, ***s'=sF/ω, γ*** is recombination coefficient, and ***I*** is intensity of light.

Denoting ***A*** and ***d*** as the electrode area and crystal thickness, the internal (volume) resistance of the illuminated crystal can be written as $\boldsymbol{r_V = d/(\sigma A)}$, where $\boldsymbol{\sigma = e\mu n}$ is the electrical conductivity. For description of high-intensity case, we consider photogalvanic coefficient ***G'*** depends on concentration of photoexcited electron concentration ***n***:

$$\boldsymbol{G' = G\,(1 + k\,n)} \qquad \textbf{(2)}$$

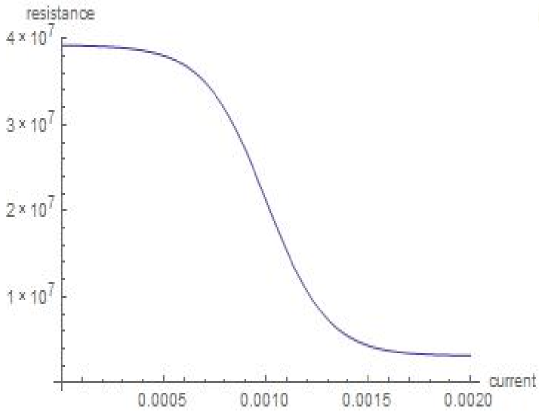
where ***k*** is nonlinear photogalvanic coefficient.

To analyze regime of self-pulsation, we will consider steady-state for generation of photoelectrons ***n***. Put $\boldsymbol{C_d=0}$ and ignore (for simplicity) pyroelectric contribution. In this case equations will be reduced to (taking into account, that now $\frac{V_d}{r_d C_d} = -J$):

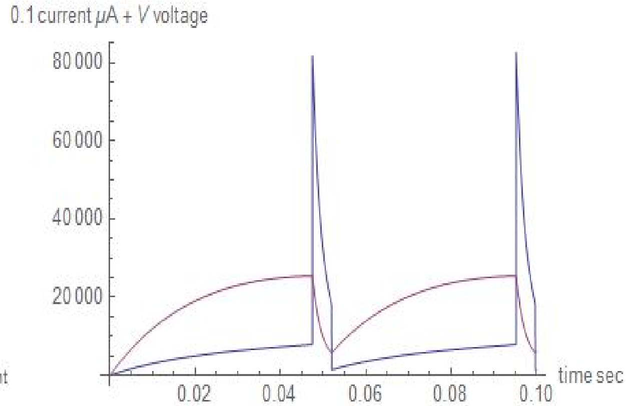
$$\frac{dV}{dt} = -\frac{V}{\tau} - AG' I\alpha / C + J / C \qquad (3)$$

$$\frac{dJ}{dt} = -(Jr_d + V) / L$$

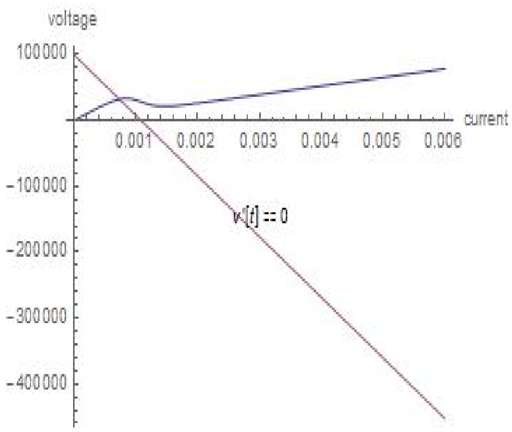
here α is absorption coefficient, $\boldsymbol{C = C_s + C_v}$.



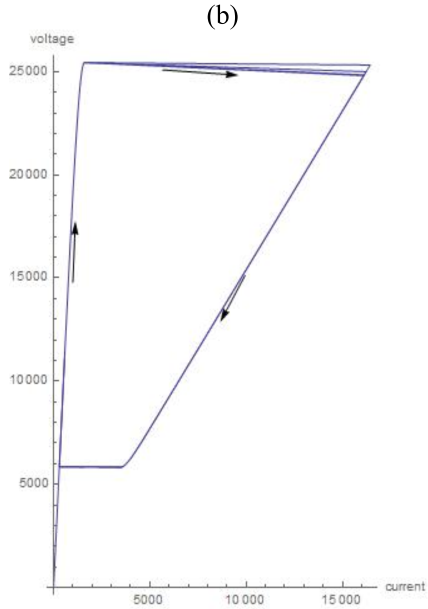
(a)



(b)



(c)



(d)

Figure 2. Solution for Eqs.2-4 for pulsations: (a) resistance as function of current, (b) pulses of current and voltage, (c)static V-A characteristic, (d) dynamic V/A characteristic. Period of pulsation T = 0.05 s. (Experiment on Sun T = 0.04 s)

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To describe self-pulsations we will chose nonlinear bulk resistance r_d on current J as:

$$r = (a - b)\tanh((J - i)/p) \quad (4)$$

Choosing parameters as: **a+b=(2.12+1.812) 10^7 Ω, i=10^{-3} A, p=3*10^{-4} A , τ = 3.08*10^{-5} s, C = 7*10^{-10} F,** ***AG'I α /C=2.1*10^7 V/s*** , we can get solution of Eqs.2-4, Figure 2 is what we got using Mathematica software.

2. Experimental results

Simple experimental setup for detection of electrical and optical self-pulsation is shown in Figure 3.

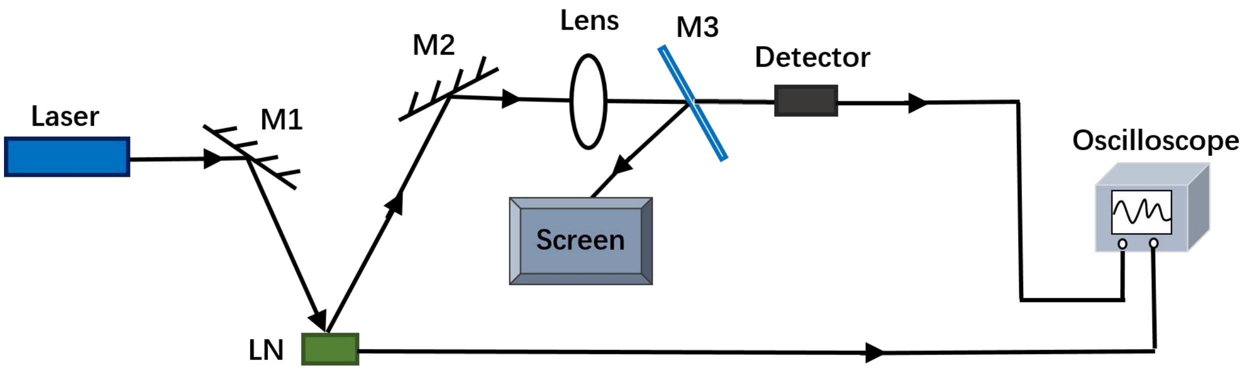

Figure 3. Experimental setup for observation of electrical and optical pulsation

We have used blue CW laser and Fe-doped C-cut LN crystal. Nematic Liquid crystal droplet (~ 5 mm diameter) was placed by pipette on the C-surface of crystal. Reflected beam was projected on the screen, with part of the beam registered by detector. Another channel of oscilloscope was connected to the electrode (one is gridded), covering C-surface. One of reflected beam from LC droplet dancing images is shown in Figure 4.

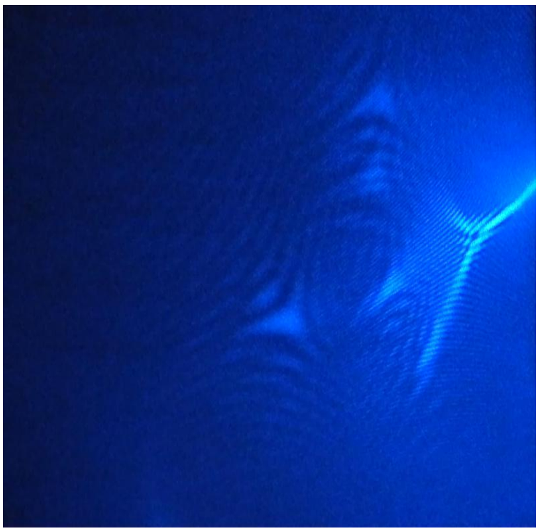

Figure 4. One of the reflected beam from LC droplet dancing images.

Examples of electrical pulses from the Sun-illuminated LN crystal are shown in Figure 5 (single pulse with 30 A amplitude) and Figure 6 (self-pulsation under Sun illumination).

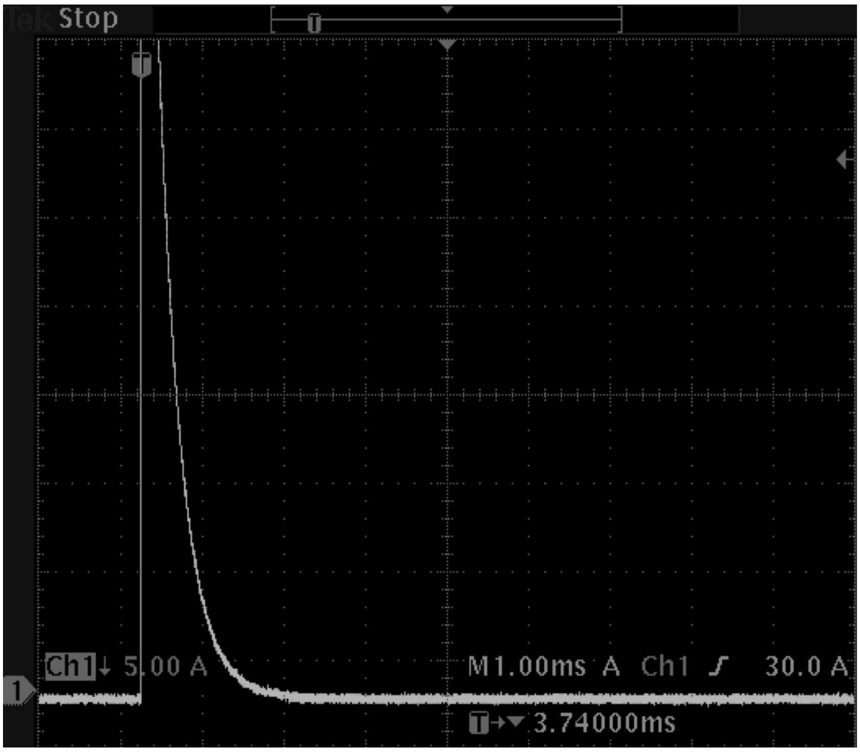

Figure 5. Current pulse from the sun-illuminated LlN crystal (more than 30 A)

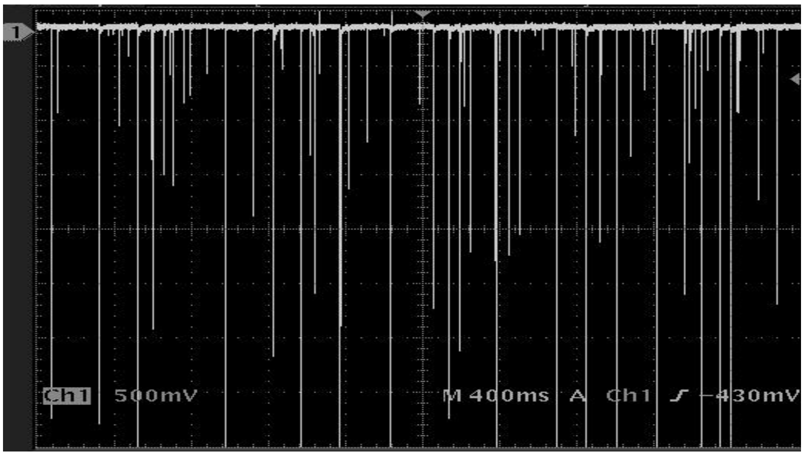

Figure 6. Electrical pulsations picked-up by grid electrode from 0.1 % Fe:LN illuminated by the concentrated solar light.

3. Discussions and conclusion

We have observed self-pulsations of electrical current, photo-induced in Fe-doped LN crystal monitored by electro-wetting effect from the drop of the nematic liquid crystal placed on C-surface of LN.

Theoretical model of the electrical self-pulsation is based on photogalvanic/pyroelectric charging of LN crystal that have nonlinear (N-type) volt-ampere characteristic (similar to discussed in [5]). Numerical simulations are illustrated by the phase-plot diagrams.

Optical pulsations of the laser beam reflected from the LC droplet coincides with the electrical pulsations. Dancing Interference patterns can be explained as single-beam parametric dynamic holograms, as parameters of electro-wetting are modulated by the same laser beam. Period of pulsations, induced by concentrated Sun illumination (~ 0.05 s) fit well with theoretical estimations (~0.04 s).

Illumination by laser and Sun light generates CW photogalvanic current with contribution from pyroelectric effect during transient heating when temperature changes in time. These currents create charge accumulations mainly on the C-surfaces until break-down voltages produce discharges.

The discharges generated by light may be mainly via the surface area with enhancements, due to plasma formation in the surrounding air. Possible contribution to the electrical discharges may come from the dynamic domain reversal [6].

Further investigation of electro-wetting pulsations may help not only for detection but also be used for characterization of electrical pulses.

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