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Generation of Femtosecond Current Pulses Using the Inverse Magneto-Optical Faraday Effect

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Abstract—A new method of generating ultrashort current pulses is proposed that is based on the optical pumping of a mesoscopic structure comprising a metal ring with a core made of a material possessing giant magneto-optical susceptibility. The main dynamic characteristics of the proposed device are calculated. © *2005 Pleiades Publishing, Inc.*

Further progress in the field of information storage media with increased density of recording requires the creation of devices capable of ultrafast data manipulation. The operation speed of such devices is determined by the duration of pulses of the applied magnetic and electric fields (i.e., of the current and voltage) inducing, for example, the magnetization reversal in magnetic nanoelements. A promising basis is provided by ultrafast lasers producing pulses with widths on the order of several tens of femtoseconds [1], but this approach is limited by the response of elements converting optical energy into electricity.

This Letter describes the design and estimates the dynamic characteristics of an ultrafast photodetector capable of converting short light pulses into electric current pulses of practically the same width.

Recently, Kimel *et al.* [2] studied the optical orientation of spins by means of the inverse Faraday effect and showed that a circularly polarized light pulse with a width of 200 fs induced magnetic field pulses of the same width and an amplitude on the order of several teslas in a dysprosium orthoferrite ($DyFeO_3$) crystal. Our idea consists in that, according to the law of electromagnetic induction, such short magnetic field pulses must generate an intense vortex electric field and, hence, induce an emf in a conductor occurring in this field.

Indeed, let us perform a simple calculation. Assume that the magnetic field B is optically induced in a dysprosium orthoferrite crystal and varies in time, following the light pulse intensity as described by the Gauss function:

$$B(t) = B_0 \exp\left(-\frac{t^2}{2\sigma^2}\right), \tag{1}$$

where t is the time, B_0 is the magnetic field amplitude, and $2\sigma\sqrt{\ln 2}$ is the pulse full width at half maximum (FWHM). Owing to the continuity of the magnetic induction component normal to the crystal surface, and due to a negligibly small spontaneous magnetization of the crystal (about 8 G for $DyFeO_3$), the field intensity in a conducting ring on the crystal surface will be virtually the same as that inside the ring. The resulting emf $\varepsilon(t)$ induced in the ring is equal to the time derivative of a magnetic flux through the ring surface:

$$\varepsilon(t) = \frac{\varepsilon_0 t}{\sigma} \exp\left(-\frac{t^2}{2\sigma^2}\right), \tag{2}$$

where $\varepsilon_0 = B_0 S/\sigma$ and S is the surface area.

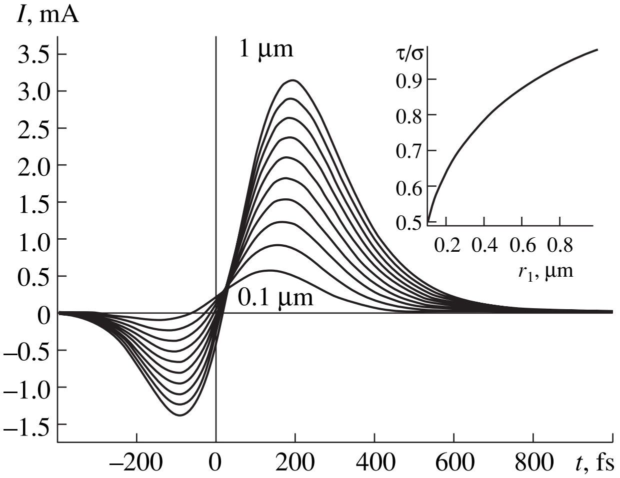
Considering the ring as a serial circuit with resistance R, inductance L, and emf given by Eq. (2), we readily obtain an expression for the current pulse in this circuit:

$$\begin{aligned} I(t) = -\frac{B_0 S}{L}\Bigg\{ &\exp\left(-\frac{t^2}{2\sigma^2}\right) \\ &- \frac{\sigma\sqrt{\pi}}{\tau}\left[1 + \operatorname{erf}\left(\frac{t}{\sigma\sqrt{2}} - \frac{\sigma}{\tau\sqrt{2}}\right)\right] \exp\left(\frac{\sigma^2}{2\tau^2} - \frac{t}{\tau}\right)\Bigg\}, \end{aligned} \tag{3}$$

where $\tau = L/R$ is the relaxation time. For the ring representing a toroid with the median radius r_1 and the cross section radius r_2, the resistance and inductance can be determined as [3]

$$\begin{aligned} R &= \frac{2\rho r_1}{r_2^2}, \\ L &= \mu_0 r_1 \left(\ln\frac{8 r_1}{r_2} - \frac{7}{4}\right), \end{aligned} \tag{4}$$

where μ_0 is the permeability of vacuum and ρ is the resistivity of the conductor. The current profiles calcu-



Time variation of the optically induced current I in a gold ring on the surface of a $DyFeO_3$ crystal. The calculations have been performed for a toroidal ring with variable radius r_1 = 0.1–1 µm and a cross section radius of r_2 = 30 nm, in which the magnetic field pulse with an amplitude of 0.01 T is induced by a 200-fs light pulse. The inset shows the plot of τ/σ versus r_1.

lated using Eq. (3) are presented in the figure. As can be seen, the current pulse amplitude increases with the radius of the ring, while the pulse duration remains virtually unchanged.

An important feature of the proposed device is a high sensitivity to the sign of the circular polarization of light. By analogy with the spintronics, where an additional quantum degree of freedom (spin) of charge carriers is employed, the proposed device makes use of an additional optical degree of freedom: the polarization of light. Therefore, this device may be classified as belonging to the new field of so-called spin-optronics.

In conclusion, it should be noted that the proposed device, in addition to performing the direct function of an ultrafast photodetector, can be applied in many other fields of physics. For example, it can be used for generating pulsed spin currents [4, 5] and for obtaining pulsed magnetic fields in investigations into the magnetization dynamics in nanomagnets [6]. Taking into account the femtosecond duration of the generated current pulses, the proposed device can also be used a source of radiation in the terahertz range, the development of which is among the urgent tasks in modern technical physics [7, 8].

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