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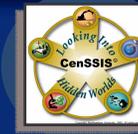
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Acoustical Sensing and Slow-down of light in dynamic holographic double-functional interferometer



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Introduction

Double-functional (optical and electrical) interferometer was realized using holographic recording of dynamic gratings in the semiconductor crystal of CdTe. We suggest a new method of the slow-down of light pulses, based on beam coupling and generation of holographic current (sometimes called holographic photo-electro-optic force (EMF)) in semiconductor materials. Two types of the nonlinear response is considered: 1) fast one (nanosecond), based on plasma, Drude-Lorentz nonlinearity, related to the electron concentration modulation and 2) based on electro-optic effect (in microsecond). Motivation: improvement of biomedical acousto-phonic imaging, acoustical sensing.

Theoretical Model

In order to describe the slow-down of light, we will use "standard" photorefractive equations [7, 8] for determination of the photoinduced electric field, E , and the electron concentration, n , generated from N -ionized impurity centers:

$$\begin{aligned} \frac{\partial N}{\partial t} &= SI(N-N^*) - mN^* \\ \epsilon_0 \frac{\partial E}{\partial t} + e\mu n E + eD \nabla^2 n &= J \\ \nabla(\epsilon_0 \epsilon E) &= e(N - N_A - n) \end{aligned}$$

Here ϕ is the phase difference between the two beams, $I_{1,2}$ are the intensities of the beams and both phase difference and intensity may be time-modulated. Seeking solutions in the form of Fourier harmonics:

$$n = n_0 + (n_1 e^{ikr} + c.c.)$$

We can also get the small contrast approximation (without external electric field):

$$\begin{aligned} \frac{\partial n_0}{\partial t} &= SI_0(N - N_A) - \frac{n_0}{\tau} \\ \tau_r \frac{\partial n_1}{\partial t} &= n_0 \left(\frac{m}{2} + i \frac{E_1}{E_k} \right) - n_1 \\ \tau_\mu \frac{\partial E_1}{\partial t} &= iE_1 \frac{n_1}{n_0} - E_1 \end{aligned}$$

ϵ is the relative dielectric constant of the material, ϵ_0 is the permittivity, e is the electron charge, μ and D are the mobility and diffusion coefficients of the electrons, respectively, S is the cross-sections of the impurity photoionization, I is the light intensity, r is the recombination coefficient, J is the total current, N is the total concentration of impurities, and N_A is the concentration of compensating centers. The electric field, E , and conductivity, $\sigma = e\mu n$, are spatially and temporally modulated by the nonstationary interference pattern given by:

$$\begin{aligned} I &= I_0 \left(1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} e^{ikr} + c.c. \right) \\ m &= m_0 e^{i\phi} \equiv \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} e^{i\phi} \end{aligned}$$

Where m is contrast of interference pattern and k is holographic grating vector

Here $\tau = 1/\rho N_A$ is the recombination time, $\tau_r = \epsilon_0/\sigma$ is the Maxwell relaxation time, and E_D and E_k are the diffusion and limiting space-charge fields. For the Maxwell wave equation for the light electric field:

$$\nabla^2 \vec{F} = -k_0^2 (\epsilon_0 + \Delta\epsilon) \vec{F}$$

With dielectric constant $\Delta\epsilon$ modulated by the linear electrooptic effect:

$$\Delta\epsilon = r_{eff} n^* E$$

For the amplitude of $Cl, 2$ of the two interfering waves and our coupled equations. Here, $\Gamma = r_{eff} n^* \cos\theta$ is the effective electro-optic coefficient, k_0 is the wave number, 2θ is the cone angle of two intersecting beams, n is the refractive index, and z is a coordinate along the crystal thickness.

$$\begin{aligned} \vec{F} &= (C_1 e^{ikr} + C_2 e^{ikr} + c.c.) \\ \frac{\partial C_1}{\partial z} &= -i\Gamma E_1 C_2 \\ \frac{\partial C_2}{\partial z} &= -i\Gamma E_2^* C_1 \end{aligned}$$

Phase Modulation: Linear Ramp and Step Modulation

For some applications, including vibrometry and biomedical imaging [1, 8], it is important to monitor phase-modulated signals, using beam-coupling technique. We will consider linear ramp phase difference between interacting beams such that $m = m_0 \exp(i\Omega t)$. For the space-charge field, choosing initial conditions for E_1 as the steady-state solution without phase modulation, we can get for the Electric Field, E_1 :

$$E_1 = E_1(0) \frac{e^{i\Omega t} + i\Gamma\Omega e^{-t/\tau}}{1 + (T\Omega)^2}$$

For the output intensity of phase-modulated beam and for holographic current, calculations give:

$$\begin{aligned} I_2 &= I_{20} + \frac{\Gamma z m_0 E_D (I_{10} I_{20})^{1/2}}{(1 + E_D/E_k)(1 + (T\Omega)^2)} [1 + T\Omega(T\Omega \cos \Omega t - \sin \Omega t) e^{-t/\tau}] \\ J_h &= \frac{\sigma_0 m^2_0 E_D T\Omega}{(1 + E_D/E_k)(1 + (T\Omega)^2)} [1 + (\cos \Omega t + T\Omega \sin \Omega t) e^{-t/\tau}] \end{aligned}$$

here z is the crystal thickness, I_{10}, I_{20} are the input intensities. Step-phase modulation may be considered as a limiting case of a linear ramp phase modulation with Ω approaching infinity, with rise-time of the ramp signal T diminishing toward zero such that the product $\Omega T = \Psi$ is the phase shift, introduced by the step-like signal. From the Electric field, E_1 we can get the time dependence of the output intensity and holographic current for the step-like phase modulation:

$$\begin{aligned} I_2 &= I_{20} + \frac{\Gamma z m_0 E_D (I_{10} I_{20})^{1/2}}{(1 + E_D/E_k)} [1 - e^{-t/\tau} + \cos \Psi e^{-t/\tau}] \\ J_h &= \sigma_0 m^2_0 E_D \sin \Psi e^{-t/\tau} / (1 + E_D/E_k) \end{aligned}$$

One can see from the output intensity is an even function of the phase shift Ψ . This means beam coupling is phase sign insensitive, or in quadrature. Switching-on of the modulation will be detected in the output beam as signal decaying with the given relaxation time, but "on" and "off" functions will give the same sign of the signal. At the same time holographic current will be an odd function of the phase step-like jump and may be used for discrimination of the "on" and "off" functions.

Plasma DLN-Intensity Modulation

For the simple case of intensity modulation as a step-function ($I_1(t > 0) = I_{10}$ and $I_1 = 0$ for $t < 0$), calculations based on the iteration procedure for DLN case [10,11] give results:

$$I_1 = I_{10} + 1/2(\alpha\epsilon\beta\tau)^2 I_{10} I_{20} (I_{30} - I_{10})(t/\tau + e^{-t/\tau} - 1)e^{-t/\tau}$$

Here, $\alpha = e(N - N_A)$ is the absorption coefficient and τ is the hologram thickness. The physical mechanism of this transformation is transient energy transfer [10,11], that is pronounced for the coupling of beams with different intensities.

Fast response: Drude-Lorentz nonlinearity (DLN)

To consider response on the high intensity and pulsed laser illumination we will analyze modulation of dielectric constant by the photo-excited free carriers (plasma of electrons), or Drude-Lorentz nonlinearity (DLN), $\Delta\epsilon = \gamma_0 n$. Here $\gamma_0 = e^2/m_0^2 n$ is an effective mass of electron in the semiconductor, n is light frequency, and n_0 is the concentration of free carriers (electrons). In a small contrast approximation, dielectric interacting laser beams can be found from equations:

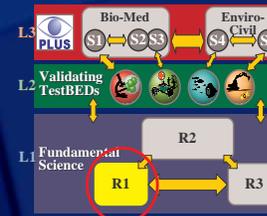
$$\frac{\partial I_1}{\partial z} = -\frac{\partial I_2}{\partial z} = 2\beta(I_1 I_2)^{1/2} \text{Im}(n_1 e^{i\phi})$$

Here $\beta = k^2 \gamma_0$, where k is the wave vector, and n_1 can be found from the estimation for DLN yield: for IR light at 1.06 microns, $\gamma_0 = 10^{22} \text{ cm}^{-3}$, for absorption coefficient 10 cm^{-1} , and recombination time 10 nanosecond we need pulsed intensity of light I_0 to reach changes in the refractive index of the order of 2×10^4 . Two types of the nonlinear response is considered: 1) fast (nanosecond), based on plasma Drude-Lorentz Nonlinearity (DLN), related to the electron concentration modulation and 2) based on electro-optic effect (in microsecond). Estimations show, that fast nanosecond response on DLN is possible for pulsed lasers with intensity about 100 MW/cm².

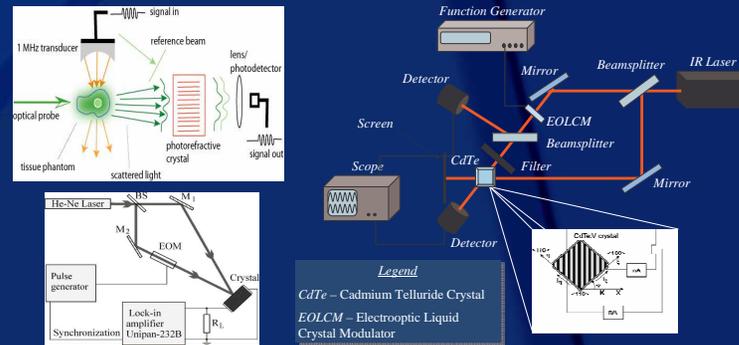
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State of the Art and Future Applications and Discussion

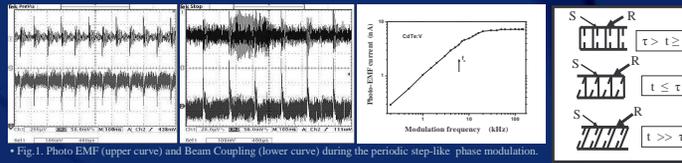
- We have developed a model that describes the transformation of time modulated optical signals by usage of the dual-dynamic holographic interferometer, with applications of the slow-down and modulation of optical signals for biomedical imaging - improving image resolution by PR crystal (NIH), acoustical 2-D sensing 2-D monitoring of the vibration source (DoD), non-destructive testing - non-contact detection of hidden defects (EPA, NIH, NASA) acoustical high-pass filtering - detecting high-frequency signals on the low-frequency noise background (DoD, NASA), slow-down of light—optical buffering in optical communication (DoD, NSF).
- The experiment was done using the semiconductor crystal CdTe, with a low-power CW IR laser with wavelength 1064 and 1150 nm. We predict the slow-down of optical pulses with the effective group velocity 555 cm/s. We suggest using both beam coupling and holographic current (holographic photo-EMF) for analyzing and delaying amplitude and phase modulated optical signals.
- Simultaneous registration of the optical and electrical signals increase reliability and sensitivity of the small phase modulation detection. Step-like phase modulation mimics pulsed modulation of the signal beam used in acousto-phonic imaging of biological objects.
- The model shows the interaction of two coherent optical beams which create holographic dynamic gratings in the semiconductor crystal and may be delayed or advanced during beam coupling.



Acousto-Photonic Medical Imaging and Experimental Setup



Results



- Fig.1. Photo EMF (upper curve) and Beam Coupling (lower curve) during the periodic step-like phase modulation.
- Fig.2. Highly sensitive vibration "bump" in Photo EMF (upper curve) and Beam Coupling (lower curve) during the periodic step-like phase modulation.
- Fig.3. High pass filter with dependence of photo-EMF current on the frequency of electrooptic modulator.
- Fig. 4. Signal to reference beam diagram.

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