Nonstationary energy transfer due to dynamic self-diffraction of light beams of equal frequency in semiconductors

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(Submitted March 31, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 9, 432–435 (5 May 1977)

Observation is reported and a theoretical explanation is presented of the redistribution of the energy of two coherent light beams intersecting in the interior of the semiconductor crystal having an induced phase-inhomogeneity relaxation time larger than or of the order of the duration of the light pulse.

PACS numbers: 78.20.—e, 42.65.Cq

It is known that the interaction of waves of equal frequency in a reactive nonlinear medium with an instantaneous local response does not lead to energy exchange between them.[1,2] Energy exchange becomes possible if the distribution of the light intensity and of the refractive index of the medium turn out to be mismatched in space; for example, in the case of a natural mismatch in unipolar crystals with nonlocal response,[3] or in the case of artificial mismatch due to the motion of the nonlinear medium,[4] or else a directed displacement of the electron-hole pairs in crossed electric and magnetic field.[5]

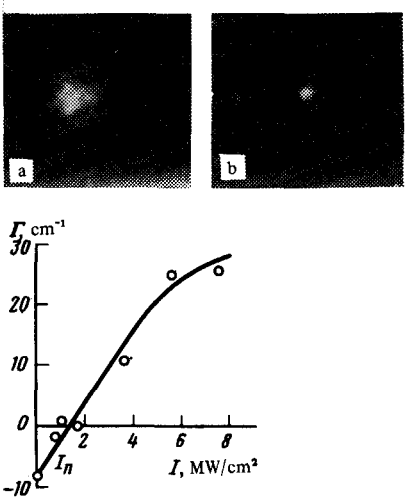

FIG. 1. Dependence of the gain on the power density of the strong beam at $2\theta = 0.03$ and $Q_{-10}/Q_{10} = 5\times10^{-3}$. The upper right corner shows the far zones of the amplified beam in the presence (a) and absence (b) of the donor beam.

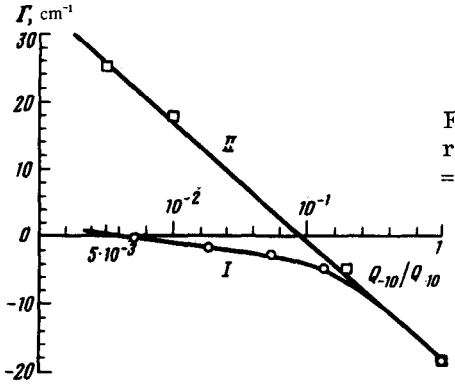

FIG. 2. Gain vs ratio of the energies of the recording beams at $I_1 = 6$ MW/cm^2 (I—$2\theta = 0.1$; II—$2\theta = 0.01$).

In semiconductor crystals, where the change of the refractive index is proportional to the concentration of the photoexcited carriers,[6] the distribution of the refractive index coincides under stationary conditions with the distribution of the light, and energy exchange is forbidden. We have observed in the present study redistribution of the energy of two pulsed light beams intersecting in a semiconductor crystal, in the case when the beam duration was comparable with the characteristic nonlinearity-relaxation time.

A single-transverse-mode neodymium-glass laser with passive Q switching (single-pulse duration 30 nsec, energy $\sim 10^{-2}$ J) was used in the experiments. The nonlinear medium was a silicon crystal, since it has a forbidden band with a width (1.15 eV) close to the energy of the neodymium-laser quantum (1.16 eV), and its absorption coefficient α (9 cm^{-1}) is sufficiently large to produce the necessary concentration of the free carriers, but small enough not to cause a strong attenuation of the intensity when the recording is affected by a three-dimensional phase grating.

The employed low-resistance ($\rho = 4$ Ω cm) silicon samples were of good optical quality and in the form of plane-parallel plates, polished with optical accuracy, and of thickness $z \sim 0.04$—0.1 cm, although the effect was observed also in high-resistance crystals.

The radiation was split into two beams, which were then applied to the crystal with a small angle 2θ between them, so as to ensure the necessary ratio of the time of diffusion erasure of the phase inhomogeneity to the pulse dura-

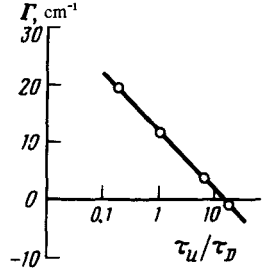

FIG. 3. Dependence of the gain on the ratio of the pulse duration to the nonlinearity-relaxation time at $I_1 = 6$ MW/cm^2 and $Q_{-10}/Q_{10} = 10^{-2}$.

tion.[1)] The crystal was mounted at an angle close to the Brewster angle, so as to reduce to a minimum the losses to Fresnel reflection. The ratio of the intensities was varied by attenuating one of the beams with neutral filters. The limiting phase shift at the maximum of the Gaussian distribution of the intensity over the beam cross section was approximately 2λ over the crystal thickness, so that the distortion of the transmitted beams was negligible (Fig. 1, grid) and the divergence did not exceed 12 minutes of angle.

A photomultiplier and oscilloscope were used to monitor the energy of the beams passing through the crystal and to calculate the exponential gain Γ. It was observed that amplification is realized when the power density is larger than or of the order of a threshold value 1 MW/cm^2 (Fig. 1). In a range of power-density variation up to 5 MW/cm^2, the gain increases approximately linearly; at higher densities, when the absorption of the light by the free carriers exceeds the usual band-band absorption, saturation is observed.

The gain depends on the ratio of the beam intensities; when the intensities are equal, there is no energy exchange and both beams are absorbed (Fig. 2). The effect has a maximum at convergence angles such that the diffusion time is longer than the light-pulse duration, but amplification is realized up to a tenfold excess of the pulse duration over the diffusion time (Fig. 3).

To explain the described phenomena, we used the concepts of nonstationary energy transfer (NET) developed in[7]. The gist of the NET effect is that as a result of the inertia of the relaxation of the inhomogeneously excited photocarriers, the variable-refractive-index grating produced by them does not manage to follow the variation of the interference field in the crystal. It is the resulting mismatch of the interference field and the grating which causes the energy exchange between the interacting beams. In the stationary case the mismatch vanishes and there is no energy exchange.[2)]

Our generalization of the NET theory to include semiconductor materials explains the main experimental regularities. It shows that the effect has a threshold with a value of the donor-beam power

$$I_b \approx m^* c\omega\sqrt{2\epsilon a z/\cos\theta}\{\pi e^2\tau_p[1-\exp(-\frac{az}{\cos\theta})]\}^{-1},$$

where τ_p is the duration of the step pulse (τ_p is less than or of the order of the relaxation time τ_D of the inhomogeneous excitation), m^* is the effective mass, and ϵ is the low-frequency dielectric constant.

At the experimental values ($\lambda = 1.06\ \mu$, $\alpha = 9$ cm^{-1}, $z = 0.1$ cm, $\tau_p = 5\times10^{-9}$ sec, $m^* = m_0$) we obtain $I_b = 10^{26}$ qu/cm^2 = 1 MW/cm^2, in good agreement with the experimental value (Fig. 1).

In accord with the theory, the energy is always transferred from the stronger to the weaker beam; in the case when the intensities of the interacting beams are equal, there is no effect. This conclusion agrees with the experimental data (Fig. 2).

Calculation shows that with increasing ratio $\tau_p/\tau_D \gtrsim 1$, the energy exchange decreases, and the effective energy transfer vanishes as $\tau_p \to \infty$. This conclusion, that the transfer is essentially nonstationary, agrees with the experimental data of Fig. 3.

In addition, the theory predicts the appearance of nonstationary oscillations of the intensity of the amplified beam; to observe these it is necessary to lengthen the generation pulse.

The agreement between the theoretical deductions and the experimental data on the aforementioned three points concerns the assumption that the NET effect has been observed.

We note in conclusion that an analogous NET phenomenon was observed when gratings were recorded in liquids,[9,10] but the thermal recording mechanism is characterized by times that are longer by several orders of magnitude than those observed here. Therefore the NET effect in semiconductors can be used to amplify rapidly-varying weak signals, conversion of wave fronts of radiation of pulse lasers, and study of rapidly oscillating processes.

[1)]The lifetime of the free carriers exceeded the duration of the light pulse even when the Auger-recombination channel was turned on (at $n = 5 \times 10^{18}$ cm^{-3}) and at an Auger-recombination probability $\gamma_3 = 2 \times 10^{-31}$ cm^6/sec [5] the lifetime is $\tau_3 = (\gamma_3 n^2)^{-1} \approx 2 \times 10^{-7}$ sec.

[2)]Computer simulation of the nonstationary processes in liquids was carried out in[8] in the given-field and weak-amplification approximations.

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