Amplitude versus frequency characteristic of a photorefractive crystal

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Two waves, one of which is reflected from a moving object and is frequency shifted, interfere in a photorefractive $Bi_{12}TiO_{20}$ crystal. It is found that at frequencies ranging from 0 to 110 Hz the amplitude of the recorded hologram is a continuous function of the frequency difference between the interacting waves. © *1995 American Institute of Physics.*

Holographic recording under nonstationary conditions was studied in detail in Refs. 1 and 2. In Ref. 2 it was shown that a static hologram can be recorded in a photorefractive crystal (PRC) even when the frequency of the wave $E_s \exp\{-i\omega_s t + i\mathbf{k}_s\mathbf{r}\}$ reflected from the object differs from the frequency of the reference wave $E_r \exp\{-i\omega_r t + i\mathbf{k}_r\mathbf{r}\}$ by an amount $\delta\omega = \omega_s - \omega_r$ exceeding the reciprocal of the recording time τ_{sc} ($\delta\omega > \tau_{sc}^{-1}$). A necessary condition is that the frequency difference between the interfering waves is equal to (or a multiple of) the frequency of the alternating field applied to the crystal.

The recording process can be represented as follows. The interference pattern (IP) formed by the signal and reference waves illuminates the PRC (Fig. 1). The electrons excited into the conduction band drift under the action of the external field and this produces a photocurrent $j(\mathbf{r},t)$ in the crystal. The magnitude of this current depends on the contrast of the interference pattern and the amplitude of the applied field. The component of the photocurrent that does not vanish upon time averaging and is nonuniform in space $\sim \exp\{i\mathbf{qr}\}$ ($\mathbf{q}$ is the lattice wave vector) is responsible for the recording of the static hologram. If the frequency difference between the interfering waves is equal to the frequency of the field applied to the crystal $\delta\omega = \Omega$, then the photocurrent has the form

$$j \sim E_s \exp\{-i\omega t\} E_r^* \exp\{i(\omega + \delta\omega)t\} E_0 \exp\{-i\Omega t\} = (E_s E_r^*) E_0. \tag{1}$$

Moreover, in the case of small the electron drift lengths compared to the period of the interference pattern, an effective response of the crystal is possible if the frequency difference between the interfering waves is a multiple of the frequency of the applied field: $\delta\omega = 2\Omega$. In this case the hologram is recorded by the component of the photocurrent

$$j \sim E_s E_r^* \exp\{i\delta\omega t\}(E_0 \exp\{-i\Omega t\})^2 = (E_s E_r^*) E_0^2. \tag{2}$$

Further investigations showed that in a two-frequency electric field of the form $E(t) = E_1 \cos(\Omega_1 t) + E_2 \cos(\Omega_2 t)$ an interference pattern travelling at both the sum and difference frequencies $\delta\omega = \Omega_1 \pm \Omega_2$ can be recorded.[3] In principle, this is the preceding case with no degeneracy with respect to the field and the corresponding nonvanishing components of the photocurrent have the form

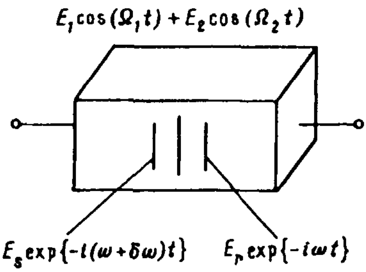

FIG. 1. Experimental arrangement.

$$j \sim E_s E_r^* \exp\{i\delta\omega t\} E_1 \exp\{-i\Omega_1 t\} E_2 \exp\{-i\Omega_2 t\} = (E_s E_r^*) E_1 E_2, \tag{3}$$

$$j \sim (E_s E_r^*) E_1 E_2^* . \tag{4}$$

Therefore, if a two-frequency electric field is applied to the crystal, then it is possible to record in the crystal moving objects such that on reflection from the objects the frequency of the incident wave is shifted, correspondingly, by the amounts $\delta\omega = \Omega_1$, Ω_2, $\Omega_1 \pm \Omega_2$, $2\Omega_1$, $2\Omega_2$.

We note that when the frequency shift $\delta\Omega$ is detuned from the "resonance" value $\delta\omega$, the amplitude of the holographic grating does not drop immediately to zero. In the case where the space-charge field relaxes exponentially as $\sim\exp\{-t/\tau_{sc}\}$, the decrease in the amplitude of the hologram has the functional dependence $\sim 1/(1+\tau_{sc}^2\delta\Omega^2)$. The width of the dropoff curve depends on the hologram formation time, and for $\delta\Omega = \tau_{sc}^{-1}$ the amplitude of the hologram will decrease by a factor of 2.

In the processes considered by us, the hologram formation time is virtually identical to the Maxwellian relaxation time $\tau_M = \epsilon^{st}\epsilon_0/\sigma_0$, where $\epsilon^{st}\epsilon_0$ is the static permittivity of the crystal and σ_0 is the average conductivity of the crystal. Ignoring the dark conductivity of the crystal, we obtain the following expression for σ_0:[4]

$$\sigma_0 \simeq e\mu\tau \frac{\alpha\beta I_0}{\hbar\omega} . \tag{5}$$

Here e is the electron charge; μ and τ are the mobility and lifetime of an electron in the conduction band; α is the optical absorption coefficient of the crystal; β is the quantum yield; $\hbar\omega$ is the energy of the absorbed photon; and I_0 is the average intensity of the light.

We now estimate the Maxwellian relaxation time for a $Bi_{12}TiO_{20}$ crystal (BTO). The characteristic values in the case where the crystal is illuminated with red light ($\lambda = 633$ nm) are as follows: $\alpha \sim 0.4-0.6$ cm^{-1}, $\epsilon = 47$, and $\mu\tau = 2 \times 10^{-8}$ cm^2/V. The result is τ_M (s)$\simeq 1/I_0$ (mW/cm^2). For light intensity of the order of 50 mW/cm^2 we have $\tau_M \approx 0.02$ s. Correspondingly, the amplitude of the hologram decreases by a factor of 2 when the frequency is detuned from "resonance" by $\delta\Omega = 50$ s^{-1}.

It is therefore indeed possible to obtain a continuous dependence of the amplitude of the hologram on the frequency difference between the interfering waves.

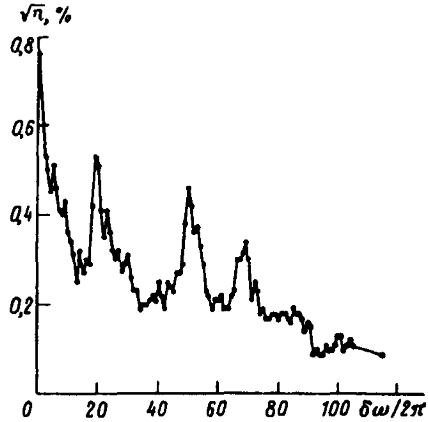

FIG. 2. Diffraction efficiency $\eta^{1/2}$ versus the frequency shift $\delta\omega$.

The experimental arrangement is shown in Fig. 1. A He–Ne laser beam ($\lambda = 633$ nm and $P = 6$ mW) was divided into two beams. One beam was reflected from a moving piezoelectric mirror, to which a sawtooth voltage with a steep trailing edge was applied. The frequency of the voltage applied to the piezoelectric mirror was varied from 0 to 110 Hz. The second beam was directed into the BTO crystal, where it interfered with the first beam and formed a travelling interference pattern with contrast $m = 0.3$. The wave vector of the grating $q = 6000$ cm^{-1} was directed along the $1\bar{1}0$ axis of the crystal. An electric field $E(t) = E_1 \cos(\Omega_1 t) + E_2 \cos(\Omega_2 t)$ was also applied in the same direction. The amplitudes E_1 and E_2 were both equal to 5 kV/cm and the frequencies were equal to $\Omega_1 = 2\pi \cdot 19$ Hz and $\Omega_2 = 2\pi \cdot 50$ Hz. The polarization of the interacting waves made an angle of 45° with the plane of incidence at the center of the crystal; this was an optimal arrangement for the given geometry of the experiment. The diffraction efficiency was determined by reading the hologram with a reference beam with the signal beam covered. The diffraction efficiency $\eta^{1/2}$ of the hologram as a function of the frequency shift $\delta\omega$ is shown in Fig. 2.

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[1] S. I. Stepanov in *Optical Holography with Recording in Three-Dimensional Media* [in Russian], edited by Yu. N. Denisyuk, Nauka, Leningrad, 1986, p. 17.

[2] A. V. Dugin, B. Ya. Zel'dovich, P. N. Il'inykh, and O. P. Nesterkin, Zh. Éksp. Teor. Fiz. **102** 1469 (1992) [Sov. Phys. JETP **75**, 796 (1992)].

[3] B. Ya. Zel'dovich and P. N. Il'inykh, *Recording of a Traveling Interference Pattern in a Two-Frequency Field in a Crystal* [in Russian] (in press).

[4] M. P. Petrov, S. I. Stepanov, and A. V. Khomenko, *Photosensitive Electro-Optic Media in Holography and Optical Information Processing* [in Russian], Nauka, Leningrad, 1983.

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