Self-diffraction of frequency modulated light in the Bi12TiO20 crystal

M. Bryushinin, V Kulikov, I. Sokolov, Philippe Delaye, Gilles Pauliat

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OPTICAL PROPERTIES

Self-Diffraction of Frequency-Modulated Light in the $Bi_{12}TiO_{20}$ Crystal

M. A. Bryushinin[a, *], V. V. Kulikov[a], I. A. Sokolov[a], P. Delaye[b], and G. Pauliat[b]

[a] *Ioffe Physical-Technical Institute, Russian Academy of Sciences, Politekhnicheskaya ul. 26, St. Petersburg, 194021 Russia*

* *e-mail: mb@mail.ioffe.ru*

[b] *Laboratoire Charles Fabry, Institut d'Optique Graduate School, Centre National de la Recherche Scientifique (CNRS), l'Université Paris-Sud, Campus Polytechnique RD 128, 2 avenue Augustin Fresnel, Palaiseau, 91127 France*

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Abstract—The self-diffraction of frequency-modulated light in the photorefractive $B_{12}TiO_{20}$ crystal was studied experimentally. To observe the effect, the crystal was illuminated by two light beams with the relative frequency shift $\Delta f(t)$. In the experiments, linear frequency modulation was used: $\Delta f(t) = At$. As a result of the light self-diffraction on a hologram moving with a constant acceleration, the power of the light beams at the crystal output changed in the form of a chirp pulse. It was found that the pulse appears at the instant of stopping the interference pattern, and its duration is determined by the rate of frequency change A and the hologram recording time τ_{sc}.

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Self-diffraction (two-wave mixing) in photorefractive materials has been studied even for several decades [1, 2]. This constant interest is due to the relative simplicity of realization of the experiments and variety of its application: the effect is observed at low light intensities and is used to study the photoelectric properties of wide-band-gap semiconductors and to detect optical phase-modulated signals, among them, in nondestructive control systems. The two-wave mixing is observed as the redistribution of the power or the phase between two light waves propagating in a photorefractive crystal. The optimization of the self-diffraction regime and the study of characteristics of the photorefractive response are often realized using the frequency shift or the phase modulation of light beams [3–5]. As a result, the self-diffraction effect is observed on a hologram that runs at a constant velocity or oscillates. In the former case, the light intensity changes detected by a photodetector (photodiode) have only a constant component, but, in the latter case, oscillations at the phase modulation frequency (sometimes, at the doubled frequency) are observed. Because the sinusoidal phase modulation can be performed due to the reflection from an oscillating object, the schemes of adaptive interferometers were proposed [6, 7] and also those allowing the measurement of the velocity [8].

In this work, we discuss our attempt of applying the linear frequency modulation (LFM) in the experiment with the two-wave mixing. In this case, the interference pattern is not simply running, but it runs at a constant acceleration, which leads to the formation of a pulsed response instead of a constant component or periodic oscillations.

The effect of two-wave mixing under conditions of linear frequency modulation of light waves was studied on the setup shown in Fig. 1. The helium–neon laser light ($\lambda = 633$ nm, $P_{out} \simeq 30$ mW) propagates through two acousto-optical modulators ML-201-1 creating frequency shifts f_0 and $f_0 + \Delta f(t)$ in diffracted beams ($f_0 = 80$ MHz). As an LFM signal generator, we used the output of an SK4-59 spectrum analyzer due to its wide

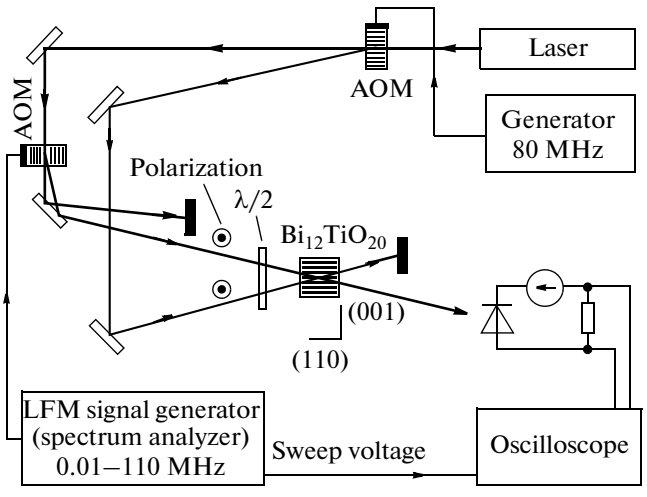

Fig. 1. Experimental setup for studying the self-diffraction of a frequency-modulated light in the photorefractive crystal $Bi_{12}TiO_{20}$. AOM is for the acousto-optical modulator.

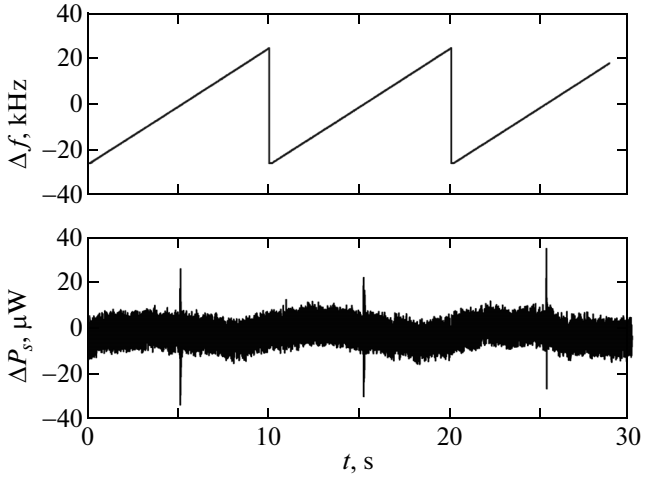

Fig. 2. Oscillograms of the frequency shift and signal of two-wave mixing ($A = 5$ kHz/s).

range of controlling the frequency deviation. The beams are directed to the sample using mirrors, where they form an interference pattern with average intensity $I_0 = 240$ mW/cm^2, spatial frequency $K = 2.3$ μm^{-1}, and contrast $m = 0.97$ (the powers of the signal and reference beams are $P_S = 3.4$ mW and $P_R = 2.0$ mW, respectively). The self-diffraction effect is studied in an undoped $B_{12}TiO_{20}$ crystal with characteristic sizes $9.5 \times 12 \times 11$ mm. The crystal has one of the standard holographic orientations: cut (110) with axis [001] lying in the light incidence plane (**K** || [001]). The front and back planes 9.5×12 mm in size were polished to the optical quality. No electrodes were deposited. Because the sample is quite thick and rotates the light polarization plane by ~70°, a half-wave plane is placed before the sample. As a result, the polarization plane in the crystal middle is perpendicular to the incidence plane. The power of the light beam propagating along the direction of the initial signal beam is measured by a photodiode and recorded on an oscilloscope. The sweep voltage of the spectrum analyzer is also applied to the oscilloscope, which allows the simultaneous measurement of the frequency shift and studied signal.

Figure 2 shows the oscillograms of the frequency shift (the difference between the modulation frequencies of the signal and reference beams) and the signal of two-wave mixing (the increase in the signal beam power) measured at the sweep rate $A = 5$ kHz/s. From the dependences, it follows that the pulses appear at the instants when $\Delta f \simeq 0$, i.e., when the interference pattern stops. In addition, it follows from Fig. 2 that the measurements are performed so that the pulses can be considered as quasi-single pulses. Actually, the characteristic time of hologram recording in $B_{12}TiO_{20}$ is $\tau_{sc} = 0.1$–1 s, and, thus, we have almost steady-state regime with $\Delta P_S \simeq 0$ at the instants of starting and finishing the sweep (in Fig. 2: 0, 10, 20, 30 s). A more

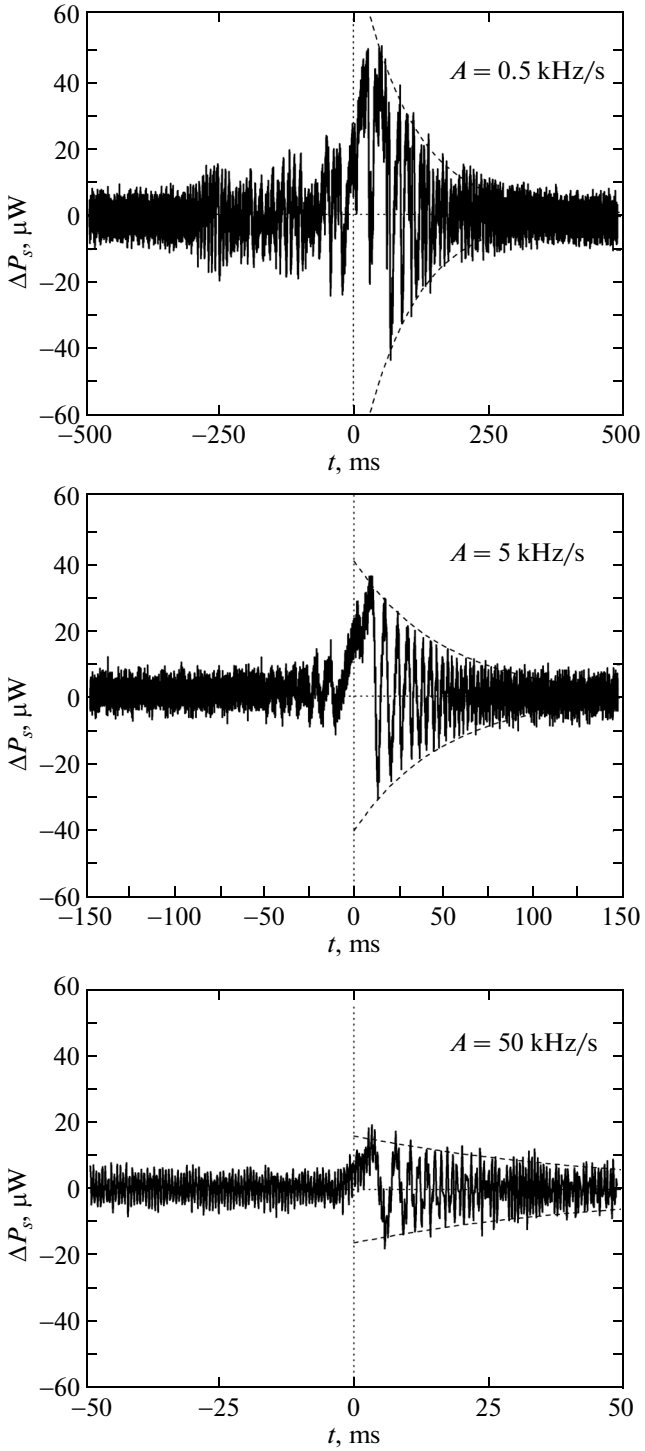

Fig. 3. Pulsed response of the two-wave mixing measured at various sweep rates.

detailed consideration shows that the time-dependent changes in the power have the form of LFM or chirp pulses (Fig. 3). The pulses with the highest amplitude are observed at the minimum sweep rate (the rates of frequency change). The choice of the sweep rate is limited. At low rates A, the pulse form becomes insta-

ble because of slow drift of the phase in the interferometer caused by insufficient vibroisolation of the optical scheme and existing air flows. At high rates A, signal becomes dim against the noise background. The appearance of the chirp pulses is explained quite simply. In the initial state ($t \longrightarrow -\infty$), frequency shift $\Delta f = At$ and the corresponding velocity of the interference pattern $2\pi\Delta f/K$ are very high, so that the space charge grating has no time to be formed in the crystal, and the two-wave mixing signal is absent. In the region $t \simeq 0$, the interference pattern slows down and stops. In the crystal, a hologram with noticeable diffraction efficiency is recorded, and the self-diffraction signal appears. Then, the interference pattern begins to accelerate, moving in the opposite direction. However, the recorded immobile hologram continues to exist in the crystal within a time on an order of τ_{sc}. The interaction of the running interference pattern and immobile hologram causes the oscillations of the power of the signal light beam. Since the immobile hologram disappears with time, the oscillations are damped. In Fig. 3, the dashed lines show the exponential decrease in the signal envelop with characteristic times τ_{sc} = 100, 50, and 50 ms. The scatter of the values of this parameter can be due to a complex structure of the impurity centers, on which the charge grating forms.

Now, we will attempt to estimate the value of the pulsed response in the case when the change in the signal beam frequency occurs very slowly, so that the phase of the "stopped" interference pattern is changed by a small value

$$|\varphi(\tau_{sc})| = \left|-2\pi\int_0^{\tau_{sc}}\Delta f(t')dt'\right| = \pi A\tau_{sc}^2 \ll 1 \qquad (1)$$

for the time of formation of space charge grating τ_{sc}.

In this case, we can assume that the two-wave mixing occurs within small time intervals as in the case with a constant frequency shift and interference pattern running at a constant velocity [9]. We begin to consider the effect from the relationship that is well known in the theory of self-diffraction: $P_S(d)/P_R(d) = P_S(0)/P_R(0)\exp(\Gamma d)$, where Γ is the gain coefficient of the two-wave mixing, and d is the crystal thickness [2]. For the increase in the "signal" beam power ΔP_S caused by a small increase in the gain coefficient $\Delta\Gamma$, the following relationship holds:

$$\Delta P_S = -\Delta P_R = \frac{P_R P_S}{P_R + P_S}\Delta\Gamma d. \qquad (2)$$

In our experiment, the initial state is that in which the difference of the light wave frequencies is very large ($\Delta f \longrightarrow -\infty$ and, correspondingly, $\Delta\Gamma = \Gamma(\Delta f) - \Gamma(-\infty)$). At a large frequency difference Δf, the interference pattern moves very fast, so that the hologram has no time to be formed in the crystal: $\Gamma(-\infty) = 0$. As a result, we have $\Delta\Gamma = \Gamma(\Delta f)$. When the spatial frequencies are not very high ($K^2L_S^2 \ll 1$, where L_S is the Debye screening length), the gain coefficient can be represented as follows [9]:

$$\Gamma(\Delta f) = 2\delta\,\mathrm{Im}\frac{iE_D}{1 + i2\pi\Delta f\tau_{sc}}, \qquad (3)$$

where $\delta = \pi n_0^3 r/\lambda'\cos\theta$ is the coefficient used when describing the diffraction in photorefractive crystals [9]; n_0 is the light refraction index; r is the effective electro-optical coefficient; $\lambda' = c/(f_L + f_0)$ is the light wave length after transmitting the acousto-optic modulator; 2θ is the angle between beams in the crystal; and Im denotes the imaginary part of a complex variable. Then, using $\Delta f(t) = At$ for the considered case of linear frequency modulation, we obtain the final expression for the pulsed response of the two-wave mixing

$$\Delta P_S(t) = \frac{2P_R P_S\delta E_D d}{P_R + P_S}\frac{1}{1 + (2\pi A\tau_{sc}t)^2}. \qquad (4)$$

It is evident that this expression is not completely applicable to the description of the experimental dependences shown in Fig. 3. In particular, Eq. (4) does not contain oscillating terms. Nevertheless, we can estimate the maximum amplitude of the pulse when the experiment would be performed at condition (1): $2P_R P_S\delta E_D d/(P_R + P_S) = 470$ μW. In our experiment, the pulse amplitude was an order of magnitude smaller, which can be explained by the facts that condition (1) is not fulfilled and also the light absorption is noticeable and the two-wave mixing has a vector character [2]. From Eq. (4), we can also estimate the pulse duration $\tau_p = 1/(\pi A\tau_{sc})$. According to the estimation, the pulse durations would be τ_p = 13, 1.3, and 0.13 ms for τ_{sc} = 50 ms and A = 0.5, 5, and 50 kHz/s, respectively. The evident difference with the experimental results (Fig. 3) indicates that it is necessary to perform a theoretical analysis of the effect describing both the "quasi-steady-state" excitation of the self-diffraction pulse at $\pi A\tau_{sc}^2 \ll 1$ and the appearance of the chirp- pulse at a high rate of frequency change ($\pi A\tau_{sc}^2 \geq 1$).

The effect revealed can be used in the problems of determination of the photoelectrical parameters of wide-band-gap semiconductors: the measurement of the time of hologram recording τ_{sc} allows the estimation of the specific photoconductivity of a crystal [1, 2]. However, the application of the effect in laser velocimeters and accelerometers seems to be most promising. Actually, the instant of appearance of the pulse is unambiguously determined by the condition of equality of the frequencies of the signal and reference light beams. Giving certain frequency shift in one of the beams and detecting the pulse, we can argue that, at this instant of time, an unknown Doppler fre-

quency shift in another beam is equal to the given shift, and thus, we measured the instantaneous velocity of an object. In addition, the time, form, and possible filling of the pulse are related to the rate of modulation frequency change (Fig. 3); thus, the measurement of the characteristics gives information on the acceleration of the object. A unique feature of this method of measuring the velocity and acceleration is that both parameters can be estimated by detecting a single pulse, which is of particular importance when studying fast processes.

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