The difference between the charged-particle currents in the ends and in the side walls of the chamber leads to the appearance of a current along the torch. It follows from the azimuthal variation of f (Fig. 1e) that, on the average, an ion current I_i flows along the torch in an outward direction. The interaction between this current and the magnetic field leads to the appearance of a force $(1/c)\vec{I}_i \times \vec{H}$, which can be responsible for the torch rotation. It must also be noted that the obtained distributions of n_i and φ over the discharge cross section are well confirmed by the plasmograms observed under these conditions [1].

[1] M. A. Vlasov, JETP Letters 2, 274 (1965), translation p.174.

OBSERVATION OF PARAMETRIC AMPLIFICATION IN THE OPTICAL RANGE

S. A. Akhmanov, A. I. Kovrigin, A. S. Piskarskas, V. V. Fadeev, and R. V. Khokhlov
Physics Faculty, Moscow State University
Submitted 23 July 1965

We report here the results of an experiment in which we observed directly parametric amplification of an optical signal with wavelength $\lambda_s = 1.06\ \mu$ in a KDP crystal excited by an intense pump wave with $\lambda_p = 0.53\ \mu$. The feasibility of such an effect in the optical band and its theory were detailed in [1-3]; results of experiments in which parametric amplification at wavelength $\lambda_s = 0.63\ \mu$ has been indirectly registered are described in [4].

In a nonlinear medium with a polarization that depends quadratically on the magnetic field intensity, the energy of an intense pump wave (frequency ω_p) can be transferred to waves with frequencies ω_1 and ω_2 satisfying the relation $\omega_p = \omega_1 + \omega_2$. The energy transfer is most effective if the following relation is satisfied between the wave vectors of the interacting waves (the so-called synchronism condition):

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_p. \qquad (1)$$

The parametric amplification effect has a clearly pronounced threshold. An approximate relation (which is valid for sufficiently large crystal length ℓ) for the threshold-pump amplitude $A_{p.thr}$ is [2]:

$$\Gamma_0^2 = \left(\frac{2\pi}{c^2}\right)^2 \frac{\omega_1^2\, \omega_2^2\, A_{p.thr}^2}{k_1 k_2} \cdot \frac{(\vec{e}_1\, \chi^{\omega_p-\omega_2}\, \vec{e}_p\, \vec{e}_2)\, (\vec{e}_2\, \chi^{\omega_p-\omega_1}\, \vec{e}_p\, \vec{e}_1)}{-\cos \widehat{\vec{k}_1 \vec{s}_1} \cdot \cos \widehat{\vec{s}_1 \vec{z}_0} \cdot \cos \widehat{\vec{k}_2 \vec{s}_2} \cdot \cos \widehat{\vec{s}_2 \vec{z}_0}} \simeq \delta_1 \delta_2. \qquad (2)$$

Here $\vec{e}_i$ are unit vectors characterizing the polarization of the interacting waves, $\vec{s}_i$ their ray vectors, $\vec{z}_0$ the normal to the boundary of the nonlinesr medium, $\chi^{\omega_p-\omega_i}$ the spectral components of the nonlinear polarizability tensor, and δ_i the damping decrements at the frequencies $\omega_{1,2}$. When $A_p < A_{p.thr}$ a wave of frequency ω_1 (signal wave) attenuates on entering the crystal, and the supplementary wave of frequency ω_2, which is produced in the crystal, first increases and then also attenuates. Therefore indirect measurements of parametric amplification, for example by recording the difference-frequency oscillations (the procedure used in [4]) are not always reliable enough.

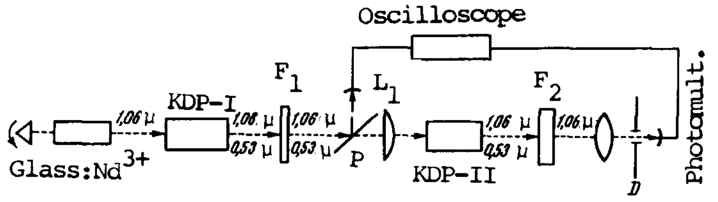

Fig. 1. Block diagram of experimental setup; F_1 - filter (S3S-21), F_2 - infrared filter (IKS-1), D - diaphragm, L_1 - cylindrical lens, P - plane-parallel plate.

In our experiments with KDP crystals, condition (2) was satisfied by using an optical frequency doubler as a pump generator.1) A block diagram of the experimental setup is shown in Fig. 1. A neodymium-glass laser was used as the master frequency-doubling generator (KDP-I crystal $l = 3$ cm long), and served simultaneously as the generator of the amplified signal. At the output of the frequency doubler, the power ratio of the second harmonic (P_2) to the fundamental radiation (P_1) was $P_2/P_1 = 0.2 - 0.3$. After passing through the filter system F_1, this ratio became equal to $P_2/P_1 = 10^4 - 10^5$. Thus, the second, amplifying KDP crystal was fed with a weak signal ($\lambda_s = 1.06$ μ) and a powerful pump wave ($\lambda_p = 0.53$ μ). The pump was focused on crystal KDP-II ($l = 3$ cm) with the aid of a cylindrical lens L_1 (focal distance 13 cm) so that the pump power density in the second crystal reached $S_2 \simeq 100$ MW/cm^2. A two-channel photoelectric circuit or photographic film was used to register the change in the signal intensity in the KDP-II crystal.

The most illustrative results are those obtained by photography of the output signal. Figure 2 shows curves obtained by photometry of the photographed cross section of the signal beam at the output of the amplifier crystal. The abscissas represent the angle θ measured from the synchronism direction in a plane passing through the optical axis; the ordinates represent the signal power in relative units. Curve 1 corresponds to the pump "turned off," and curves 2 - 5 to the pump "turned on." The latter were obtained under identical controlled experimental conditions. The pump was "turned off" either with the aid of an infrared filter, which left the signal power practically unchanged, or by changing the orientation of the pump beam relative to the synchronism direction in the KDP-II crystal (the gain dropped almost to zero when the beam deflection exceeded 10').

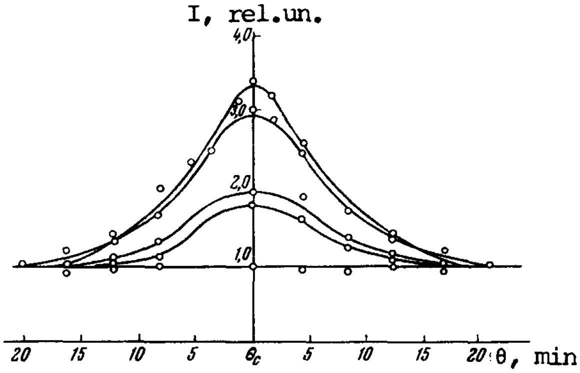

Fig. 2. Angular distribution of signal intensity at the output of the amplifying crystal.

The curves show that appreciable parametric amplification takes place only in a relatively narrow angle $\Delta\theta_y^{(e)} \simeq 10'$. The maximum gain G_{max} corresponds to the exact synchronism direction. In our experiments, G_{max} fluctuated from flash to flash (see Fig. 2); the average value registered experimentally was $\overline{G}_{max} \simeq 2.5$. The theoretical value is $G_{max}^{(theor)} = \exp[2(\Gamma_0 - \delta_s)l]$ for our experimental conditions amounts to 14 (we used the following values: $\Gamma_0 = 2.2 \times 10^{-6} A_p$ cm^{-1} (A_p is in V/cm), $S_2 = 10^8$ W/cm^2, $l = 3$

cm, and $\delta_s = 0.05$ cm^{-1}). The theoretical value of $\Delta\theta_y^{(t)}$ (the so-called capture angle) is determined from the condition $\Delta = k\Delta\theta_y^{(t)} = 2k\Gamma_0$ (here $\Delta = 2k_s - k_p$ for rays deviating from the synchronism direction). For our crystals $k = 0.25 \times 10^4$ cm^{-1} and $\Delta\theta_y^{(t)} \simeq 1.5'$. The difference between $\Delta\theta_y^{(t)}$ and $\Delta\theta_y^{(e)}$ is connected, in our opinion, with the finite width of the spectrum and with the divergence of the pump wave.

The appreciable fluctuations of the parametric amplification from pulse to pulse and the small average gain (compared with theoretical) may be due to singularities of the parametric interaction in the degenerate mode. Indeed, we know that in the degenerate mode the gain is equal to $G_{\max}^{(\text{theor})}$ only in the presence of an optimal phase shift between the pump and the signal. In our installation the phase shift was produced by a system of filters located between crystals I and II. At the same time, it must be noted that the phase selectivity of the degenerate optical parametric amplifier with multimode pumping (in our experiments the width of the pump spectrum reached 10 Å) is smaller than under single-mode conditions; the spectrum of the multimode signal broadens upon interaction with the multimode pump; additional modes appear, the gain of which is governed by the laws of nondegenerate parametric amplification.

The gain attained by us is sufficient for realization of a parametric light generator - a device which makes possible continuous tuning of the frequency of coherent optical oscillations. 2)

We are grateful to V. G. Dmitriev for useful discussions.

[1] R. H. Kingston, Proc. IRE 50, 472 (1962).

[2] S. A. Akhmanov and R. V. Khokhlov, JETP 43, 351 (1962), Soviet Phys. JETP 16, 252 (1963); Problema nelineinoi optiki (The Problem of Nonlinear Optics), M., 1964.

[3] N. M. Kroll, Phys. Rev. 127, 1207 (1962).

[4] C. Wang and G. Rocette, Appl. Phys. Lett. 8, No. 8 (1965).

[5] Akhmanov, Kovrigin, Strukov, and Khokhlov, JETP Letters 1, No. 1, 42 (1965), translation 1, 25 (1965).

[6] J. A. Giordmaine and R. C. Miller, Paper at the Conference on Quantum Electronics, 28 - 30 June, 1965, San Juan, Puerto Rico.

1) The possibility of observing nonlinear effects in the radiation field of such a generator was demonstrated earlier [5].

2) Giordmaine and Miller [6] recently reported the construction of a tunable light generator with a new, high-efficiency nonlinear $LiNbO_3$ crystal.