NONLINEAR NEGATIVE ABSORPTION OF RESONANCE LIGHT IN RUBY AND NEODYMIUM GLASS

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Submitted to JETP editor June 29, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) **49**, 1718-1722 (December, 1965)

A drop of the negative absorption of resonance light in the course of a monopulse and its distortion during propagation in inverted ruby single crystals and neodymium glass have been observed. The experimental results are compared with the calculation.

THE negative light absorption maintained in a medium by a constant pumping of limited intensity drops under the stimulating influence of the resonance signal. For this reason, negative absorption is nonlinear with respect to the energy of the signal propagated through the medium, and the shape of resonance light pulse changes in the medium [1-5]. This phenomenon has been observed in synthetic ruby by high-speed photography but no quantitative comparison of the results with the calculation has been made [6].

The present experiment was aimed at drawing such a comparison for ruby, and also observing a similar phenomenon in the four-level system of neodymium ions in glass.

The experimental conditions for ruby were as follows: a sample with a 90-degree orientation, a chromium ion content of 0.05% and bleached end surfaces was 239 mm long and 13 mm in diameter; the pumping was done with two IFP-5000 lamps; the input light monopulse came from a ruby laser with a nonlinear filter of KS-19 glass; the input and output light pulses were recorded with F-5 photocells on an S1-7 oscilloscope (as a result, the experimental plots pertaining to the single pulse do not contain individual points, but are in the form of continuous curves obtained from the oscillograms); the absolute energies of the light signals were determined calorimetrically.

To exclude the masking effect of the complex waveform of the input pulse on the phenomenon under study, the ratio of ordinates of the oscillograms of the input and output signals was found at each point of the scan; taking the calibration of the recording system into account, this represented essentially the dependence of the gain G(t) on time, measured from the start of the pulse. Graphical integration of the oscillogram of the input pulse and measurement of its energy, relative to the cross-section area of the light beam, gave the running value E(t) of the signal energy density which penetrated into the sample during time t. The function G(E) (Fig. 1) was obtained by eliminating the time from G(t) and E(t). Each continuous curve of Fig. 1, obtained from the oscillogram, represents the amplification of a separate pulse differing from the others in the total energy of the input signal or in the pumping level of the ruby. The curves are grouped in branches corresponding to various electric pump energies of the amplifier (from 3.2 to 4.7 kJ). The lack of a complete superposition of the segments of curves belonging to the same branch characterizes the experimental scatter. The isolated points of maximum amplification lying on the axis of ordinates were obtained at input signals attenuated to a maximum (E → 0). The value of the relative unit on the axis of abscissas is approximately 0.15 j/cm^2. The graphs of Fig. 1 are essentially reduced formulas of the

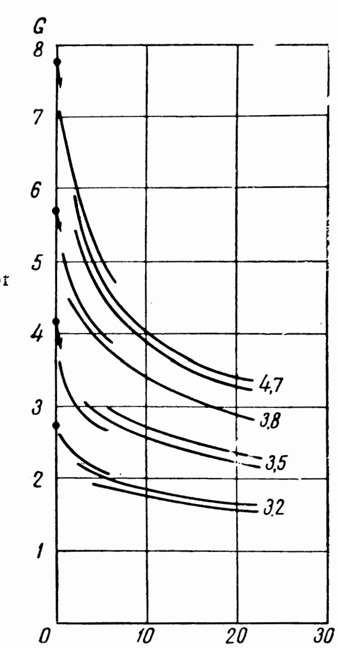

FIG. 1. Amplification factor G of ruby vs. current value of energy of input signal E(t) in the course of a monopulse

output signals of the amplifier, the input of which gets a square pulse of unit amplitude.

For comparison with the calculation, the experimental data were treated both with a formula obtained without allowing for energy dissipation in the medium [2] and with a formula allowing for nonresonance absorption with coefficient $\alpha > 0$ [3]. After some transformations and reduction to the same notation, these formulas become

$$F_1(E) = \ln[(1 - G_0^{-1})(1 - G^{-1})^{-1}] = 2Bu^{-1}E, \quad (1)$$

$$F_2(E) = (G_0G^{-1} - 1)^{1/2}(G - 1)^{-1} = (1 - \beta)^{-1}Bu^{-1}E, \quad (2)$$

where u is the velocity of light in the medium, B the Einstein coefficient of stimulated emission, $\beta \equiv \alpha u(Bh\nu n)^{-1}$, $h\nu$ the energy of a photon; n the initial excess population prior to the arrival of the amplifying pulse, $G_0 \equiv \exp[\alpha(\beta^{-1} - 1)L]$ the highest value of the amplification for $E \to 0$, and L the length of the sample. Formula (2) applies to the interval $0 \leq E \leq u(4B)^{-1}$.

The graph of $F_1(E)$ (Fig. 2a), plotted from the data of Fig. 1 by reducing the separate curves of each branch to a single average curve, obviously indicates that formula (1), written with the assumption that $\alpha = 0$, does not apply to ruby (the expected single straight line is shown dashed).

The graph of $F_2(E)$ (Fig. 2b), plotted from the same experimental data, shows the expected bundle of straight lines with the family parameter

$$Bu^{-1}(1 - \beta)^{-1} = Bu^{-1}[1 + \alpha L(\ln G_0)^{-1}],$$

that results from the linear dependence on $(\ln G_0)^{-1}$ (Fig. 3). The segment intercepted on the axis of ordinates by the straight line (Fig. 3) gives $Bu^{-1} = 0.065\ \mathrm{cm^2/J}$, and the slope gives

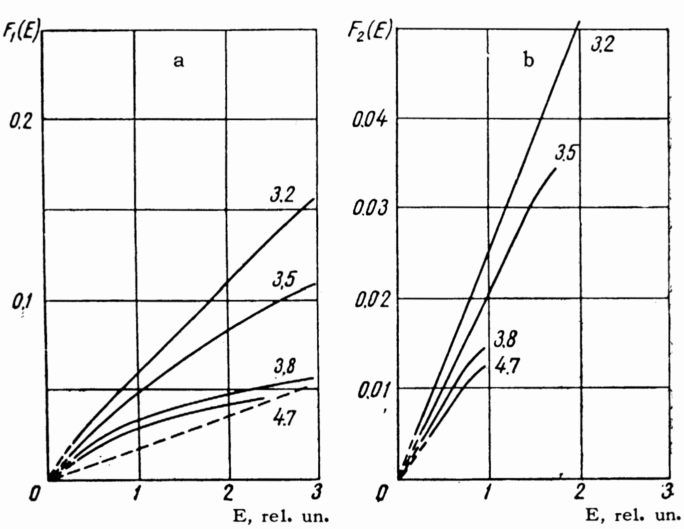

FIG. 2. Comparison of experimental data of Fig. 1 with calculated formulas: a – with (1) and b – with (2).

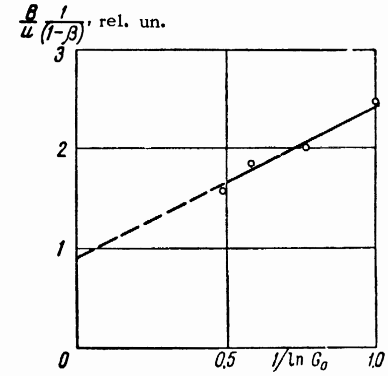

FIG. 3. Determination of the values of Bu^{-1} and α.

$\alpha = 0.064\ \mathrm{cm^{-1}}$, which, when the experimental error (about 30%) is taken into account, is not at variance with the known values [7,8] (the value of the relative unit on the axis of ordinates of Fig. 3 is about $0.07\ \mathrm{cm^2/j}$).

The experimental conditions for neodymium glass [9] were as follows. Ten samples of glass with a content of neodymium ions of about 4%, each 80 mm long and 9 mm in diameter, were placed in two compact illuminators with twelve IFP-800 lamps. The monopulse of resonance light with energy up to 0.1 j and a duration of about 150 nsec originated from a laser with a rotating prism and was directed from sample to sample by means of a system of sixteen adjustable prisms with total internal reflection. To avoid the self-excitation of the array of samples, all the reflecting planes in the path of the beam were placed in positions which excluded the possibility of the formation of a Fabry-Perot resonator of a sufficiently high Q. The preliminary adjustment of the optical system for the signal transmission was made with the beam of a red helium-neon laser. The input and output signals were recorded with a CI-7 double-beam oscilloscope by means of F-5 photocells, on which the voltage was raised to 300 V in order to increase the resolution.

A schematic representation of a typical oscillogram is shown on the right of Fig. 4. The horizontal deflection of both beams is proportional to the input power of the signal P_1. The vertical deflection of the upper beam is proportional to the output power P_2, and that of the lower beam to the running value of the input energy $E = \int_0 P_1 dt$. The slope of the straight line traced from the origin to any point of the upper oscillogram gives directly (to scale) the running value of the gain of the array $G = P_2/P_1$ at this point of the monopulse.

Thus, the deviation of the shape of the oscillo-

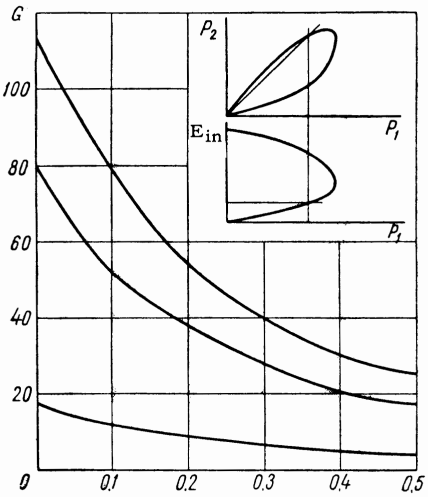

FIG. 4. Amplification factor G of an array of neodymium glass samples vs. current value of input signal energy E(t) in the course of a monopulse.

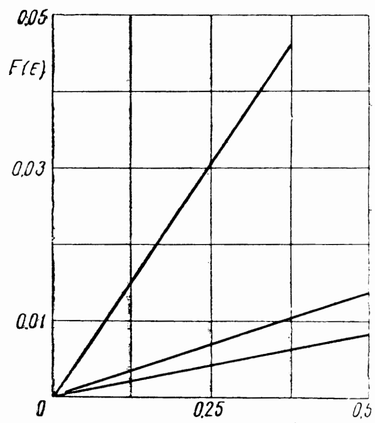

FIG. 5. Comparison of the experimental data of Fig. 4 with the calculated formula (2).

gram from a straight line immediately indicates nonlinearity of the negative absorption and deformation of the pulse. Each value G of the upper oscillogram can be compared with the corresponding value E of the lower one; when the scale calibration is taken into account, this gives the explicit function G(E). The gain unit G = 1 was determined from the slope on an oscillogram obtained by removing all the elements located between the input and output of the array. The linearity of the oscillograms in this calibration experiment simultaneously indicates a satisfactory adjustment of the input and output recording channels, which must be identical within very close tolerances because of the sensitivity of the method (for example, a 5 nsec discrepancy in the time of signal propagation in the channels is distinctly recorded on the oscillograms). The input energy of the monopulse was calibrated calorimetrically.

As a rule, in the amplification regime, the oscillograms had a loop shape which demonstrated the drop of G with increasing E in the course of the monopulse. The continuous curves of Fig. 4 were obtained by processing individual oscillograms (the relative unit on the axis of abscissas is about 0.15 j/cm^2). The upper curve pertains to fresh glass samples, and the lower curve to the same samples aged in the course of prolonged tests. The middle curve was obtained with fresh samples with additional gray filters introduced between them.

In all the experiments, the electric pump energy amounted to about 1 kj per sample for a flash of about 0.6 msec.

The comparison, of the experimental results and the calculated expression (2) in Fig. 5 shows agreement with the expected linear dependence.

When two consecutive monopulses passed through the array, a decrease was also observed in the gain of the second (G_2) as compared to that of the first (G_1), and the ratio G_2/G_1 increased with increasing interval between the pulses as a result of the effect of the pumping.

The authors are grateful to N. Al'tshil', Yu. Romanov, V. Trukhan, and A. Uits, who participated in the preparation and execution of the experiment.

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Translated by A. Peiperl
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