DISCRIMINATION OF AXIAL OSCILLATION MODES IN A LASER WITH EXTERNAL MIRRORS

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Submitted to JETP editor August 3, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) **50**, 339–342 (February, 1966)

The dependence of the beat frequency of axial oscillation modes of a neodymium laser on the distance the mirrors and the position of the neodymium rod within the resonator is investigated. It is shown that the beat frequency varies with variation of the position of the neodymium rod. The phenomenon is ascribed to a discrimination of axial oscillation modes, due to variation of the parameters of the compound resonator consisting of the external mirrors and the ends of the neodymium rod.

As is well known, a rather large number of axial and nonaxial modes can be excited in laser resonators. In the case of a resonator with plane mirrors, the frequency difference between neighboring axial modes is determined by the optical length of the resonator L and is equal to $\Delta\nu = c/2L$, where c is the velocity of light. As a result of the interaction of axial modes that differ in frequency, beats should appear and should be manifest in the modulation of the laser-emission amplitude. The beat frequencies are in this case multiples of the minimum frequency $f_1 = c/2L$, determined by the frequency difference of neighboring modes. This minimal beat frequency will determine the maximum period of the resulting periodic function, which is a superposition of all possible frequencies of the axial-mode beats.

If the laser emission contains nonaxial modes, the resultant modulation with frequency f_1 will "smear out," since the frequencies of the beats of the nonaxial modes are smaller than f_1. The effect of the beat of the axial modes was observed many times both in gas lasers[1] and in some solid-state lasers. Modulation of radiation in ruby lasers was observed both in the ordinary "spike" mode,[2, 3] and in the Q-switching mode.[4] On the other hand, no such modulation has been observed as yet in neodymium glass lasers. A possible reason is the more complicated spectral composition in a neodymium laser and the presence of a large number of nonaxial modes, the appearance of which is aided by the higher homogeneity of the neodymium glass.[5, 6]

In this paper we report an attempt to observe beats in neodymium-glass laser emission and to investigate the dependence of the modulation frequency on different laser parameters. We used in our investigation a neodymium-glass laser with external plane dielectric mirrors R_1 and R_2 with reflection coefficients of 98 and 65% respectively at a wavelength at $\lambda = 1.06$ micron. The cylindrical neodymium-glass rod had a diameter of 12 mm and a length of 120 mm. The Q-switching was with the aid of a liquid bleaching filter,[7] usually installed near one of the mirrors.[1)] The laser emission was recorded with a coaxial photocell connected directly to the deflecting plates of the cathode-ray tube of an S1-11 oscilloscope. The time constant of the entire recording system did not exceed 1×10^{-9} sec. To separate any desired section of the laser-emission beam, a diaphragm of 3 mm diameter was installed between the photocell and the mirror. The optical length of the resonator could be varied from 40 to 320 cm.

In the first experiments, the neodymium rod was installed near the mirror R_1, and the distance between the mirrors was varied by moving mirror R_2. When the resonator length L was increased from 40 to ~150 cm, the duration of the "giant" pulse increased from 25 nsec (at 40 cm) to 80 nsec (at 150 cm), but the shape of the pulse remained smooth. Starting with distances between mirrors $L \gtrsim 150$ cm, a regular structure was observed on the time sweep of the giant pulse, with a period τ_c that coincided with the quantity $\tau = 2L/c$ within the limits of experimental error (< 10%). The appearance of a structure and the depth of modulation were unstable from pulse to pulse if the radia-

[1)]The position of the filter inside the resonator did not influence the observed phenomena, and consequently it was always installed near the mirror R_1.

tion incident on the receiving surface of the photocell came from the entire end surface of the neodymium rod. When the aforementioned diaphragm was introduced into the beam, the stability increased sharply and the depth of modulation increased. The appearance of modulation at only large resonator lengths ($L \gtrsim 150$ cm) and the increase in the depth of modulation with increasing L are apparently connected with the fact that at small lengths L there can be excited in the laser, besides the axial modes, also nonaxial modes which, as already indicated, "smear out" the regular structure on the time sweep of the pulse. With increasing L the conditions for the excitation of the nonaxial modes become worse, and axial modes are predominantly excited.

On the other hand, we ascribe the increase in the stability and depth of the modulation following installation of the diaphragm to the existence of individual generation regions distributed over the cross section of the rod; these regions are not connected with one another. In the absence of a diaphragm, the modulation of the resultant signal becomes "smeared out" as a result of superposition of beats of radiation from individual regions. Installation of the diaphragm also decreases the contribution of the nonaxial modes in the radiation beam incident on the receiver. It must be noted that in these experiments, when L increases continuously, the period of the beats also changes continuously, from 11.1 to 22.4 nsec for $L = 150$ and $L = 320$ cm, respectively.

The most interesting results were obtained when the neodymium rod was displaced along the resonator axis and the resonator length L was maintained constant. The experiment was carried out at $L = 320$ cm. The distance L_1 from the center of the neodymium rod to the mirror R_1 changed in the range from 20 to 280 cm. It turned out that the displacement of the neodymium rod was accompanied by change in the modulation frequency, but this change had a jump-like character: in some interval of values of L_1 the modulation frequency remained constant, and further change in L_1 caused the modulation frequency to change. The table lists the regions L_1 where the maximum depth of modulation is attained at the corresponding constant frequency, and the measured modulation frequency f_{exp}. The same table gives the values of the beat frequencies f_m that are multiples of the minimum beat frequencies f_1 for the given resonator: $f_m = mc/2L$, where $m = 2, 3, 4$.

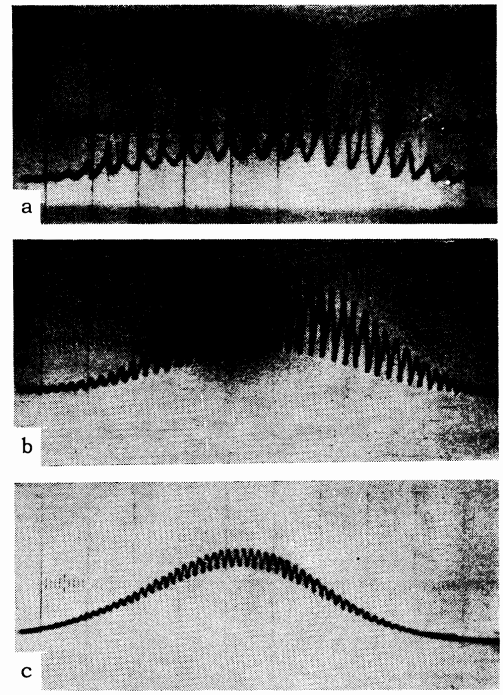

FIG. 1. Oscillograms of a "giant" pulse at $L = 320$ cm: a – $L_1 = 30$ cm; b – $L_1 = 161$ cm; c – $L_1 = 107$ cm. Sweep scale – 50 nsec/cm, sweep direction – right to left.

By way of illustration, Fig. 1 shows photographs of the oscillograms of the pulse at $L_1 = 30$, 160 and 107 cm.

As seen from the table, when the neodymium rod is located at distances $L_1 > 60$ cm from the mirrors R_1 or R_2, the observed modulation frequencies coincide (within the limits of experimental error) with one of the values of f_m ($m = 2, 3, 4$). When $L_1 < 50$ cm the modulation frequency is close to f_1. It must be noted that in the intervals of L_1 indicated in the table, the maximum depth of modulation at frequency f_m is observed at values of L_1 that are approximately equal to $L_{1m} = L/m$. In addition, the depth of modulation at frequencies f_m decreases with increasing M (see Fig. 1). At values of L_1 differing from L_{1m} by 15–20 cm, the stability of the appearance of the corresponding multiple frequency f_m decreases,

L_1, cm	20–50	60–85	95–115	150–170	205–230	235–260	270–300
f_{exp}, Mc	44.5	180	133	90	134	180	44
f_m, Mc	46.9 $m=1$	187.6 $m=4$	140.7 $m=3$	93.8 $m=2$	140.7 $m=3$	187.6 $m=4$	469 $m=1$

and the "fundamental" frequency f_1 is sometimes observed besides. In particular, when $L_1 < 60$ cm, we observe not a higher modulation frequency f_m corresponding to values of $m = 5, 6, \ldots$, but only the "fundamental" frequency f_1. One of the reasons for this is apparently that when $L < 60$ cm the length of the neodymium rod becomes commensurate with L_1, and this complicates the phenomenon.

The existence of multiple modulation frequencies $f_m = mf_1$ can be explained by assuming that the Q values of the different axial modes change with the position of the active-medium rod inside the resonator. At definite rod positions there are excited not neighboring modes, but modes that differ in frequency by mf_1, and this leads to an increase in the modulation frequency. Thus, the phenomenon observed by us can be interpreted as a discrimination of the axial modes by the installation of the neodymium rod at distances $L_{1m} = L/m$ from one of the resonator mirrors. This discrimination makes the spectrum of the generated axial modes of the resonator less dense, a fact manifest in the corresponding increase of the modulation frequency.

The discrimination of the axial modes can be explained by regarding the system under consideration as a compound resonator made up of the outer mirrors R_1 and R_2 and the ends of the neodymium rod, which play the role of the internal mirrors of this resonator.[2)] To check on this assumption, we are planning new experiments and also a rigorous calculation of the above-mentioned compound resonator. It must be noted that the phenomenon observed by us, the discrimination of the neodymium laser modes, takes place not only in the mode with Q-switching, but also in the usual "spike" mode. Thus under the same measurement conditions, but without a bleaching filter in the resonator, we observed modulation of the radiation intensity in each individual "spike" (Fig. 2). Here, however, the depth of modulation was considerably lower than in the Q-switching mode.

[2)]This explanation was proposed by T. I. Kuznetsova.

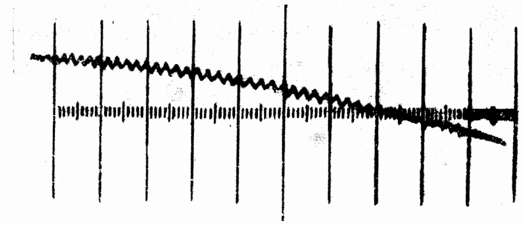

FIG. 2. Oscillogram of "spike" of usual laser generation ($L = 320$ cm, $L_1 = 161$ cm). Sweep scale – 50 nsec/cm, direction – right to left.

In conclusion, the authors are grateful to P. A. Bazhulin for interest in the work, T. I. Kuznetsova and S. G. Rautian for useful discussion, and Yu. S. Ivanov for help with the experiment.

Postscript (October 20, 1965): After this article went to press, we became aware of the article by Singh, Smith, and Di Domenico[8] who described a similar experiment with a ruby laser. They also reached the conclusion that selection of excited axial modes can occur when the position of the ruby rod between the external mirrors of the resonator is changed. However, they leave open the question of the causes of this selection.

[1] W. R. Bennett, Jr., Gas Lasers (Russ. Transl.), Mir, 1964.

[2] B. J. McMurtry and A. E. Siegman, Appl. Optics **1**, 51 (1962).

[3] B. J. McMurtry, Appl. Optics **2**, 767 (1963).

[4] L. Waszak, Proc. IEEE **52**, 428 (1964).

[5] M. P. Vanyukov, V. I. Isaenko, and V. A. Serebryakov, JETP **44**, 1493 (1963), Soviet Phys. JETP **17**, 1004 (1963).

[6] V. I. Malyshev, A. S. Markin, and V. S. Petrov, Zhurn. prikl. spektr. (J. of Applied Spectroscopy) 3, 415 (1965).

[7] V. I. Malyshev, A. S. Markin, and V. S. Petrov, JETP Letters **1**, No. 3, 49 (1965), transl. **1**, 99 (1965).

[8] S. Singh, R. G. Smith, and M. Di Domenico, Jr., Proc. IEEE **53**, 507 (1965).

Translated by J. G. Adashko
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