SOVIET PHYSICS JETP VOLUME 17, NUMBER 5 NOVEMBER, 1963

INVESTIGATION OF THE DIRECTIVITY OF A LASER

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Submitted to JETP editor December 12, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **44**, 1493-1496 (May, 1963)

An experimental investigation of the directivity of the stimulated radiation from lasers with square, rectangular, and octagonal cross sections establishes that this radiation may be distributed over several discrete directions. The existence of such directions is ascribed to the formation of additional closed paths for the generating rays due to the multiple reflections at the parallel sidewalls.

INTRODUCTION

THE directivity of the radiation of lasers is usually investigated in samples having a cylindrical shape.[1,2] For the purpose of studying the mechanism of excitation of directed radiation, we have been interested in samples having different cross sections. For this, we have used samples molded from Nd-activated glass the end surfaces of which were finished to that same high degree of accuracy required in interferometry, and covered with a dielectric reflecting film. The lateral surfaces were polished, but not as well. The samples were excited with two IFK-2000 flashlamps, and the radiation was investigated by means of an electron-optical image converter. To record the angular distribution of the generated radiation, the photocathode of the converter was placed in the focal plane of an object on which the radiation was incident. The distribution of generating zones over the end of the sample was photographed by projecting the plane of the end on the photocathode of the image converter.

We present below the results of an investigation of the angular distribution of the radiation of samples with square, rectangular, octagonal, and circular cross section.

EXPERIMENTAL RESULTS

Square cross section. The angular distribution of the radiation from a sample having a square cross section is shown in Figs. 1a—c. The photographs were obtained by locating the photocathode of the image converter in the focal plane of the objective. They therefore represent a two-dimensional pattern of the intersection with the plane of the axes of beams of parallel rays. It can be seen from Fig. 1a that, besides the radiation in the main direction, perpendicular to the interferometer end-plates (the central spot), there is additional radiation (the supplementary lines). The axes of the additional beams lie in a plane perpendicular to the edges formed by the end surface of the sample and a pair of sidewalls.

Figure 2 shows, schematically, the distribution of directions of the generated beams. Figure 1d is a photograph of the end-plate of the generating sample which gave the angular distribution indicated in Fig. 1a. With an increase in pump power additional beams arise the axes of which are more narrowly distributed in two mutually perpendicular planes which are in turn perpendicular to the edges formed by the end plane of the sample and two pairs of sidewalls. In all the examined generation modes the intensity of radiation in the principal direction remains the greatest with a characteristic distribution in angle (the diamond-shaped spot in the center of Fig. 1a).

To determine the effect of the sidewalls on the directivity of the laser, the angular distribution of the radiation from samples having differently treated surfaces was recorded. Figure 1b pertains to a sample the sidewalls of which had numerous fine scratches and pits. The photograph shows a smearing of the radiation over the various angles in the two principal planes (the two mutually perpendicular lines in Fig. 1a, b). When the sidewalls are dulled (Fig. 1c), practically all the radiation goes into the principal direction (the central spot in Fig. 1c).

Rectangular cross section. In Fig. 3a, b are presented photographs showing the angular distribution of the radiation of a sample having a rectangular cross section and the distribution of the radiating zones over the end of this sample. It is seen that for the given sample there is practically no radiation in the principal direction, and all the generated light is propagated in different directions in a rather large number of beams, the axes of which

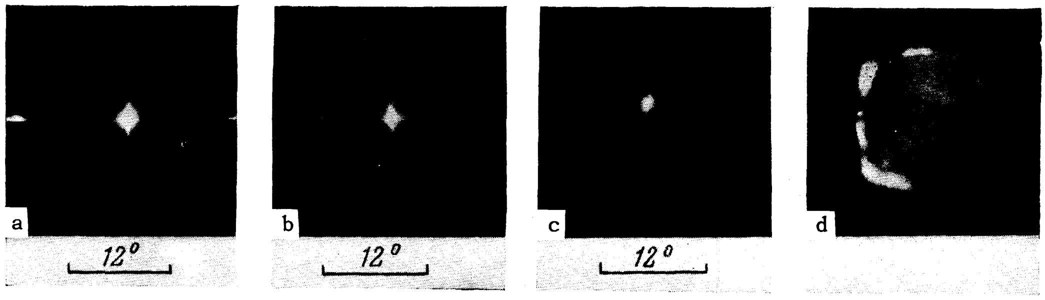

FIG. 1. Angular distribution of radiation (a, b, c) and distribution of radiation over the end surface (d) of a laser. The sample has a square cross section. The ratio h/l (h is the distance between parallel faces, l is the sample length) is 0.09. Lateral surfaces: a – polished, b – with tiny pits and fine scratches, c – dulled.

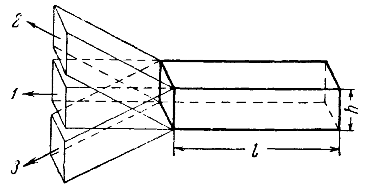

FIG. 2. Directional distribution of the main beam (1) and the two additional beams (2, 3) from a sample having having square cross section.

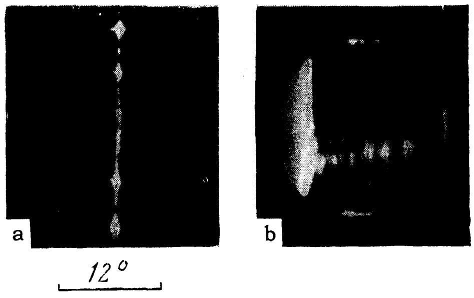

FIG. 3. Angular distribution of radiation (a) and distribution of radiation over the end (b) for a sample with rectangular cross section. The ratio h/l for lateral surfaces forming radiation in additional directions is 0.15.

are distributed in a plane perpendicular to the narrow sidewalls of the sample.

Section in the shape of a regular octagon. Figures 4a, c, e present photographs of the angular distribution of the radiation of a sample the cross section of which has the shape of a regular octagon at various pumping levels. At moderate levels the axes of the light beams are disposed in two mutually perpendicular planes. With an increase in level there is at first an increase in the number of angles over which the radiation is distributed, but no departure of the beams from the two planes (Fig. 4c). With a further increase in pump power, there now appear two new planes, inclined at an angle of 45° with respect to the original ones (Fig. 4e). Figures 4b, d, and f are photographs of the ends corresponding to the angular distributions represented by Figs. 4a, c, and e. The pictures of the ends show that the radiation is not emitted over the entire surface of the end, but only in distinct zones having the shape of bands perpendicular to the sidewalls that determine in the given conditions the directivity of the generated radiation. As the pumping level goes up the width of the bands increases and new bands appear.

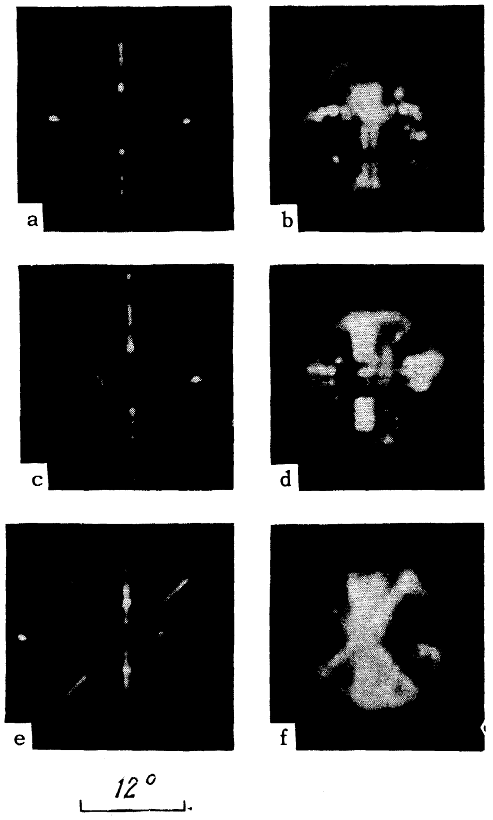

FIG. 4. Angular distribution of radiation (a, c, e) and distribution of radiation over the end (b, d, f) for a sample of octagonal cross section. The ratio h/l is 0.083. The "pump" energy exceeds the generation threshold by: a, b – 1.4 times; c, d – 1.8 times; e, f – 2 times.

Circular cross section. Investigation of cylindrical samples has shown that under all operating conditions the radiation is observed only in the principal direction, perpendicular to the end plates of the interferometer (Fig. 5a—angular distribution, Fig. 5b—end section). It must be borne in mind that in cylindrical samples generation takes place over almost the entire end surface.

We shall now try to give a qualitative explanation of the phenomena we have observed. In sam-

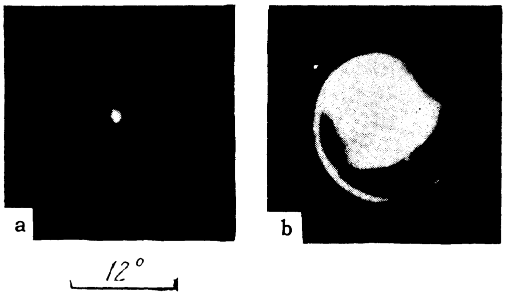

FIG. 5. Angular distribution of radiation (a) and distribution of radiation over the end (b) for a sample of circular cross section.

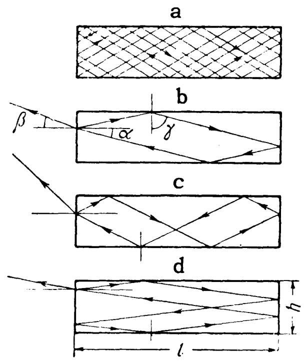

FIG. 6. Paths of rays inside a laser leading to formation of additional directions. The rays do not form closed paths (a); the rays form a closed circuit with a single reflection on the side and end walls of the sample (b), with a single reflection on the end and double from the side (c), with a double reflection from the end and single from the side (d).

ples having parallel sidewalls and end surfaces perpendicular to them, the sections in planes perpendicular to these sidewalls are rectangular in shape. Rays lying in these planes and incident at an angle γ to the sidewalls will undergo multiple reflections if the angle of incidence on the sidewall exceeds the angle of total internal reflection γ_k (Fig. 6a). If it is assumed that generation arises in the first place in those directions that provide closed paths for the rays, then besides the principal direction, perpendicular to the ends of the sample, there can be distinguished a number of other additional directions. Some variations of the possible discrete directions are shown in Figs. 6b, d. It is seen that closed contours are possible both for a single reflection from each of the side and end walls of the sample (Fig. 6b) and for an unequal number of reflections from the side and end surfaces (Figs. 6c, d). It is easily shown that the angle α at which the ray is incident on the surface of the interferometer is determined from the relation $\tan \alpha = mh/l$, where m is the ratio of the number of reflections from the side walls of the sample to the number of reflections from the interferometer end-plates for the case of a closed circuit for the rays, h is the distance between parallel side boundaries, and l is the length of the sample.

The greatest angle of incidence of the rays on the end surface for which multiple reflections from the walls are possible is $\alpha_{\max} = (\pi/4) - \gamma_k$. The numbers m for which closed circuits are possible must satisfy the condition $m < (l/h) \cot \gamma_k$. The exit angle of the rays into space will be given by the relation $\sin \beta = n \sin \alpha$, where n is the index of refraction of the medium.

These relations show that it is possible to have conditions such that rays incident on the end surface at an angle α greater than the angle of total internal reflection α_k will be amplified. Such rays will not exit from the end and will be completely absorbed inside the active medium, creating heat and disrupting the generation. This phenomenon can set in for certain relations between the longitudinal and transverse dimensions of the sample. From geometrical considerations it follows that for this to happen it is necessary that the angle of total internal reflection of the medium be somewhat less than $\pi/4$ $(n > 1.27)$.

If this is true, that generation should occur in the first place in directions making a closed path for the rays, then we should observe a distribution of the radiation over discrete directions. On the basis of an analysis of the experimental data we can state that we see most clearly two additional directions $(m = 1/2, 1)$. These directions are evidently established as a result of single reflections from the side walls (Fig. 6b) and single and double reflections from the end wall, respectively. Further directions can develop in case of excitation of several reflections of closed rays from the side walls. This is strongly affected by inaccuracies in the finish of the side surfaces, by which is explained the diffusion of the radiation over angle observed in the experiment (Fig. 4).

The existence of angular distribution of radiation in the main direction for samples with square cross section (Fig. 1a) can be attributed to the influence of the side walls. It should be realized that closed paths can occur in which there are a large number of reflections from the end walls and a small number from the sides, corresponding to values of $m \ll 1$.

The absence of radiation in the main direction (Fig. 4) can be ascribed to the circumstance that rays emitted in lateral directions travel large distances in the medium and so draw off a significant amount of the energy of the excited centers.

The angular distribution of radiation with a concentration of light in the principal direction observed in cylindrical samples can be ascribed to the curvature of the lateral surfaces.

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[1] D. J. Nelson and R. J. Collins, J. Appl. Phys. **32**, 739 (1961).

[2] Galanin, Leontovich, and Chizhikova, JETP **43**, 347 (1962), Soviet Phys. JETP **16**, 249 (1963).

Translated by L. M. Matarrese
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