SOVIET PHYSICS

JETP

A translation of the Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki

Vol. 21, No. 1, pp. 1-251 (Russ. Orig. Vol. 48, No. 1, pp. 3-382, January 1965) July, 1965

EXCITATION OF AUXILIARY OFF-AXIS LASER MODES

M. P. VANYUKOV, V. I. ISAENKO, L. A. LUIZOVA, and O. A. SHOROKHOV

Vavilov State Institute of Optics

Submitted to JETP editor February 6, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) **48**, 3-6 (January, 1965)

Data are presented on excitation of off-axis beams of stimulated radiation by inclining the generating sample with respect to the interferometer axis. It is shown that the radiation coincides in time with the radiation propagated in the axial direction and is directed at angles corresponding to equal-inclination rings in the Fabry-Perot interferometer formed by the resonator mirrors.

INTRODUCTION

IT is well known that laser action produces beams of light directed not only along the axis of the laser rod but also in directions making other discrete angles with respect to the rod axis. This results in a far-field pattern which exhibits, in addition to a central spot, a series of rings whose angular diameters are determined by the condition for rings of equal inclination in the Fabry-Perot interferometer formed by the cavity mirrors[1-5]. It has also been shown that the emission in these rings is coherent with the axial emission, so that both types of radiation must be ascribed to a single modified mode produced by the coupling between different modes caused by the presence of random nonuniformities in the laser rod and defects in the mirrors[1].

The present paper describes the excitation of off-axis emission when the laser rod is inclined with respect to the resonator axis.

EXPERIMENTAL METHOD

The experimental optics are shown in Fig. 1. The apparatus allowed the recording of the time variation of the angular distribution of the stimulated emission from the laser rod 1, placed in a resonator with plane parallel mirrors 2 and 3, for various angles of inclination of the laser rod with respect to the axis of the cavity. The rod 1 was of neodymium glass. The separation between the mirrors was chosen to be either 1 or 1.5 meters. Using an autocollimator the axes of the sample and the resonator were adjusted to coincide within 2″ and could be inclined with respect to each other by an angle α up to 2′. The laser radiation fell on a lens 4, in whose focal plane was located the photocathode of an electro-optic image converter 7. The image converter output was photographed to show the development of the far field pattern of

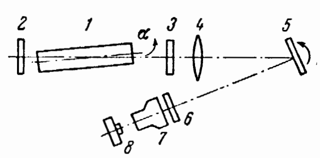

FIG. 1. The optical set-up: 1 – neodymium glass rod of diameter either 8 or 10 mm., length either 67 or 120 mm., and with polished side walls; 2 – dielectrically coated mirror with a reflectivity of 98.5%; 3 – dielectrically coated mirror with reflectivity of 80%; 4 – lens of focal length f = 4m; 5 – rotating mirror; 6 – neutral density filter; 7 – image converter; 8 – camera.

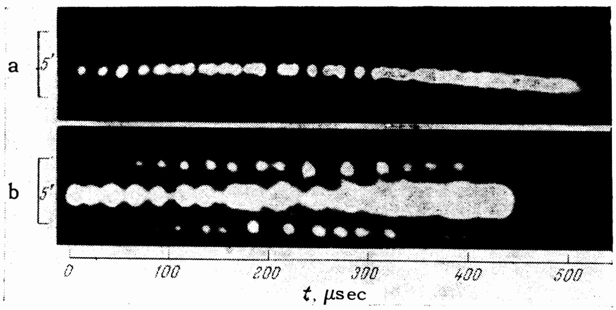

FIG. 2. Time development of the angular distribution in far field pattern. a – axis of the laser rod coincident with that of the cavity to within 2″, b – the axes misaligned by 40″.

the emission by using a mirror rotating at ~3000 rpm. The surfaces of the cavity mirrors 2 and 3 were flat to 0.1 λ; the optical nonuniformities of the sample were characterized by path differences not exceeding 0.1–0.5 λ. The measurements were made with a pump power 50% above threshold.

RESULTS

In Figure 2a we show photographs of the time development of the far field pattern of the stimulated emission from a well-aligned rod ($\alpha = 0$). In this case all of the emission is in the primary direction and has a beam divergence of 1–1.5′, which is 3–5 times the diffraction limit. The angular divergence of the last spikes in the output is about two times greater than that of the initial spikes. When the sample was misaligned by a comparatively small angle (20–40″) the angular divergence increased somewhat and in some cases exhibited structure. When the sample was misaligned by a large angle (40″ to 2′) there appeared in the far-field pattern, in addition to the central spot, two additional spots located symmetrically with respect to the center of the pattern in the plane of inclination of the sample (Fig. 2b). Photometric measurements of the pictures showed that the intensity emitted in the non-axial directions amounted to some 5% of the intensity in the axial direction and that this quantity varied little from rod to rod. One exception was the rod with anti-reflection coatings on its ends, for which the present effect was not observed.

The angle between these auxiliary light beams was independent of the dimensions of the rod, the pump energy, or the angle of misalignment, and corresponded instead to the angle for a ring of equal inclination in the Fabry-Perot interferometer formed by the mirrors 2 and 3;

$$\varphi = 2(n\lambda / t)^{1/2},$$

where φ is the angular diameter of the ring, n is the order of the ring, λ is the wavelength of the laser light, and t is the mirror separation.

To test this interpretation pictures were taken of the far field pattern of the emission from a well-aligned resonator without using the rotating mirror (Figs. 3b-c). These pictures show Fabry-Perot rings; the first ring has a diameter equal, within the experimental error, to the separation between the auxiliary spots which appear when the laser rod is misaligned (Fig. 3d). There is also a displacement of the direction of the primary radiation in the vertical direction on the diagram. (In Fig. 3c we show for comparison the far field pattern from the well-aligned sample.)

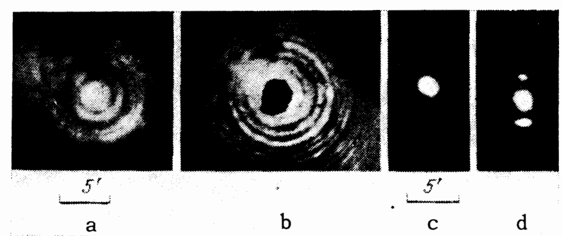

FIG. 3. Far field pattern of the emission from a well-aligned sample. a – normal exposure; b – increased ring contrast obtained by screening out the central spot; c – for the case where the total radiation is strongly attenuated; d – for the case where the sample is inclined by 1′ to the axis of the cavity.

When the angle of inclination α between the rod and the interferometer axis was increased beyond 2′, a rapid decrease in the output energy occurred, and for $\alpha = 5'$ laser action ceased simultaneously in the fundamental and the auxiliary modes. It should be mentioned that misaligning the laser by inclining one of the cavity mirrors prevented laser action (for the same pump energy) for a mirror inclination of only 1′.

DISCUSSION OF RESULTS

The coincidence between the angular directions of the light beams caused by misaligning the laser rod in the resonator with the direction of the light beams forming the rings in the far field pattern of a well-adjusted laser shows that the mechanism for producing both effects is the same. A complex mode in the non-ideal cavity can be considered in both cases as the result of coupling between the axial and off-axis modes of the ideal resonator.

In the case of the well-aligned crystal this coupling is due to scattering of the primary radiation at random nonuniformities in the sample and in the mirrors. This scattering is not large and is equally probable in all directions and hence gives rise to weak rings with angular diameters corresponding to the Fabry-Perot resonance condition (only at these angles can modes exist with a frequency equal to the frequency of the primary radiation). In the case of the inclined rod Fresnel reflection at the end faces of the rod is responsible for the coupling between the axial modes and those off-axis modes which propagate at angles with respect to the axis and lie in the same plane as the angle between the axis of the rod and the axis of the cavity. It is clear that this coupling is more effective than the coupling due to non-uniformities and that it leads to the formation in the far field pattern of spots which are considerably more intense than the corresponding rings. The absence of these additional off-axis modes when the end faces of the crystal are anti-reflection coated supports our interpretation of the nature of the observed effect.

[1] J. D. Abella and C. H. Townes, Nature **192**, 957 (1961).

[2] Maiman, Hoskins, D'Haenens, Asawa, and Evtuhov, Phys. Rev. **123**, 1151 (1961).

[3] C. M. Stickley and R. A. Bradbury, Appl. Optics **2**, 867 (1963).

[4] C. M. Stickley, Appl. Optics **2**, 855 (1963).

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

Translated by J. A. Armstrong
1