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# THE TIME VARIATION OF STIMULATED EMISSION INTENSITY IN INDIVIDUAL SIDE MODES

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A spatial and temporal analysis is made of the side and axial modes of stimulated emission in rectangular specimens. It was established that generation of side modes takes place simultaneously with generation of axial modes. The different side modes arising because a specimen has two different pairs of polished side surfaces are generated independently in time and space.

A number of workers [1-3] have shown that specimens generating stimulated emission and having polished side surfaces can produce light beams not only in the principal direction, but also in various discrete directions deviating from the specimen axis by angles up to tens of degrees. In the present communication data are given on the spatial and temporal relations between emission in the axial and the individual side modes.

To record the discrete directions in which emission occurred, an apparatus previously described [1] was used. In this apparatus the emission from glass specimens activated with neodymium ($\lambda = 1.06\,\mu$) was guided into an objective, in the focal plane of which was placed the photocathode of an image converter. The system of points observed on the screen gave the angular distribution of the individual beams. The objective was so chosen that it was possible to obtain an image of the end of the generating specimen on the image converter screen using the total emission from the specimen. Then, by placing a diaphragm in the focal plane of the objective, one could select the individual side modes generated in a definite direction. The optical arrangement used for photography is shown in Fig. 1a. The diagram shows the case when the emission from the specimen consists of two beams. By moving the diaphragm, one can obtain images of the end showing the generating regions that are emitting along the direction of either beam 1 or beam 2, and, if the diaphragm is removed, one can also obtain a picture of the total generation. The arrangement shown in Fig. 1b made it possible to compare the temporal characteristics of the emission in the individual beams. For this purpose a two-aperture diaphragm which separated the light beams was set up in the focal plane. After separation the radiation was directed to different photomultipliers (type FÉU-22) and recorded on a two-beam oscilloscope (type OK-17).

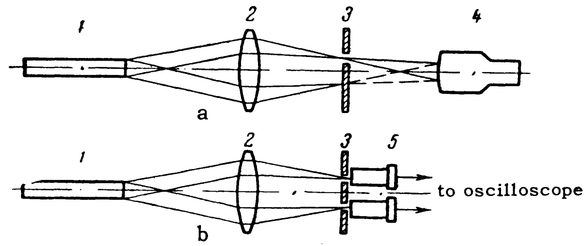


FIG. 1. Optical arrangement for spatial (a) and spatial and temporal selection (b) of stimulated emmission. 1 – specimen giving stimulated emission; 2 – objective; 3 – diaphragm; 4 – image converter; 5 – photomultiplier.

A specimen of neodymium glass of rectangular cross section was chosen for detailed study. This specimen emitted five beams of light. In the focal plane of the objective five bright spots were observed which were disposed symmetrically (Fig. 2a). The central spot was made by emission in the principal axial modes. The two pairs of spots disposed on lines passing through the central spot were produced by modes apparently due to the formation inside the specimen of closed optical paths involving reflections from the two pairs of parallel side walls on the specimen. [1] Photographs of the generating regions on the end (Figs. 2b–e) showed that the light beams emitted at the various angles differed in their structure. For example, the emission in the axial direction (Fig. 2b) was distributed comparatively uniformly over the entire end, although a fine structure was also observed. The radiation generated came out of regions on the end that had the form of comparatively thin strips.

Figures 2c and d are photographs of the ends,

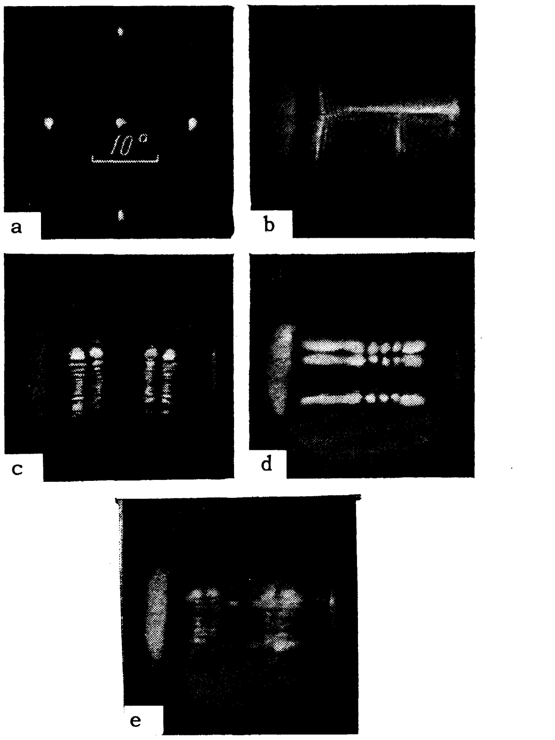


FIG. 2. Distribution of stimulated emission from a neodymium specimen in the form of a rectangular parallelepiped (the ratio of the sides of the specimen was 1:2:12); a: far field; b: near field for axial modes (end of specimen); c, d: near field for side modes; e: near field for total emission. The pump energy is 1.4 times the generation threshold.

showing the output of radiation reflected from the two pairs of side surfaces. In the first case (Fig. 2c) the generating regions corresponded to the beam reflected from the upper and lower walls of the specimen (the cross-section shape of the specimen is visible in the photographs as a dark rectangle). The photograph was made using the light beam, the direction of which corresponded to the upper spot of photograph 2a. It is natural to expect that, owing to symmetry, the same distribution of generating regions should also be associated with the lower spot. In the next photograph (Fig. 2d) is shown the end image obtained using the light beams reflected from the vertical side walls of the specimen.

Examination of these photographs allows one to conclude that the generating regions are strips lying parallel to those specimen walls and reflecting the radiation. The strips taken together form several columns, the axes of which are perpendicular to the walls of the specimen. The presence in a rectangular specimen of two mutually perpendicular side walls produces generating regions consisting of two intersecting systems of strips. Figure 2e is a photograph of the end taken with the total light emitted. It is seen that intense emission proceeds from two extensive regions formed by the superposition of the emission in the side modes. The emission in the axial modes is distributed over the entire end and has a weak surface intensity; therefore it is not recorded on the photograph.

Oscilloscope displays showing the temporal distribution of emission intensity in the beams of light from the given specimen of neodymium glass are shown in Fig. 3. As expected, the outputs in the two beams, defined by a single pair of parallel side surfaces (Fig. 3a), are completely identical. The emission spikes on the oscilloscope traces always start simultaneously, and almost always agree in intensity. However, if one compares the outputs in the side beams defined by mutually perpendicular pairs of side surfaces (Fig. 3b), then one can see that the emission spikes are almost non-coincident in this case. The impression is created that they do not have general regularities. If one compares the temporal characteristics of any of the side beams and the principal axial beam (Figs. 3c and d), one can note that to each emission spike in the side modes there always corresponds in time an emission spike of the axial modes. The emission spikes follow one another much more frequently in the principal direction than in the side direction. Where the side modes have a large intensity, the axial modes are significantly weakened.

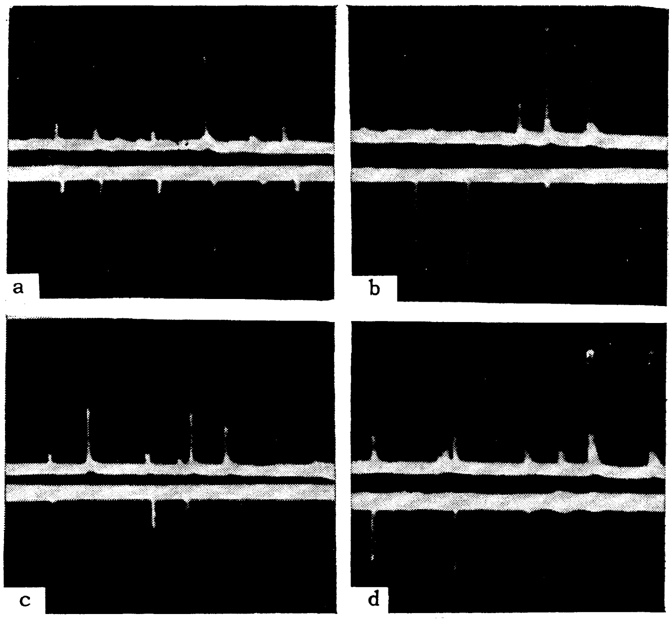


FIG. 3. Oscilloscope traces showing the distribution with time of the emission intensity from the rectangular specimen; a: for the side modes determined by one pair of parallel side surfaces; b: for the side modes determined by perpendicular pairs of side surfaces; c, d: for axial modes (upper trace) and individual side modes (lower trace).

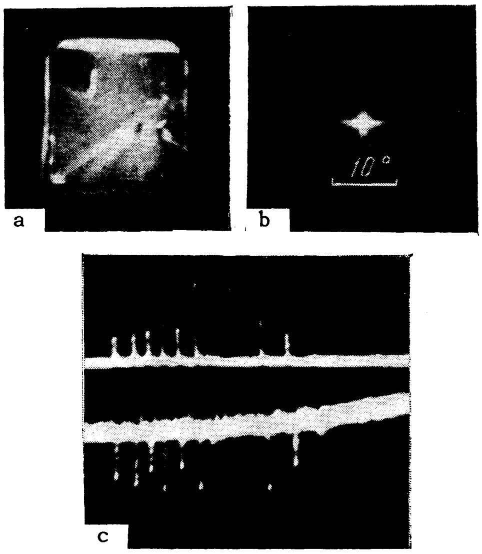


FIG. 4. Spatial (a, b) and temporal (c) distribution of stimulated emission from a square specimen with matte side walls: a: near field; b: far field; c: upper trace for axial modes and lower trace for modes directed at small angles to the axis.

Figure 4a is a photograph of the generating end of a specimen having matte side walls, which rule out the appearance of discrete side beams (Fig. 4b). The apertures in the diaphragm were situated a small distance apart, which made it possible to separate the emission in the principal axial modes and in the modes having small angles of inclination to the specimen axis. For both types of modes the emission spikes (Fig. 4c) start simultaneously, although the intensity of emission in the side modes falls off rapidly with inclination to the specimen axis.

We now attempt to compare the results obtained with theoretical ideas on the excitation of various types of vibration in a resonator having the shape of a parallelepiped. In such a resonator it is possible to establish, as is well known, an infinite number of different modes, each defined by three integers (m, n, l) associated with the wave vector **k**. The wavelengths of such modes are given by the expression

$$(2/\lambda)^2 = (m/a)^2 + (n/b)^2 + (l/c)^2, \tag{1}$$

where a, b, c, are the linear dimensions of the resonator.

We consider the case when one of the numbers, for example, n, is zero. This means that standing waves are formed in the resonator by reflection from only two pairs of mutually perpendicular walls (Fig. 5a). Then the following conditions must be satisfied:

$$a = m\lambda/2\sin\theta, \quad c = l\lambda/2\cos\theta, \quad \tan\theta = cm/la. \tag{2}$$

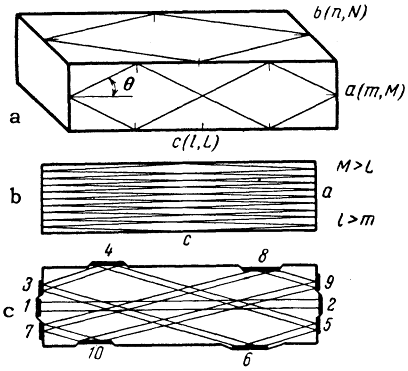


FIG. 5. Diagram showing the formation of various types of vibrations: a: side types (due to reflection from side walls); b: nearly axial (due to reflection from end and side walls); c: side and axial types in a complex cavity having significant deviations from the ideal parallelepiped.

On the other hand from considerations of geometrical optics the following relation should hold:

$$\tan\theta = aL/Mc, \tag{3}$$

where M, L, are integers corresponding to the number of reflections of the wave front from the walls. It is obvious that the relation between the two pairs of characteristic numbers determined by the theory of resonators and the conditions of geometrical optics is the equation:

$$mM/lL = a^2/c^2 = \text{const}. \tag{4}$$

In Fig. 5b is shown the case when there are many reflections from the end walls of the specimen and few from the side walls, which corresponds to the condition $M \gg L$ in geometrical optics, and the condition $l \gg m$ in the theory of resonators. Here radiation will be emitted at small angles (see Fig. 4).

As would also be expected, emission in side modes always consists of pairs of light beams defining planes in which the axial beam lies—the two members of a pair making equal angles with the axis (in the photograph of Fig. 2a there are two symmetrical spots, for example, the upper and lower). The identical variation of emission intensity with time in these beams (Fig. 3a) confirms the prediction of resonator theory that this emission belongs to the same mode.

It should be borne in mind, however, that by no means all the phenomena we observed can be explained by the existing theory of resonators, owing to the inadequate approximation our specimens made to an ideal parallelepiped. In fact, only the end surfaces of the specimen were worked to an accuracy of 0.1 wavelength (λ), the parallelism of the side surfaces was only held within 1–5′, and the optical length of the specimen changed across its cross section by 0.2—1 $\lambda$, so that for the frequencies generated the resonator was not a parallelepiped, but was a cavity of more complicated configuration. One can assume that in this cavity certain regions of the volume generate—these regions constituting individual interferometers with closed beam paths. For example, in Fig. 5c three such elementary interferometers are shown. Parts of the end surfaces 1 and 2 form a Fabry-Perot interferometer, and parts of the end and side surfaces 3—6 and 7—10 form more complicated interferometers with four reflecting surfaces. At present only the theory of the Fabry-Perot type resonator has been given.[4,5]

The temporal coincidence of the generation spikes associated with the side and axial modes, and the lack of coincidence for the emission spikes caused by reflections from mutually perpendicular side surfaces, show that the polarization of the radiation plays an essential role in these phenomena; this polarization is acquired by the side modes when the light beams fall on the side surfaces at inclined incidence.

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Translated by K. F. Hulme
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