

OPTICAL MASER ACTION OF  $\text{Nd}^{+3}$  IN A BARIUM CROWN GLASS

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Since the original suggestion for an optical maser,<sup>1</sup> maser oscillations have been reported in a number of crystals<sup>2-6</sup> and in the gas mixture of He-Ne.<sup>7</sup> This Letter describes a glass optical maser which operates at room temperature and contains trivalent neodymium as the active ion. The output consists of a number of sharp lines in a wavelength interval of about 30 angstroms centered at approximately 1.06 microns.

Concentrations of  $\text{Nd}_2\text{O}_3$  varying from 0.13 to 2.0 weight percent were added to a barium crown glass whose composition is 59 wt.%  $\text{SiO}_2$ , 25%  $\text{BaO}$ , 15%  $\text{K}_2\text{O}$ , and 1%  $\text{Sb}_2\text{O}_3$ . The glass has a density of approximately 3 and a nominal index of refraction of 1.54. Because of the  $4f^3$  electron configuration is well shielded in  $\text{Nd}^{+3}$ , the term values are virtually the same as one would find in a crystal or the free ion. The energy level diagram is easily identified by reference to the spectrum of  $\text{NdCl}_3$ .<sup>8</sup> There is an absorption at  $880 \mu$  which is due to the transition from the  $^4I_{9/2}$  ground state to the  $^4F_{3/2}$  level, which is the level from which the fluorescence originates. There are other absorption lines in the visible and near infrared; the strongest one is at  $580 \text{ m}\mu$ . The  $^4I_{9/2,11/2,13/2}$  levels are the terminal states for spontaneous emission which give broad lines (several hundred angstroms wide) at  $0.88 \mu$ ,  $1.06 \mu$ , and  $1.3 \mu$ . From the absorption and fluorescent spectra the lifetime for radiative decay from the  $^4F_{3/2}$  state was calculated to be about 0.6 msec. The measured lifetime is 0.56 msec, which indicates a high quantum efficiency for fluorescence from the  $^4F_{3/2}$  state.

The quantum efficiency, as determined by the lifetime, was checked in eight different glass bases and for a number of concentrations of Nd. The barium crown was selected because it gave the longest lifetime for fluorescent decay. There was only a barely perceptible concentration quenching for 2 wt.%  $\text{Nd}_2\text{O}_3$ . The quantum efficiency rapidly decreased for higher concentrations; for 10 wt.%  $\text{Nd}_2\text{O}_3$  in barium crown the lifetime is less than 0.15 msec.

The glass samples were in the form of clad rods. Two cross sections were investigated, 0.012 in. and 32 microns in diameter. The cladding was an ordinary soda-lime-silicate with an index of refraction of 1.52. The samples were

3 in. long and the polished ends partially silvered for 2% transmission.

There were several reasons for using clad rods. While glass can be made with excellent optical quality, this requires large melts. In the experimental program of glass investigation that was carried out, the usual melt size was one pound. It is difficult to get such small glass melts free from stria and other imperfections. Even though the core glass was of poor optical quality, a cladding of lower refractive index can improve the mode properties.

First, some mode selection is provided by the small numerical aperture of the fiber if the indices of core and cladding are close to one another. Second, the good optical interface between the core and the cladding for a drawn glass fiber can provide high- $Q$  surface wave modes. There is evidence for both types of modes being excited in maser oscillations in the clad Nd glass rods.

Because of the relatively strong and narrow absorption lines in  $\text{Nd}^{+3}$ , the pumping light does not penetrate very far into the sample. This suggests a small cross section for optimum pumping. A thick cladding makes it easier to handle small diameter samples. Also, the cladding glass acts as an immersion medium which increases the pumping flux density by about 50%.

Figure 1(a) shows the output as a function of time near threshold for the 0.012-in. diameter rod of 2 weight%  $\text{Nd}_2\text{O}_3$  in the barium crown. The sample was illuminated by a G.E. FT524 flashtube with 75 microfarads charged to 2.0, 2.2, 2.4, and 2.6 kv, respectively, for the four curves shown. The time scale is  $10^{-4}$  sec/division. Just above threshold there is a slow buildup of light, giving the hump shown at about 200 microseconds after the initiation of the flashtube light. At about 50% above threshold, "ringing" is observed in the output. Figure 1(b) shows this when pumping the same rod with an E.G. and G. FX-33 flashtube through which 50 watt-seconds was discharged. The 32-micron diameter fibers show substantially the same threshold as the 0.012-in. rod.

The 0.13 wt.%  $\text{Nd}_2\text{O}_3$  in barium crown samples do not show ringing when illuminated with the maximum light available from the FT524. However, maser action is suggested by the appearance of a hump in the light output versus time curve for

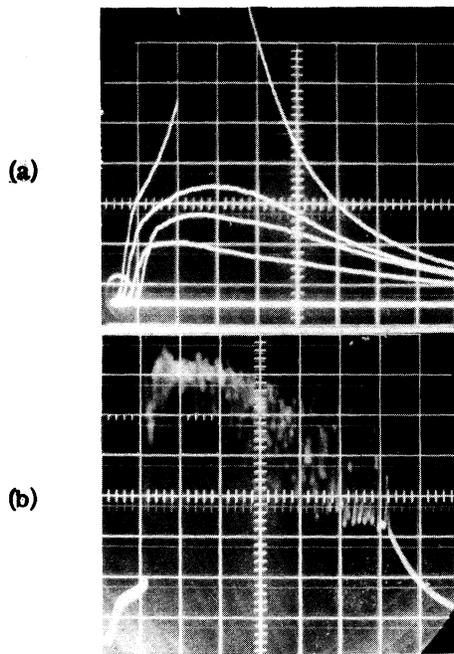


FIG. 1. Light output as a function of time from a clad 0.012-in. diameter rod of 2 wt. %  $\text{Nd}_2\text{O}_3$  in the barium crown glass. (a) The time trace when pumped by a G.E. FT524 with 75 microfarads charged, respectively, to 2.0, 2.2, 2.4, and 2.6 kv. (b) The ringing produced by pumping with 50 watt-sec from an E.G. and G. FX-33.

discharges of the FT524 in excess of about 3000 watt-seconds.

In Fig. 2 is shown the end of the 0.012-in. rod for a single flash with the FX-33 light level at 10% above that required for ringing. The pictures were taken by use of an infrared image converter with an S-1 surface. The circular ring is at the interface between the core and cladding.

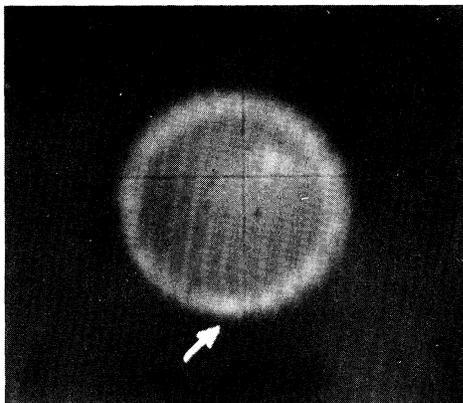


FIG. 2. The image of the end of a clad 0.012-in. diameter rod when pumped with 35 watt-sec from an E.G.G. FX-33 flashtube.

Just at threshold for ringing, only the spot shown by the arrow appeared. As the pump power was increased, the spot extended to the ring. Still further increase of pump light gave the interior filament. Finally, well above threshold the whole fiber was illuminated, but still with the surface wave modes appearing to be more strongly excited. For the 32-micron diameter fiber, threshold maser oscillations gave a uniform ring at the surface; and well above threshold the center of the fiber was filled in with light. Not all of the rods examined showed the surface waves at threshold.

The parallelism of the ends was not found to be critical. For the 3-in. long rods of 0.012-in. diameter with parallelism to 20 seconds or parallelism to only 6 minutes of arc gave the same threshold value. Various length samples were examined. There was no change in threshold power for lengths down to 2 cm. At 1 cm the threshold power doubled. Assuming a 5% absorption for the silver films on the ends with 2% transmission, this would indicate a  $Q$  of  $10^6$  due to scattering along the length of the rod. This corresponds to a 50% attenuation in the rod in about 8 inches. With better optical quality glass this should be improved. Measurements made on good fibers used in fiber optic devices have a 50% loss in about seven feet.

Figure 3 shows the spectrum of the maser output of one of the 0.012-in. rods taken on Kodak type 1-Z plates with a 3.4-meter focal length, plane grating spectrometer with a dispersion of 4.8 A/mm. Twenty 100-watt-sec flashes of the FX-33 flashtube were required. Except for small details the spectrum was reproducible in a given sample. From sample to sample the most intense lines occurred in about the same place, but the number of lines and the wavelength interval over which they occurred varied by a factor of two. The normal fluorescent line is about 200 A wide with no indication of lines within this interval.

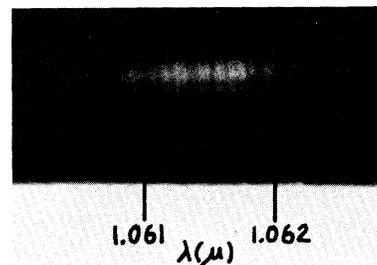


FIG. 3. The maser spectrum of 2 wt. %  $\text{Nd}_2\text{O}_3$  in a barium crown glass.

The lines in the maser spectrum could be due either to the properties of the glass or to the effect of maser action in a resonant cavity. If the  $\text{Nd}^{+3}$  ions are in a limited number of well-defined atomic sites in the glass many lines could result,<sup>9</sup> similar to the satellite lines found in red ruby.<sup>6</sup> Alternatively, the lines could be due to the effect of the resonant cavity which gives standing waves only at discrete wavelengths.

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## EXPERIMENTAL OBSERVATION OF A NEW REGION OF NUCLEAR DEFORMATION\*

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The nuclear periodic table has three or possibly four regions where nuclei have been experimentally shown to be deformed, namely  $A \cong 19$  to 28 and 150 to 190,  $A \geq 222$ , and possibly  $A \sim 8$ . The work presented in this Letter gives experimental evidence for an additional region of deformation.

Figure 1 is a schematic representation of the nuclear periodic table in which previously observed regions of nuclear deformation are labeled 2, 4, 5, and 6. Up to  $A \cong 40$ , the line of beta stability of the nuclear periodic table involves nuclei whose neutron and proton numbers are about the same. Therefore, the first limited regions of deformation, labeled 5 and 6 in Fig. 1, have  $N \cong Z$ . Above  $A \cong 40$ , however, the line of beta stability shifts toward a higher neutron ratio. Consequently the neutron and proton shells are somewhat out of phase until one reaches the rare earths and actinides, where extended regions of deformation are observed because the 50- to 82-proton region is approximately in phase with the 82- to 126-neutron region and the 82- to 126-proton region with the 126- to 184-neutron region. On the other hand, though highly neutron-deficient and correspondingly unstable, the regions labeled 1 and 3 in Fig. 1, where  $N \cong Z$ , should contain deformed nuclei. We have concentrated our effort in region 1.

In order to study the energy levels of nuclei in region 1, it was necessary to discover a number of new La and Pr nuclides. We will report here

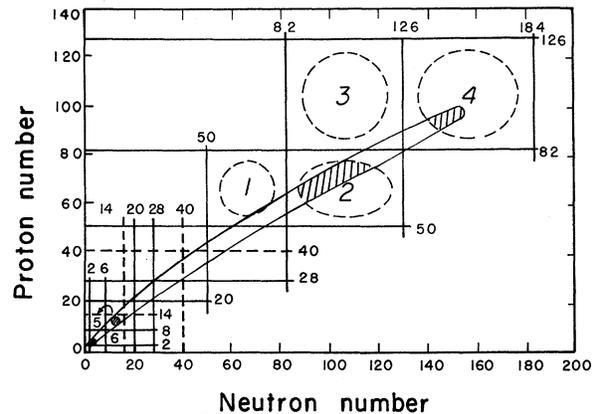


FIG. 1. Schematic representation of the nuclear periodic table showing the neutron (vertical solid lines) and proton (horizontal solid lines) closed shells. The dashed vertical and horizontal lines represent semiclosed shells, which have an effect on regions of deformation. The thin banana-shaped curve approximately encloses nuclei that have been experimentally studied. Regions where nuclei have been experimentally observed to be deformed are indicated with cross hatching. Additional regions where it is reasonable to expect to find deformed nuclei are labeled 1 and 3. This research is concerned with region 1. This figure is patterned after one suggested by E. K. Hyde.

only on those new nuclides whose mass number, half-life, and first excited state are relatively certain.

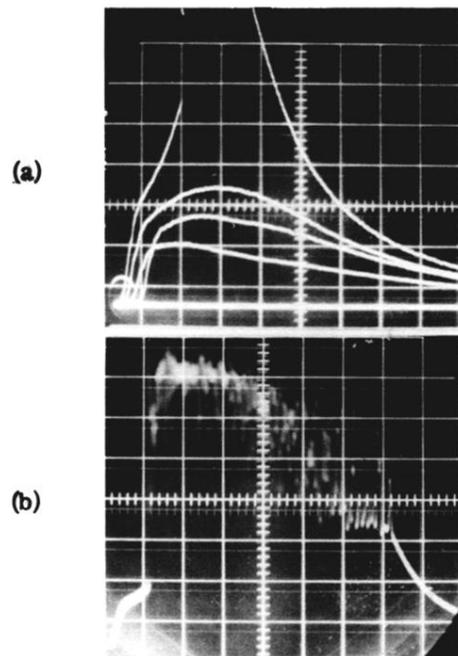


FIG. 1. Light output as a function of time from a clad 0.012-in. diameter rod of 2 wt. %  $\text{Nd}_2\text{O}_3$  in the barium crown glass. (a) The time trace when pumped by a G. E. FT524 with 75 microfarads charged, respectively, to 2.0, 2.2, 2.4, and 2.6 kv. (b) The ringing produced by pumping with 50 watt-sec from an E. G. and G. FX-33.

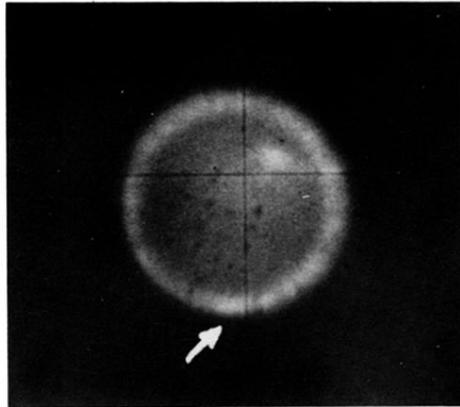


FIG. 2. The image of the end of a clad 0.012-in. diameter rod when pumped with 35 watt-sec from an E.G.G. FX-33 flashtube.

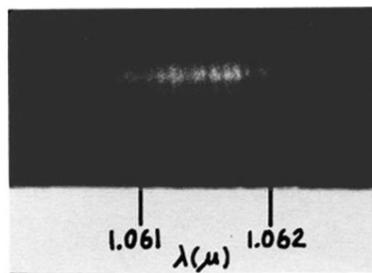


FIG. 3. The maser spectrum of 2 wt. %  $\text{Nd}_2\text{O}_3$  in a barium crown glass.