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Effects of Gamma Irradiation on the Energy Output of Ruby Laser Crystals*

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THE energy output of ruby (Cr^{3+} in Al_2O_3) laser crystals operating at a given energy input level has been significantly increased by the effective use of gamma irradiation.[1] Investigations of the effects of gamma rays on ruby crystals were initiated because it has been known for some time that the fluorescent and phosphorescent transitions of many crystals are considerably enhanced by either x- or gamma radiation. In particular, some crystals which do not fluoresce appreciably when excited with visible or ultraviolet light sources are found to fluoresce brilliantly with the same light source after prior irradiation with x- or gamma rays.[2]

After the irradiation of laser quality ruby crystals with a dosage of the order of 15 000–30 000 R of ^{60}Co gamma rays[3] it was found that: (a) while the ruby transmission spectrum was considerably changed below 550 mμ, the primary pumping bands ($\approx$550 and 400 mμ) for the ruby R_1 and R_2 levels as well as the region of the spectrum containing the R_1 and R_2 levels themselves were comparatively unchanged; and (b) the ruby exhibited a rather brilliant initial phosphorescence in the immediate region of the R_1 and R_2 lines which decayed over a period of several hours after removal from the irradiation facility.

The work of Levy,[4] as well as that of Hunt and Schuler,[5] discusses the absorption bands of Al_2O_3 crystals produced by gamma irradiation. In particular Levy found that the formation of centers created by gamma irradiation produced at least two additional absorption bands in the region of 405 and 227 mμ, which have full-widths (at half-maximum) of approximately 210 and 50 mμ, respectively. These radiation-produced absorption bands are sufficient to account for the observation (a) above. While the nature of the centers producing the additional absorption bands is not well understood,[6] it is known that energy can be stored in these centers and be emitted, as observed in (b) above, either as a phosphorescent after glow or by light stimulated luminescence.[7] Since for ruby this energy is transferred to the lasing levels by what appear to be nonradiative energy transport processes, the effects of this energy storage mechanism on the energy output of the laser became the object of a series of experiments. Typical results of these experiments are summarized below.

Commercial ruby laser crystals (with 0.04%–0.05% Cr^{3+}) were used in the experiments. In order to eliminate any effect which radiation might produce on the dielectric surfaces of the laser rods, external dielectric reflectors were employed. Simultaneous detection of the laser output was made by a phototube and a calorimeter. The phototube output, consisting of the normal type ruby laser spiking, was fed into one channel of a dual-beam oscilloscope. In addition, the output of the phototube was electronically integrated and fed into the second channel of the oscilloscope. The amplitude of this trace, which was displayed simultaneously with the spiked laser output, was approximately linear with increasing total laser output energy. Before each individual laser firing the system was optically aligned by use of an autocollimator to minimize any effects due to system misalignment. The ruby crystal could then be removed from the head assembly

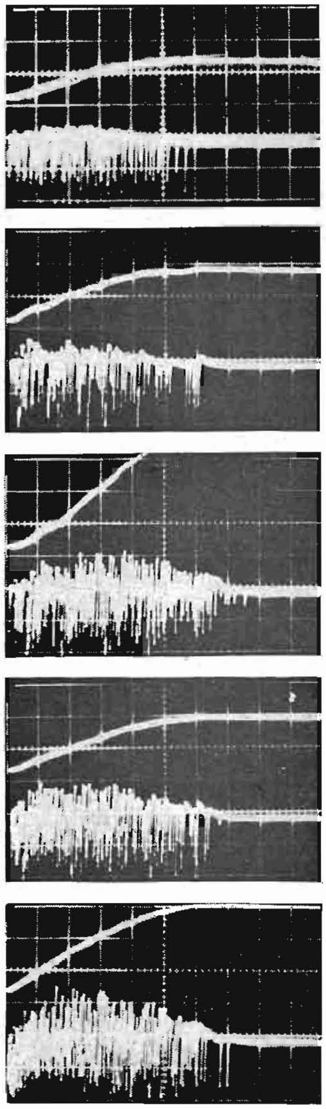
(a) (b) (c) (d) (e)

FIG. 1. Oscilloscope traces of the enhancement in ruby laser output with increasing ^{60}Co γ-dosages. The upper traces in the sequences of figures compare the total or integrated energy of the ruby laser spikes. For (d) and (e) the integrated output is reduced by a factor of two from that of (a), (b), and (c). Horizontal scale, 100 μsec/major div.

and replaced with precision, as verified by repeated calibration firings.

Figure 1(a) presents a typical pre-irradiation calibration firing of a ruby laser crystal. The spiked laser output trace is easily discernible from the total integrated laser output. The relative energy output as measured by the calorimeter is given in Table I. The same ruby crystal was then irradiated with ^{60}Co gamma rays, receiving a total dosage of approximately 800 R. Figure 1(b) presents a typical post irradiation firing of the ruby crystal with the same input energy (approximately double the lasing threshold energy). The integrated energy output shown in Fig. 1(b) clearly indicates a definite increase in output energy. The laser energy output measured by the calorimeter for this firing indicated an increase of approximately 70% (see Table I).

The increased output energy of the ruby laser after gamma irradiation persisted for a number of pulsed firings at the same energy input level. Further experiments showed that for small total gamma dosages (of the order of 500–1000 R) the laser output energy approached its original or pre-irradiation value after prolonged firing.[8] This general type of effect, which was predicted earlier by Gabrysh *et al.*,[9] is attributed to optical bleaching[10] of the irradiated crystal by the flash tubes.

Figures 1(c), 1(d), and 1(e) present further results of the laser output (as determined from the phototube detector) as a function of total accumulated ^{60}Co gamma dosage—with the same constant energy input to the laser system. The corresponding calorimeter data are given in Table I. The magnitude of the individual ruby laser output spikes and their number per unit time are both observed to be significantly increased after gamma irradiation.

Table I shows that the ruby laser energy output increased by approximately a factor of three after a total ^{60}Co gamma dosage of 1700 R. Other results using the same ruby are presented in graphical form in Fig. 2. Several measurements were also made at higher total radiation dosages. It was found that after a total accumulated dosage of approximately 15 000 R the ruby laser output was essentially reduced to its pre-irradiation output level. This decrease of the laser output for large gamma dosages is thought to be tentatively explained in terms of the effects related to the progressive destruction of the crystalline lattice (defect formation) by prolonged gamma irradiation.[11,12] Different experiments with other laser crystals have yielded increases in the output energy larger than a factor of five. Qualitative experiments further indicated that with larger gamma dosages the input energy threshold increased substantially.

The effects which have been discussed in this communication are in accord with the earlier speculation of Gabrysh *et al.*[7] These authors noted in their study of the thermoluminescence of gamma irradiated ruby crystals that ". . . continuance of the phosphorescent after glow, long after the crystal has reached room temperature, indicates an energy-storing property in gamma ray damaged ruby which might be of use to favorably affect 'memory' capabilities and optical laser properties." At this time it is not known if this energy-storing property is sufficient to account for the observed increase in laser energy output, or to what extent the gamma irradiation alters the efficiency of the ruby laser energy output (independent of energy storage) with respect to the pumping light source. Indeed, the mechanism of energy storage by gamma rays in terms of center formations and the subsequent energy release by what has been called "light-induced thermoluminescence" (Gabrysh *et al.*[7]) or "radio-photoluminescence" (Przibram[2]) is not well understood. Further investigations by the authors regarding the underlying phenomena involved in this effect are in progress.

TABLE I. Energy output of ruby laser at room temperature (26.0±0.5°C) as a function of ^{60}Co gamma dosage.

Gamma dose (R)	Calorimeter energy output (relative)	Comparison figure
0	1.0	1(a)
700	1.7	1(b)
1000	2.0	1(c)
1400	2.2	1(d)
1700	2.8	1(e)

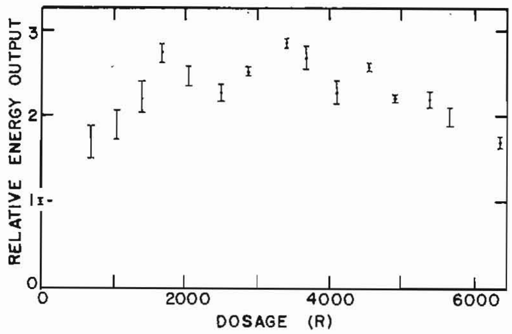

FIG. 2. Ruby output at room temperature as a function of ^{60}Co γ-dosage.

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1 Some of these results were reported by the present authors in a post-deadline paper contributed to The Spring Meeting of the American Physical Society, 1964, Washington, D. C., Session FI, Paper No. 3.

2 K. Przibram, *Irradiation Colours and Luminescence* (Pergamon Press Ltd., London, 1956); M. Furst and H. Kallman, Phys. Rev. 82, 964 (1951).

3 Use of the word dosage here refers to the total accumulated γ-ray exposure, expressed in roentgen units, as determined by ionization chamber dosimetry.

4 P. W. Levy, Phys. Rev. 123, 1226 (1961).

5 R. A. Hunt and R. H. Schuler, Phys. Rev. 89, 664 (1953).

6 J. H. Schulman and W. D. Compton, *Color Centers in Solids* (The Macmillan Company, New York, 1962), p. 291. However, some progress has recently been made in tentatively identifying several types of centers formed by the gamma irradiation of Al_2O_3 [F. T. Gamble, P. H. Bartram, C. G. Young, O. R. Gilliam, and P. W. Levy, Phys. Rev. 134, A589 (1964)].

7 See, for example, A. F. Gabrysh, H. Eyring, V. LeFebre, and M. D. Evans, J. Appl. Phys. 33, 3389 (1962); H. Kallman and M. Furst, Phys. Rev. 83, 674 (1951). Also it is interesting to note that Furst and Kallman [M. Furst and H. Kallman, Phys. Rev. 83, 964 (1951)] have estimated that 20% of the energy stored by gamma irradiation of AgCl activated NaCl crystals can be expelled by light excitation.

8 It was recently pointed out to the authors that W. Flowers and J. Jenney [Proc. IEEE 51, 858 (1963)] have also observed this same type of effect after repeated firings, in addition to a considerably smaller increase in the efficiency of ^{60}Co γ-irradiated ruby laser rods (by a factor of 5–10) than observed in the present experiments. However, close comparisons of their results with the results reported in this paper are not possible, primarily because the present experiments were performed with (a) higher temperatures (i.e., room temperatures rather than −100° to −130°C); (b) no ultraviolet filtering of the pumping lamps; and (c) lower γ-ray dosages to the laser rods.

9 A. F. Gabrysh, J. M. Kennedy, H. Eyring, and V. R. Johnson, Phys. Rev. 131, 1543 (1963).

10 See, for example, Schulman and Compton, Ref. 6.

11 J. Estermann, W. J. Leivo, and O. Stern, Phys. Rev. 75, 627 (1949).

12 J. L. Mador, R. F. Wallis, M. C. Williams, and R. C. Herman, Phys. Rev. 96, 617 (1954).