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CHANGES IN THE RESONATOR OF A RUBY LASER WHEN HEATED BY PUMPING

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Changes of the equal-width interference fringes from ruby crystals having plane parallel ends during pumping are investigated using an SFR-2M camera and a gas laser oscillating at 6328 Å. It is found that due to nonuniform heating of the ruby by the pump light the corresponding resonator acquires a spherical shape which promotes oscillation. The nonuniform heating results from focusing of the pump light by the lateral cylindrical surfaces of the ruby and from the generation of internal modes. Heating of the crystal was proportional to the chromium concentration (c); with 5-kJ pump energy and c = 0.018% the temperature rise was 4.8°C, which is 1.5 times the calculated result. The pump energy absorbed by the crystal and the efficiency of the illuminator are calculated.

IT is known that the fluorescent quantum efficiency of a ruby is 70%,[1] and that its energy efficiency is 20—40%. Therefore about 60—80% of the absorbed light energy is lost through heating of the crystal lattice. It has been calculated[2] that up to the onset of laser oscillation, when the ground-state and excited-state populations are nearly equal, a ruby crystal should be heated 1—2°C; during oscillation, when the threshold is exceeded by 20—30% it should be heated ~ 0.3°C; experimental confirmation has been obtained.[3] Because of thermal expansion and the increased refractive index of the ruby[4] the laser resonator is changed. Since the pump light is distributed unevenly over the cross section of the ruby rod,[5] the initial resonator shape is distorted and the emission characteristics of the laser are modified. We confirmed this experimentally in[2], where modes corresponding to a spherical cavity were observed in a laser having plane reflectors.

EXPERIMENT

In the present work the change of the resonator was investigated by means of an interferometer having as its light source a He-Ne gas laser oscillating at 6328 Å with the requisite coherence. The light beam from the gas laser GL (Fig. 1), rendered parallel by the lenses L_1 and L_2, traversed a semitransparent dividing plate DP and impinged at right angles on the end of a ruby R located within the pumping apparatus (PL, C). The plane parallel ends of the crystal were silver-coated; the back end was rendered opaque while the front end was 65—85% transmitting. The interference pattern formed by the light beams reflected from the two ends was photographed during pumping by a SFR-2M high-speed sequence camera. Emission from the ruby and scattered pump light were eliminated by two 6328-Å interference filters IF. The beam was focused, by means of a lens L_3,

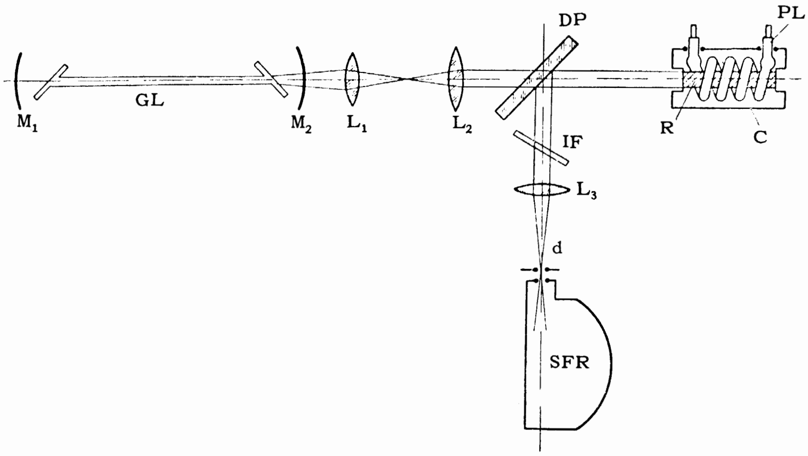

FIG. 1. Schematic diagram of the setup.

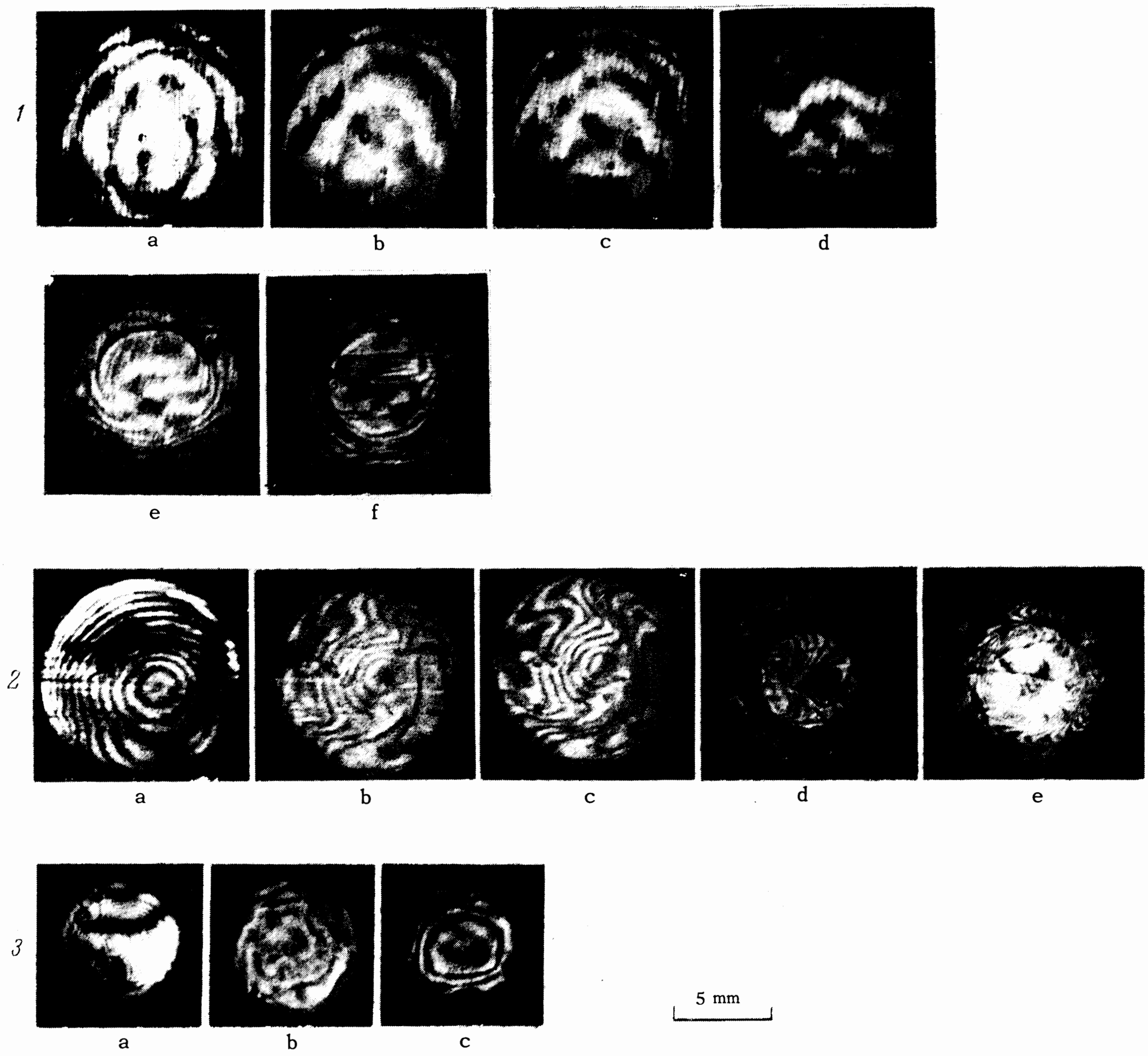

FIG. 2. Inteference patterns of rubies at different times following the onset of pumping, for different pumping energies. For rubies 1 and 3 – ordinary beam; for ruby 2 – extraordinary beam. The optic axes of the crystals are horizontal. Ruby 1: 1a – 0 msec; 1b – 5 kJ, 0.7 msec; 1c – 5 kJ, 2msec; 1d – 5 kJ, 3.5msec; 1e – 10 kJ, 3.5msec; 1f – 15 kJ, 3.5msec. Ruby 2: 2a – 0 msec; 2b – 5 kJ, 1.3msec; 2c – 5 kJ, 3.5msec; 2d – 10 kJ, 3.5msec; 2e – 15 kJ, 32msec. Ruby 3: 3a – 0 msec; 3b – 5 kJ, 1.0 msec; 3c – 5 kJ, 3.5msec.

on the diaphragm d of 2-mm diameter placed ahead of the entrance pupil of the SFR-2M instrument. We used rubies 50 mm and ~ 74 mm long with polished sides, and an IFK-15000 pumping lamp inside a polished duraluminum cylinder; the lamp was activated by a 1200-μF capacitor bank. The SFR-2M was used as a single-frame camera (operating as a "time magnifier"); the 67-μsec frame exposures were spaced 134-μsec apart. In a single run of 4.0 msec we obtained 30 frames.

RESULTS

The fringes in the interference patterns are of approximately equal width and $\lambda/2 = 0.32\,\mu$ separation; examples of individual frames are seen in Fig. 2. It can be seen that the positions, number, and shapes of the fringes change during pumping. This indicates, as was anticipated, that the overall optical length and shape of the resonator are highly modified during pumping.

The change of the optical path at any point in the cross section of the ruby rod can be calculated by computing the number of fringes Δm passing the point. The corresponding change ΔT in the mean temperature along the rod is calculated from

$$\Delta T = \frac{\lambda \Delta m}{2l(\partial\mu/\partial T + \mu\alpha)}, \qquad (1)$$

where l is the length of the rod, μ is the refractive

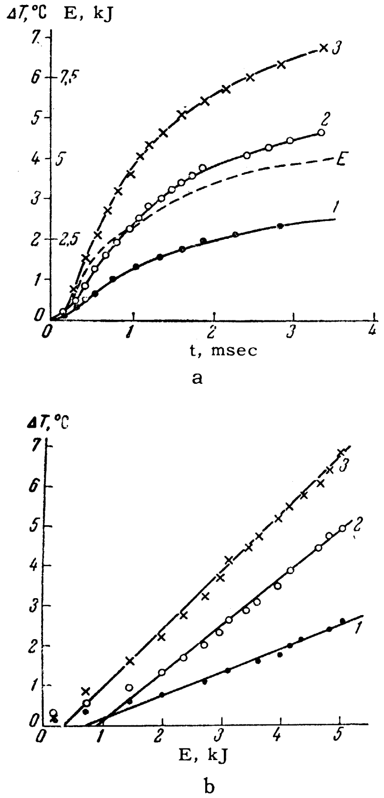

FIG. 3. Variation of mean temperature increase ΔT along ruby rod axis for total electrical pump energy 5 kJ. a – temperature increase ΔT and integrated pumping power E vs. time t; b – temperature increase ΔT vs. integrated pumping power E. Curve 1 – ruby 1 (c = 0.007% Cr); 2 – ruby 2 (c = 0.018% Cr); 3 – ruby 3 (c = 0.03% Cr).

index, α is the thermal expansion coefficient, and $\partial\mu/\partial T$ is the temperature coefficient of change in the refractive index of the ruby. The values of these quantities, taken from[6,4], were: $\mu_0 = 1.77$, $\mu_e = 1.76$, $\partial\mu_0/\partial T = 13.6 \times 10^{-6}$ deg^{-1}, $\partial\mu_e/\partial T = 14.7 \times 10^{-6}$ deg^{-1}, and $\alpha = 4.3 \times 10^{-6}$ deg^{-1} (refraction of the ordinary beam is denoted by the subscript 0, and that of the extraordinary beam by e). The calculation neglected changes of the refractive index resulting from mechanical strains. Estimates show that as these strains are generated (as will be discussed) by the developing thermal gradients, they cause a change of μ which is one order of magnitude smaller than that calculated from (1).

In Fig. 3a we see curves plotted from the foregoing formula and averaged over several photographs such as those in Fig. 2, representing the time dependence of the temperature change on the crystal axis for total electrical pump energy 5 kJ in the cases of three rubies containing different chromium concentrations. The same figure shows the integrated pumping power E vs. time, derived from an oscillogram of lamp emission normalized to the electrical pump energy. This graph was used to calculate the dependence of temperature at the center of the ruby on the integrated pumping power, which is shown in Fig. 3b to be of the expected approximately linear form. The slopes of the straight lines are approximately proportional to the chromium concentration. The nonlinear region near the origin appears to result from errors in counting the number of passing fringes when they move so rapidly that the pattern is smeared during the exposure of a single frame and counting becomes difficult (for example, frame 3b in Fig. 2). Nonlinearity could also result from changes in the lamp spectrum during pumping.

The alteration of the interference pattern observed visually immediately following a pump pulse also indicated a further change of the ruby temperature. Air at room temperature was blown through the illuminator to cool the ruby. It was found that the ruby remains heated 2–3 sec following a lamp flash. The ruby then begins to cool and its interference pattern returns gradually (within 3–4 min) to its original form, while the temperature of the ruby returns to that observed before the flash. The maximum heating of the ruby was determined from the number of fringes passing during the cooling period, and was found to be approximately twice as great as during the pumping period alone. The cause probably lies in the absorption of infrared radiation from parts of the outer cylinder which are heated during a light flash. The accompanying table presents data on the heating of the different crystals, as well as the thresholds and oscillation onset and termination times, which were determined from the oscillograms of oscillation with dielectric reflectors. Also shown are the calculated temperature increases (as in[2]) at the onset of oscillation (or more accurately, when the ground-state and excited-state populations are equal).

The experimental and calculated data in the table differ by a factor of 1.5–2, for reasons that remain unclear. Light may possibly be absorbed into a metastable state,[7] or internal modes may be excited,[8,9] resulting in a reduction of the radiation energy efficiency and also in a reduction of the excited-state lifetime.[9]

The change of equal-width fringes in the interference patterns during pumping (Fig. 2) indicates directly the change of resonator shape. The photographs show that the character of the resonator also changes. While before pumping begins rubies usually resemble a divergent lens (frames 1a and 2a), during pumping they resemble converging lenses (frames 1e, f; 2c, d, e; 3b, c). The inter-

	Cr concentration, %	Rod length, cm	Crystal volume, cm³	Oscillation threshold, kJ	Temperature increase, °C						
					To time of population equality (cal	To onset of oscillation	To end of oscillation (2.5msec)	To end of pumping (3.5msec)		Subsequent maximum heating	
					Pump energy						
					5 kJ					10kJ	15kJ
Ruby 1	0,007	7,35	5,30	4	0.5	10 (0.75 msec)	2.2	2.5	5,0	12,2	18.4
Ruby 2	0,018	7.37	5.50	4	1.3	1.8 (0.75 msec)	4.3	4.8	—	—	—
Ruby 3	0.03	5.00	1,87	2.5	2.1	2.8 (0.65 msec)	6.0	6.7	12.0	23,4	36.0

ference patterns were used to measure the equivalent focal lengths, which were found to be 1—4 m. It was shown in[2] that the modes excited during oscillation correspond to a resonator with inhomogeneities having effective focal lengths of this order of magnitude. The photographs show that the resulting resonator is asymmetric (astigmatic) and varies with time. The corresponding effect on the excited modes was observed in[2].

Thus, in the interior of a ruby having a polished lateral surface the optical inhomogeneities formed during pumping correspond to a converging lens which will promote oscillation. As already stated, the apparent cause is the stronger heating of the central region of the ruby due to the focusing of pump light by the cylindrical lateral surface.[5] This effect can also have a strong influence on the oscillation threshold, especially in crystals of poor optical quality. The onset of oscillation may depend not on the attainment of the population inversion, but on the time when the resonator becomes spherical, making it easy to excite oscillation. The discrepancy shown in the table between the calculated and experimental temperature increases corresponding to the onset of oscillation may also depend on this factor.

The mean optical length of the resonator changes as well as its shape. The cause of this effect appears to lie in the altered mean emission frequency during oscillation, which was observed in[10,11].

Calculations show that heat transport in a ruby during pumping can be neglected. Therefore temperature gradients of considerable magnitude arise in the ruby, especially in the case of high pump energy. The cross-sectional temperature distribution averaged over the length of a rod can be obtained approximately simply by subtracting the original interference pattern from any given later interference pattern; examples of the isotherms are shown in Fig. 4.

Following a 5-kJ pump pulse the temperature differences between the interior and peripheral regions of a crystal were 0.6° for ruby 1, 2.0° for ruby 2, and 1.5° for ruby 3. The maximum observed temperature gradients are ~ 1 deg/mm, which, according to calculations, induce mechanical strains of the order 1 kg/mm^2.

Figure 4 shows that the character of the temperature distribution varies between different rubies. In the case of ruby 2 (Fig. 4, d and e) the temperature inside the crystal is higher than at the edges, as we have already explained. However, the temperature distribution in rubies 1 and 3 is more complex, since the least heated region is not the surface but lies between the center and the edges. The surface region is heated almost as highly as the center. It appears that this surface heating can only be accounted for by the generation of internal modes which result from total internal reflection on the polished lateral surface and occupy the surface region.[8,9] Inactive light absorption, which occurs ordinarily in all rubies, results in heating, especially in the regions of greatest inactive absorption. The absence of internal modes in ruby 2 for 5-kJ pumping is probably accounted for by a higher, than in rubies 1 and 3, oscillation threshold of these modes, which depends on the quality of treatment of the lateral surface. Indeed, for higher pump energies (≥ 10 kJ) the interference patterns of this ruby correspond to the heating of the edges and center and resemble the patterns of ruby 1 (for example, frames 1d and 1f of Fig. 2), this indicating the generation of internal modes. It must be noted that in these frames the interference fringes are so closely spaced (up to 10 lines per mm) that they are no longer equal-width fringes.[12] In addition, at such temperature gradients it is necessary to consider mechanical strains and deformations; therefore Eq. (1) can no longer be used for a correct temperature calculation.

The energy absorbed by a ruby can be calculated from the temperature increase distribution over its cross section during a pumping cycle, its heat capacity (3 J/cm^3-deg), and its fluorescent energy efficiency (25%). By comparing this result with the useful light energy in a flash, which is 13% of the

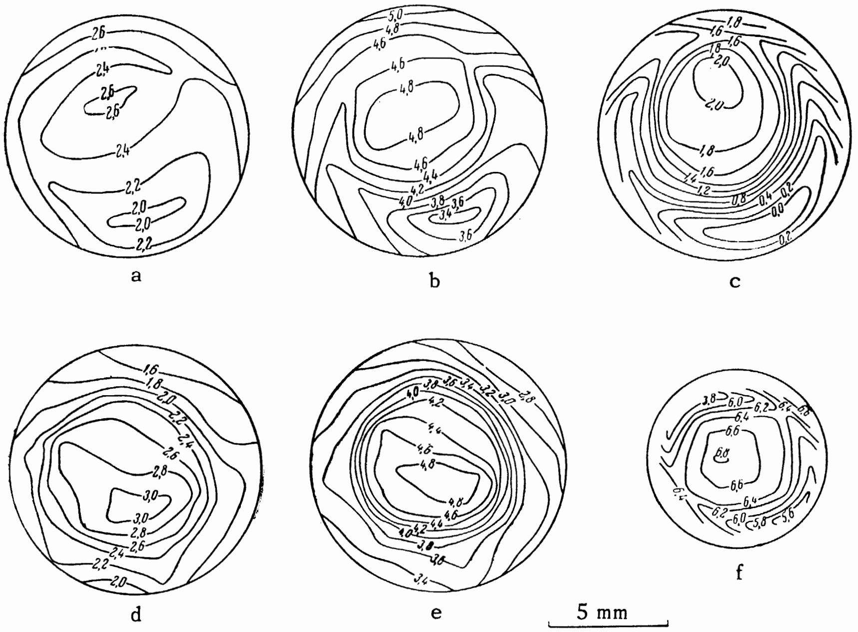

FIG. 4. Distribution of temperature increase over ruby cross section, averaged over the length of the ruby rod. The isotherm separation is 0.2°C. a – ruby 1, 5 kJ, 3.5 msec; b – ruby 1, 10 kJ, 3.5msec; c – ruby 1, 15 kJ, 3.5msec, with temperatures given relative to the least heated region; d – ruby 2, 5 kJ, 1.2msec; e – ruby 2, 5 kJ, 3.5msec; f – ruby 3, 5 kJ, 3.5msec.

electrical energy,[13] we obtain the efficiency of the illuminator. Out of 5 kJ electrical pump energy. ruby 1 absorbed 53 J (8.2% efficiency), ruby 2 absorbed 83 J (13% efficiency), and ruby 3 absorbed 47 J (7.2% efficiency). The low efficiency of the illuminator is explained by the fact that the heating of the rubies (as can be seen from the table and from Fig. 3) is proportional to the chromium concentration. Pump light is absorbed in rubies mainly through direct illumination by the lamp, without the participation of the entire illuminator. The rubies make little use of light scattered by the illuminator.

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