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Abstract

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PHYSICS

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INTERNAL MODES OF OSCILLATION IN A RUBY OPTICAL GENERATOR

Internal modes of oscillation exist in any optical resonator whose dimensions are much greater than the wavelength of light. The onset of generation in these modes leads to a decrease in the number of particles on metastable levels (^{1}) and to an additional release of heat in the ruby rod during generation (^{2}).

In the present work, the energy of internal modes of oscillation has been determined experimentally for an optical resonator in the form of a cylinder. The method for determining the energy of internal modes of oscillation is based on an analysis of the thermal energy that accumulates in the ruby crystal during operation of the optical generator.

We assume that the release of thermal energy in the ruby rod during the generation process occurs because of nonradiative transitions of the chromium ion from the excited states $^4F_2$ and $^4F_1$ to the ground $^4A_2$ and to the metastable levels $\bar{2}A$ and $\bar{E}$. Table 1 lists possible nonradiative transitions (column 1), the energies (in joules) transferred to the corundum crystal lattice by one chromium ion that has undergone a nonradiative transition (column 2), and the relative probabilities of the processes (column 3).

For interpretation of the experimental data, the values of three quantities should be determined by calculation: w, the energy transferred on average by each absorbed photon to the crystal lattice; p, the mean quantum yield; and ε_0, the mean energy of the absorbed photons. The values of w, p, and ε_0 depend on the spectral composition of the exciting radiation and on the specific characteristics of the ruby rod (geometrical dimensions, concentration of chromium impurity, orientation of the optical axis); for example, for the ruby sample on which generation of internal modes of oscillation was observed, $w = 1.9 \cdot 10^{-19}$ J, $p = 0.75$, $\varepsilon_0 = 4.1 \cdot 10^{-19}$ J. The crystal had the form of a cylinder 1.10 cm in diameter and 10.5 cm long, with an atomic chromium concentration of $(3 \pm 0.5) \cdot 10^{-2}\%$ and with the optical axis perpendicular to the generatrix of the cylinder. The source of the exciting radiation was a pulsed lamp with a color temperature of about 7000° K. One can indicate upper limits beyond which the values of w, p, and ε_0 cannot go under any variations in the spectral composition of the exciting radiation and in the characteristics of the ruby rods in absorption:

$$1.2 \cdot 10^{-19}\ \text{J} \leqslant w \leqslant 2.8 \cdot 10^{-19}\ \text{J},$$

$$0.7 \leqslant p \leqslant 0.8,$$

$$3.6 \cdot 10^{-19}\ \text{J} \leqslant \varepsilon_0 \leqslant 4.8 \cdot 10^{-19}\ \text{J}.$$

The lower limit corresponds to the case when absorption of photons from the exciting light field occurs only through the green absorption band; the upper limit corresponds to absorption through the blue band.

The increase in the thermal energy H of the ruby rod during genera-

cycle t can be represented by a formula containing three terms:

$$H = \frac{E}{\varepsilon p} w + \frac{rVt}{2\tau p} w + \frac{W}{\varepsilon p} \varepsilon_0.$$

The first term is the increase in the thermal energy of the crystal due to the generation of directed radiation, where E is the energy of the directed radiation, $\varepsilon = 2.8 \cdot 10^{-19}$ J is the energy of a photon of the generated light.

Table 1

	1	2	3
Blue absorption band, $(28 \div 21) \cdot 10^3$ cm^{-1}	${}^4F_1 \to {}^4A_2$	$4.8 \cdot 10^{-19}$	0.3
Blue absorption band, $(28 \div 21) \cdot 10^3$ cm^{-1}	${}^4F_1 \to {}^2\bar{A},\ \bar{E}$	$2.0 \cdot 10^{-19}$	0.7
Green absorption band, $(21 \div 16) \cdot 10^3$ cm^{-1}	${}^4F_2 \to {}^4A_2$	$3.6 \cdot 10^{-19}$	0.2
Green absorption band, $(21 \div 16) \cdot 10^3$ cm^{-1}	${}^4F_2 \to {}^2\bar{A},\ \bar{E}$	$0.72 \cdot 10^{-19}$	0.8

Fig. 1. Amount of thermal energy in 1 cm^3 of the volume of a ruby rod as a function of generation time for various operating regimes of an optical generator

Figure 1: Fig. 1. Amount of thermal energy in 1 cm^3 of the volume of a ruby rod as a function of generation time for various operating regimes of an optical generator

The second term gives the increase in thermal energy due to losses of particles from the metastable levels $\bar{E}$ and $^2\bar{A}$ to luminescent emission of the crystal. We assume that the inversion coefficient during generation is small and that the number of particles on the metastable levels, $rV/2$, is close to one half of the number of chromium ions in the ruby crystal; V is the volume of the ruby rod, r is the chromium concentration in it, and $\tau = 4.3$ msec is the lifetime of the metastable states. The third term is the increase in thermal energy due to generation in internal modes of oscillation; W is the energy of this generation.

We assume that radiation during generation in internal modes of oscillation only weakly emerges beyond the boundaries of the ruby crystal and is completely absorbed in it. If, on the contrary, one assumes that the radiation leaves the ruby rod completely, then the factor ε_0 should be replaced by the factor w, which is approximately half as large.

Fig. 1. Amount of thermal energy in 1 cm^3 of the volume of a ruby rod as a function of generation time for various operating regimes of an optical generator.

Figure 1 shows plots of the thermal energy H (J/cm^3) released in 1 cm^3 of the volume of the generating crystal as a function of the generation time t (msec) for different operating regimes of the generator. The measurements were carried out at a temperature of $80 \div 130^\circ$ K on a ruby rod with a polished lateral surface. The temperature rise of the generating crystal was recorded from the decrease in the frequency of the outgoing radiation (2). The electrical energy stored in the capacitor banks by the beginning of the flash-lamp discharge corresponds, for curve 1, to the threshold value for the onset of generation, and for curves 2 and 3 is respectively 1.3 and 1.9 times larger. The dashed line denotes the thermal energy 470 W/cm^3 released in 1 cm^3 of the sample volume owing to losses of particles from the metastable levels to the luminescent emission of the crystal.

Curve 1 corresponds to the smallest value of the excitation energy. Most of the heat released in the ruby crystal in this generation regime arises from losses of particles to the luminescent emission of the crystal. The heat release due to the generation of directed radiation may be neglected. The rate of accumulation of thermal energy in the ruby rod depends only on the concentration of chromium ions. Taking into account that the slope of curve 1 is determined with an accuracy of ±20%, the calculated and experimental curves agree within the limits of error.

This means that near the threshold for the onset of generation, a mode of operation of the optical generator is realized in which practically all particles pass from metastable states to the ground state spontaneously, giving up their energy to the luminescent glow of the crystal.

Curve 3 corresponds to the greatest value of the excitation energy. The increase in thermal energy in the ruby rod by 260 J over the generation time of 13 msec cannot be explained either by heating due to particle losses to luminescence (60 J) or by heating due to generation of directed radiation. The liberation of the main amount of heat, 200 J, should be explained by intense generation on internal types of oscillations. The generation energy, calculated from the heat-balance formula, is equal to 100 J.

This means that, when the threshold for the onset of generation is exceeded twofold, a mode of operation of the optical generator is realized in which the larger part (60%) of the energy of the particles leaving the metastable states is converted into the energy of internal types of oscillations. The energy W is tens of times greater than the energy of directed radiation under similar experimental conditions. The same conclusion can be reached by analyzing the heat liberation during the generation process in samples of ruby rods with a matted lateral surface (^{2}); however, the energy of the directed radiation increases because of partial suppression of internal types of oscillations. The liberation of excess heat in the ruby rod can be explained in part by an additional expenditure of particles on the amplification of spontaneous radiation.

The small energy of the directed radiation of an optical generator with pulsed switching of the quality factor, in comparison with the normal mode of operation, should be explained by the occurrence of generation on internal types of oscillations. The effort to obtain a large inversion coefficient creates especially favorable conditions for the occurrence of generation on internal types of oscillations and, as a consequence of this, for the loss of accumulated particles even before the moment at which directed radiation arises.

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Note: Figure translations are in progress. See original paper for figures.

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