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Abstract

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THE INFLUENCE OF NOISE RADIATION ON THE OPERATION OF A RUBY QUANTUM GENERATOR

The radiation of an optical quantum generator includes not only the directed flux emerging through the ends, but also radiation emitted in lateral directions. This radiation, consisting of amplified luminescence and scattered generation, may conventionally be called the generator' s "noise" radiation. The magnitude of the noise directly reflects the radiative losses of the laser and is one of its most important characteristics.

The noises of quantum generators have been considered by a number of authors ([1–4]). A more complete theoretical analysis of the influence of noise radiation on the properties of an optical quantum generator is given in ([5,6]). In the present work we consider a method which, on the basis of experimental measurements of the populations of energy levels and of the relative magnitudes of the pump power, makes it possible to calculate the noise intensity of a ruby laser.

In the stationary regime the total emission power per unit volume of ruby in all directions is determined by the density of the pump radiation and by the population of the ground state:

$$W^{\mathrm{em}} = h\nu_{21} n_1 \eta B_{13} u_{31}. \tag{1}$$

Here $h\nu_{21}$ is the energy of a quantum at the emission frequency; $\eta B_{13} u_{31}$ is the probability that a particle passes from the ground state to the metastable state under the action of the density of the exciting radiation u_{31}; n_1 is the population of the ground state of ruby; the indices 1, 2, and 3 here and below denote, respectively, the ruby levels ${}^4A_2^2E$ and both levels ${}^4F_1$ and ${}^4F_2$, or the transitions between them. The quantum yield of ruby in the channel $2 \to 1$ is assumed equal to unity ([7]).

Of the total power W^{em}, only part of the radiation is separated out in the form of the useful generation flux S^{gen}; the remaining part goes into the creation of noise radiation W^{n}. Thus, the intensity of the generation flux depends both on the total emission power and on the noise power:

$$S^{\text{gen}} = W^{\text{em}} - W^{\text{n}}. \tag{2}$$

The relation between S^{gen} and W^{n} largely determines the efficiency of the generator and is an essential characteristic of it.

The power of the noise radiation can be represented in the form of a sum

$$W^{\text{n}} = W^{\text{lum}}_{\text{ampl}} + W^{\text{scat}}_{\text{ampl}}, \tag{3}$$

where $W^{\text{lum}}_{\text{ampl}}$ and $W^{\text{scat}}_{\text{ampl}}$ are, respectively, the powers of luminescence and scattered generation, taking into account amplification in the medium.

By analogy with the expression for the flux of generated radiation ([8])

$$S^{\text{gen}} = vk^{\text{mirr}}u^{\text{gen}}, \tag{4}$$

one may write ([5]):

$$W^{\text{lum}}_{\text{ampl}} = vRu^{\text{lum}}, \tag{5}$$

$$W^{\text{scat}}_{\text{ampl}} = vRu^{\text{scat}}. \tag{6}$$

Here $k^{\text{mirr}} = \dfrac{1}{l} \ln \dfrac{1}{\sqrt{r_1 r_2}}$ is the coefficient of useful losses, depending on the reflection of the mirrors r_1 and r_2 and on the length of the ruby l; R is the coefficient of noise losses; u^{lum}, u^{scat}, and u^{gen} are the corresponding radiation densities inside the ruby.

The magnitude of the coefficient R can be determined using the method described in work (9). To calculate the fluxes (4)–(6), it remains to find the densities u^{lum}, u^{scat}, and u^{gen}.

With the aid of the balance equations for the system of ruby levels, the frequency-integrated density of emission inside the specimen u_{21} can be related to the relative population of the metastable level n_2/n and to the pump-radiation density u_{31} (10)

$$X = \frac{\alpha_{12}u_{31} - (n_2/n)(\alpha_{13}u_{31} - 1)}{2n_2/n - 1}. \tag{7}$$

Here

$$X = B_{21}u_{21}/A_{21}; \tag{8}$$

$$\alpha_{13} u_{31} = \tau_2^0 \eta B_{13} u_{31}; \tag{9}$$

τ_2^0 is the luminescent lifetime of the excited particles; $A_{21} = \int A_{21}(\nu)\, d\nu$; $B_{21} u_{21} = \int B_{21}(\nu) u(\nu)\, d\nu$ *.

In work (11) an experimental method is described which makes it possible to measure the relative population of the metastable level of ruby n_2/n and the value $\alpha_{13} u_{31}$. Using this method, one can, by means of formulas (7) and (8), for any pump intensity find the emission density inside the ruby

$$u_{21}^{\text{sum}} = u^{\text{lum}} + u^{\text{scat}} + u^{\text{gen}}. \tag{10}$$

Since at threshold $u^{\text{scat}} = u^{\text{gen}} = 0$, in order to calculate u^{lum} it is necessary to substitute into (7) the values n_2^{gen}/n and $\alpha_{13} u_{31}^{\text{thr}}$ corresponding to the generation threshold. The quantity $\alpha_{13} u_{31}^{\text{thr}}$ is found from the minimum pump intensity which creates in the ruby a relative population of the metastable level equal to n_2^{gen}/n. We now determine the density of scattered generation u^{scat}. Since the populations of the energy levels do not change in the course of generation, it is not difficult to show that, for a pump density exceeding the threshold by N times, the relation

$$(S^{\text{gen}} + W_{\text{ampl}}^{\text{scat}})/W_{\text{ampl}}^{\text{mol}} = N - 1 \tag{11}$$

is satisfied. Substituting formulas (4)–(6) into the last equation and using (10), we find

$$u^{\text{scat}} = u^{\text{lum}} \frac{N - 1 + (k^{\text{mirr}}/R)(1 - u_{21}^{\text{sum}}/u^{\text{lum}})}{1 - k^{\text{mirr}}/R}. \tag{12}$$

Knowing u_{21}^{sum}, u^{lum}, and u^{scat}, we calculate with the aid of (10) the density of the generated radiation u^{gen}.

Thus, with the aid of experimental measurements of the quantities n_2/n and $\alpha_{13} u_{31}$, it is possible to find the absolute values of the radiation density inside the ruby caused by luminescence, generation, and scattered generation. In work (9) it is shown that the same measurements make it possible to determine the noise-loss coefficient R, which is required for calculating the fluxes (4)–(6).

* Expression (8) may be represented in the form $X = \varepsilon B_{21}(\nu^{\max}) u_{21} \tau_2^0$, where $B_{21}(\nu^{\max})$ is the Einstein coefficient at the maximum of the contour $B_{21}(\nu)$; u_{21} is the frequency-integrated radiation density; ε is a coefficient depending on the coincidence of the spectral course of the curves $B_{21}(\nu)$ and $u_{21}(\nu)$. For the generated radiation $\varepsilon = 1$.

Using the method described above, the principal characteristics determining the influence of noise radiation on the operation of a ruby quantum generator were

Figure 1 and Figure 2 graphs

Figure 1: Figure 1 and Figure 2 graphs

found. For the measurements a pink-ruby crystal was used, in the form of a cylinder 48 mm long and 8 mm in diameter.

Figure 1a shows the dependences of the quantities u^{gen} and u^{sh} on the loss coefficient k^{mirr} for three pump intensities.

Fig. 1. Dependence of the radiation density inside the ruby u^{gen} (a, curves 1-3) and u^{sh} (a, curves 4-6), and of the emission powers S^{gen} (b, curves 1-3) and W^{sh} (b, curves 4-6) on the mirror-loss coefficient. The curves were obtained for the following values of $\alpha_{13}u_{31}$: curves 1 and 4 $-\alpha_{13}u_{31} = 8.5$; 2 and 5 $-\alpha_{13}u_{31} = 15$; 3 and 6 $-\alpha_{13}u_{31} = 25$.

Fig. 2. a $-$dependence of the ratios $W^{\text{lum}}_{\text{ampl}}/W^{\text{sh}}$ (1, 2, and 3) and W/W^{sh} (4, 5, and 6) on k^{mirr}. The quantity $\alpha_{13}u_{31}$ has the following values: curves 1 and 6 $-\alpha_{13}u_{31} = 25$; 2 and 5 $-\alpha_{13}u_{31} = 15$; 3 and 4 $-\alpha_{13}u_{31} = 8.5$. b $-$variation of the ratio $u^{\text{por}}/u^{\text{por}}_0$ (1) and $S_{\text{gen}}/S^{\text{gen}}_0$ (2 and 4) as a function of k^{mirr}. Curves 2-4 were obtained for values of $\alpha_{13}u_{31}$, respectively equal to 8.5; 15; 25.

pump intensities. It is seen from the figure that both quantities decrease as the mirror transmission increases; however, the noise-radiation density u^{sh} falls considerably more slowly than u^{gen}. It should be noted that even for small values of k^{mirr} the density u^{gen} exceeds u^{sh} by only a factor of three. For large mirror transmissions the noise density may even exceed the generation density (curves 1 and 4).

If one compares not the radiation densities inside the crystal, but the emission powers calculated per unit volume, the picture becomes sharply worse (Fig. 1b). In the case under consideration, the noise-emission power for all k^{mirr} considerably exceeds the useful radiation S^{gen}. The curves of the dependence of S^{gen} on k^{mirr} have a maximum, which is connected with the presence of scattering losses in the generator. Since W^{sh} decreases monotonically with increasing k^{mirr},

then the ratio $S^{\text{gen}}/W^{\text{sh}}$ also has a maximum. Its position is characterized by such a mirror transmission coefficient that, at the given pumping intensity, ensures a mode of operation of the ruby laser with a minimum relative noise level.

Figure 2a gives the ratios $W^{\text{lum}}_{\text{ampl}}$ and $W^{\text{sc}}_{\text{ampl}}$ to W^{sh} for different values of k^{mir} and different pumping intensities. It is seen from the figure that, at small transmissions of the resonator mirrors, the principal source of noise radiation is the scattered generation light, whereas at large transmissions it is luminescence.

Noise radiation substantially worsens the energy properties of the quantum generator. In particular, the presence of noise leads to an increase in the threshold and to a decrease in the generation power.

Figure 2b presents the dependence, on the mirror loss coefficient, of the ratio of the threshold pumping intensities without and with allowance for the influence of noise (curve 1). It is seen from the figure that, at large mirror transmissions, the generation threshold of the given ruby sample is increased, owing to the presence of noise, by almost a factor of two. With an increase in the Q of the resonator this influence decreases.

The losses of useful-radiation power are determined not only by luminescence and scattering, but also by stimulated emission under the action of the luminescence light and of the scattered generation. If this emission were absent (i.e., if $u^{\mathrm{sh}} = 0$), then, according to (4), the useful generation power S_0^{gen} would exceed the actually obtained power S^{gen} by as many times as the total radiation density of the ruby u_{21}^{sum} is greater than the density u^{gen}:

$$S_0^{\mathrm{gen}}/S^{\mathrm{gen}} = u_{21}^{\mathrm{sum}}/u^{\mathrm{gen}}.$$

Curves 2–4 in Fig. 2b show the dependence of the ratio $S^{\mathrm{gen}}/S_0^{\mathrm{gen}}$ on k^{mir} for different pumping values. It is seen from the figure that the presence of noise radiation noticeably reduces the generation power. The degree of influence of this factor evidently depends on the noise loss coefficient R. An increase in the value of R (for example, by clarifying the side walls) will contribute to an increase in the useful power of the generator.

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