ENERGY BALANCE OF RADIATION NOISE IN OPTICAL QUANTUM GENERATORS

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Abstract

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In work ([1]) attention was drawn to the need to take into account the influence of noise on the optical properties of quantum generators. The processing of experimental data carried out in ([2]) showed that the presence of noise causes a substantial decrease in the power of the generated flux. In the present work an energy balance is considered which makes it possible to relate the radiation density of the noise to the characteristics of the resonator, and a general scheme is proposed for calculating the energy characteristics of solid-state optical quantum generators (OQG) with allowance for the influence of radiation noise.

In a stationary or quasi-stationary generation regime, the input of noise radiation must be compensated by its losses upon leaving the limits of the active rod. It is expedient to characterize the magnitude of the losses by the mean noise-loss coefficient $R_{\text{loss}}(\nu)$, calculated per unit path of a light ray. The averaging refers both to the volume of the rod and to all directions of propagation of the noise radiation. The amount of noise energy lost per unit time in a unit spectral interval may be represented in the form

$$lsvR_{\text{loss}}(\nu)\,[u_{\text{lum}}(\nu)+u_\rho(\nu)].$$

Here l is the length of the rod, s is the area of its cross section, v is the speed of light, and u_{lum} and u_ρ are the densities of the noise radiation arising from luminescence and scattering. The mean input of noise energy is determined by the luminescence power $W_{\text{lum}}(\nu)$ and the scattering power of the principal flux $W_\rho(\nu)$. In addition, noise energy is released owing to its amplification. It is equal to $lsvk(\nu)[u_{\text{lum}}(\nu)+u_\rho(\nu)]$, where $k(\nu)$ is the mean amplification coefficient.

The stationary regime can be maintained if

$$W_{\text{lum}}(\nu)+W_\rho(\nu)+lsvk(\nu)[u_{\text{lum}}(\nu)+u_\rho(\nu)] = lsvR_{\text{loss}}(\nu)[u_{\text{lum}}(\nu)+u_\rho(\nu)]. \quad (1)$$

It follows from (1) that the loss coefficient of the noise radiation must exceed the amplification coefficient. Otherwise, inside the rod there would occur an accumulation of noise radiation, ending in the disruption of directed generation.

The energy balance of the noise must be satisfied for each noise source separately. Hence it follows that

$$u_{\text{lum}}(\nu) = \frac{W_{\text{lum}}(\nu)}{lsv\,[R_{\text{loss}}(\nu) - k(\nu)]}, \tag{2}$$

$$u_{\rho}(\nu) = \frac{W_{\rho}(\nu)}{lsv\,[R_{\text{loss}}(\nu) - k(\nu)]}. \tag{3}$$

For given $W_{\text{lum}}(\nu)$ and $W_{\rho}(\nu)$, the noise densities are determined by the ratio of the coefficients $R_{\text{loss}}(\nu)$ and $k(\nu)$. If, by improving the resonator, it is possible to ensure high values of $R_{\text{loss}}(\nu)$, then the density

the noise will be small even for large $W_{\text{lum}}(\nu)$, $W_{\rho}(\nu)$, and $k(\nu)$. Conversely, for $R_{\text{loss}}(\nu)$ close to $k(\nu)$, the noise density is very large.

Expressions (2) and (3) are valid for each frequency separately and determine the spectral distribution of the noise density. Since the spectral width of the functions $R_{\text{loss}}(\nu)$ and $k(\nu)$ is considerably greater than the width of the function $W_{\rho}(\nu)$, the spectral distribution of the noise density $u_{\rho}(\nu)$ coincides with the corresponding distribution of the generated radiation. The integral density of the noise arising from scattering of the principal flux is equal to

$$u_{\rho} = \int u_{\rho}(\nu)\,d\nu = \frac{W_{\rho}}{ls\nu\,[R(\nu_r) - k_{\text{loss}}]}, \qquad k_{\text{loss}} = \rho + \frac{1}{l}\ln\sqrt{\frac{1}{r_1 r_2}}, \tag{4}$$

where k_{loss} is the loss coefficient of the generated radiation; $W_{\rho} = \int W_{\rho}(\nu)\,d\nu$; ρ is the coefficient of harmful losses; $\frac{1}{l}\ln\sqrt{\frac{1}{r_1 r_2}}$ is the coefficient of useful losses [1]. In integrating (2), we have taken into account that in the steady-state regime the gain coefficient of the generated frequency $\nu = \nu_r$ is equal to the loss coefficient.

The spectral distribution of the noise density arising from luminescence depends not only on the form of the function $W_{\text{lum}}(\nu)$, but also on the magnitude and spectral distributions of the coefficients $R_{\text{loss}}(\nu)$ and $k(\nu)$. The value of R_{loss} usually depends only weakly on ν, while the contour of the gain band $k(\nu)$ is close to the contour of the function $W_{\text{lum}}(\nu)$. If R_{loss} is considerably greater than the maximum value of $k(\nu)$, i.e., $k(\nu_r)$, then the dependences of u_{lum} and W_{lum} on ν coincide. The closer $k(\nu_r)$ and R_{loss} are, the sharper the function $u_{\text{lum}}(\nu)$. For $k(\nu_r) \geq R_{\text{loss}}$, the noise density is practically monochromatic.

To calculate the integral noise density u_{lum}, it is necessary to have analytic expressions for $W_{\text{lum}}(\nu)$ and $k(\nu)$. Suppose that they are represented by dispersion functions. Integration of (2) is easy to carry out only for the limiting cases considered. As a result we have

$$u_{\text{lum}} = \int u_{\text{lum}}(\nu)\, d\nu = \frac{W_{\text{lum}}}{ls\nu\,[R_{\text{loss}}(\nu_r) - k_{\text{loss}}/\xi]}, \tag{5}$$

where $W_{\text{lum}} = \int W_{\text{lum}}(\nu)\, d\nu$, and ξ is a parameter equal to 1 for $R_{\text{loss}} \sim k_{\text{loss}}$ and to 2 for $R_{\text{loss}} \gg k_{\text{loss}}$. Naturally, one may assume that formula (5) is approximately valid also for all intermediate cases, with ξ depending on the loss coefficient and varying from unity to two.*

With the aid of expressions (4) for the density and the noise, it is not difficult to obtain an analytic expression for the power of the generated radiation. In [1] it was shown that

$$W_{\text{gen}} = W_{\text{gen}}^0 - ls\nu\left(\rho + \frac{1}{l}\ln\sqrt{\frac{1}{r_1 r_2}}\right)u_{\text{sh}}, \tag{6}$$

where W_{gen}^0 is the generation power in the absence of noise, equal to

$$W_{\text{gen}}^0 = \frac{ls\nu}{\alpha(\nu_r)}\left[k_0(\nu_r) - \left(\rho + \frac{1}{l}\ln\sqrt{\frac{1}{r_1 r_2}}\right)\right]; \tag{7}$$

k_0 and α are the initial gain coefficient and the nonlinearity parameter, determined by the properties of the substance and by the pump intensity, and $u_{\text{sh}} = u_{\text{lum}} + u_\rho$. The magnitudes of the fluxes leaving the resonator,

* If it is assumed that the functions $W_{\text{lum}}(\nu)$ and $k(\nu)$ are approximated by Gaussian functions, it is not difficult to arrive at the same formula (5) with values of ξ varying from 1 to $\sqrt{2}$.

and the powers of the scattering losses are equal to

$$S = W_{\text{gen}}\frac{\frac{1}{l}\ln\sqrt{\frac{1}{r_1 r_2}}}{\rho + \frac{1}{l}\ln\sqrt{\frac{1}{r_1 r_2}}}, \tag{8}$$

$$W_\rho = W_{\text{gen}}\frac{\rho_{\text{sc}}}{\rho + \frac{1}{l}\ln\sqrt{\frac{1}{r_1 r_2}}}, \tag{9}$$

where ρ_{sc} is the scattering coefficient ($\rho_{\mathrm{sc}} \leqslant \rho$).

It follows from (9) and (6) that the amount of scattered radiation, which is one of the noise sources, itself depends on the noise density. An increase in the noise reduces W_ρ. This relation can be eliminated by solving the system of equations (4) and (9) with respect to W_ρ and u_{n}. Taking (5)–(7) into account, we obtain:

$$u_{\mathrm{lum}} = \frac{W_{\mathrm{lum}}}{lsv\left(R_{\mathrm{loss}} - \dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}\right)} \frac{R_{\mathrm{loss}} - k_{\mathrm{loss}}}{\xi R_{\mathrm{loss}} - k_{\mathrm{loss}}}, \tag{10}$$

$$u_\rho = \frac{W^0_{\mathrm{gen}}}{lsv\left(R_{\mathrm{loss}} - \dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}\right)} \frac{\rho_{\mathrm{sc}}}{\rho + \dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}}. \tag{11}$$

Substituting (10) and (11) into (8), we find:

$$S = S^0\left[1 - \frac{\rho_{\mathrm{sc}}}{R_{\mathrm{loss}} - \dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}}\right] - \frac{\dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}\, W_{\mathrm{lum}}}{R_{\mathrm{loss}} - \dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}} \frac{R_{\mathrm{loss}} - k_{\mathrm{loss}}}{R_{\mathrm{loss}} - k_{\mathrm{loss}}}. \tag{12}$$

In formula (12) the magnitude of the noise density has been eliminated; it is replaced by the parameters R_{loss} and ξ. The first of these is determined by the properties of the resonator; the second, in addition, by the spectral distribution of the luminescence power and by the gain coefficient.

Formula (12) is valid for arbitrary substances. For specific calculations it is necessary to substitute into (12) the values of k_0, α, and W_{lum} appropriate for generators operating according to three-level and four-level schemes (1).

For a three-level generator we have

$$S = \frac{lsnh\nu_{\mathrm{r}}}{1 + g_2/g_1}(1-\delta)\eta B\left(u_{\mathrm{pump}} - u^{\mathrm{thr}}_{\mathrm{pump}}\right)\left(1 - \frac{\rho_{\mathrm{sc}}}{R_{\mathrm{loss}} - \dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}}\right) \frac{\dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}}{\rho + \dfrac{1}{l}\ln\sqrt{\dfrac{1}{r_1 r_2}}}, \tag{13}$$

where

$$\delta = k^{\mathrm{loss}}/\chi, \tag{14}$$

$$\eta B u_{\text{pump}}^{\text{thr}} = p_{21}\frac{g_2/g_1+\delta}{1-\delta}\left(1+\frac{A_{21}}{p_{21}}\frac{\rho+\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}{\xi R-\rho-\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}\,\frac{R-\rho-\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}{R-\rho_{\text{sc}}-\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}\right); \tag{15}$$

g_2 and g_1 are the statistical weights of the levels; η is the quantum yield of luminescence; B is the Einstein coefficient in the pump channel, integrated over frequency; u_{pump} is the pump radiation density; χ is the limiting gain coefficient reached as $u_{\text{pump}} \to \infty$; p_{21} is the probability of transition from level 2 to level 1; A_{21} is the probability of spontaneous transition.

It follows from (13)–(15) that the presence of noise increases the threshold and decreases the slope of the straight lines $S(u\ \ )$. The first is associated with noise arising due to luminescence, the second due to scattering. As $\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}$ increases up to $R\ \ -\rho$, the slope of the curve tends to zero; generation breaks down.

For a four-level generator, for which $h\nu_{21} \gg kT$, the corresponding formulas have the form

$$S = lsnh\nu\,(1-\delta)\eta B\,(u\ \ \ -u\ \ )\left(1-\frac{\rho}{R\ \ -\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}\rho+\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}\right)\frac{\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}{\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}, \tag{16}$$

$$\eta B u\ \ \ = (p_{31}+p_{32})\frac{\delta}{1+\delta}\left[1+\frac{A_{32}}{p_{31}+p_{32}}\,\frac{k}{\xi R\ \ -k}\,\frac{R\ \ -k}{R\ \ -\rho\ \ -\frac{1}{l}\ln\sqrt{\frac{1}{r_1r_2}}}\right], \tag{17}$$

where p_{31} and p_{32} are the probabilities of the corresponding transitions, and A_{32} is the probability of spontaneous transition.

Processing experimental data by formulas of the type (13) and (16) is not difficult. Using the data given in [2], it is easy to find the value of R for the studied neodymium-glass sample. The calculations gave $R\ \ = 0.09$ cm^{-1}. In [3] the value of R was determined for one of the ruby samples. It turned out to be independent of k (with an accuracy of up to 5%) and equal to 0.51 cm^{-1}. In both cases, especially in the first, the influence of noise is very substantial. The parameter R , along with the parameter ρ, is a principal characteristic of the resonator.

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CITED LITERATURE

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