** By virtue of the periodic boundary conditions, the momentum variables p, q, etc. run through the values $\pm 2\pi n/L$, n = 0, 1, 2, ...

EMISSION STATISTICS OF A LASER WITH NONRESONANT FEEDBACK

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1. In [1,2] we proposed and investigated a laser with nonresonant feedback produced by radiation scattering. In this letter we report the results of a theoretical and experimental investigation of the statistical properties of the emission of such a laser. We shall show that the emission statistics of a laser with nonresonant feedback differs greatly from the emission statistics of ordinary lasers. The radiation intensity within extremely narrow solid angles is subject to strong fluctuations, and the distribution function of the intensity fluctuations coincides with the distribution function of the number of photons in one quantum state of black-body radiation at large occupation numbers.

2. Generation in a laser with nonresonant feedback is effected in a large number of low-Q modes that interact strongly with one another as a result of scattering. Their number L (for one polarization) is given by

$$L \simeq \Omega_{gen}/(\frac{\lambda}{D})^2, \tag{1}$$

where Ω_{gen}, D, and λ are the solid angle, diameter, and wavelength of the generated emission, respectively. Generation in a set L of scattering-coupled modes is due to the fact that the radiation losses of the set of interacting modes is much lower than the loss of any single mode [1].

The theoretical analysis of the emission statistics of a laser with nonresonant feedback is based on the following model: We consider an ensemble of a large number L of modes that interact nonlinearly with the active medium and interact linearly with one another via exchange of radiation (by scattering). The active medium is described by a set of M two-level atoms, and the radiation field in the i-th mode, by the number of photons n_i. A method similar to that developed in [3] yields a pilot equation for the probability $P_m^{n_1,n_2,\ldots n_L}$ of the state with n_i photons in the i-th mode (i = 1, 2, ..., L) and m atoms at the lower level, and also for the probability P_m^N of the state with $N = \sum_{i=1}^{L} n_i$ photons in all L modes and m atoms at the lower level.

In the stationary state, the pilot equation for the probability P_m^N determines fully the distribution function of the total number of photons, P^N, which turns out to be analogous, owing to saturation of the atoms, to the distribution function of the number of photons in one mode of an ordinary laser (it has a sharp maximum at $N = \bar{N}$ with relative width $\sim 1/\sqrt{N}$, [3-5]). From the pilot equation for the probability $P_m^{n_1,n_2,\ldots,n_L}$ in the stationary state we get the distribution function P^{n_i} of the number of photons in the i-th mode. Assuming that all $\bar{n}_i = \bar{n} >> 1$, this distribution takes a form

$$P^{n_i} = \frac{1}{\bar{n}} \exp(-\frac{n_i}{\bar{n}}) \quad (i = 1,2,\ldots,L) \tag{2}$$

analogous to the Bose-Einstein distribution function for the number of photons in one quantum state of black-body radiation with $\bar{n} \gg 1$ [6,7].

We see that the probability of filling one mode with photons experiences considerable fluctuations, whereas the number of photons N in all the modes is relatively stable. Physically this is connected with the fact that the nonlinearity of the generator (saturation effect) effect) stabilizes the intensity of the entire generated radiation $N = \sum_{i=1}^{L} n_i$, while the linear interaction of the modes with one another admits of considerable fluctuations of n_i at a fixed value of N.

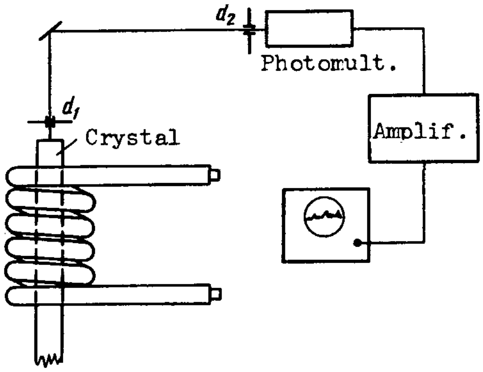
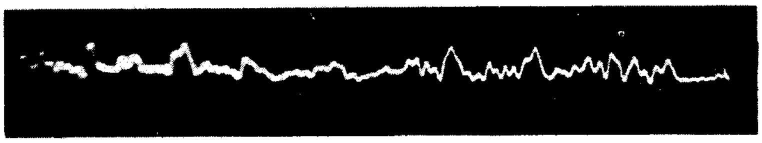


Fig. 1. Experimental setup

3. The experiment consisted of measuring the distribution function $p(n_i)$. The experimental setup is shown in Fig. 1. The nonresonant-feedback laser comprised a ruby crystal of length ℓ = 110 mm and diameter D = 9.5 mm, placed in a dewar with liquid nitrogen and pumped with a spiral flash lamp. One end of the crystal was silvered ($r \simeq 50\%$), and the other was rounded off and ground dull to effect feedback via scattering; the side surface of the crystal was also ground.

The laser radiation was fed to a photomultiplier through two diaphragms D_1 and D_2 with hole diameter d = 0.5 mm, placed at a distance h = 60 cm apart. To register radiation in one mode the diaphragm diameter d must satisfy the condition $d \leq \sqrt{\lambda h}$, and the time resolution τ of the recording apparatus must satisfy the condition

Fig.2. Oscillogram of radiation intensity in a small solid angle 400 μsec after start of generation; sweep duration 500 μsec.



$\tau < 1/2\pi\Delta\nu c$, where $\Delta\nu$ is the width of the emission spectrum in cm^{-1}. We had at our disposal a photomultiplier with $\tau \simeq (2\text{-}3)\times 10^{-9}$ sec, calling for a generation line width $\Delta\nu \leq 10^{-3}$ cm^{-1}. Since the narrowing of the spectrum in a nonresonant-feedback laser is a rather slow process [2], it was necessary to cool the ruby to 77°K in order to obtain such a line width in a time 10^{-4} sec.

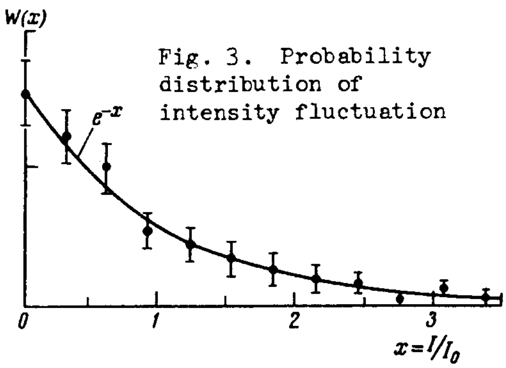


Fig. 3. Probability distribution of intensity fluctuation

4. Figure 2 shows a typical oscillogram of the radiation intensity in a small solid angle (with diaphragms) at instants of stationary generation. The intensity fluctuations are clearly seen, the fluctuation amplitude being of the same order as the mean value of the intensity. Processing of the oscillograms yielded the distribution of the intensity fluctuations (Fig. 3). The experimental points are satisfactorily approximated by the theoretical distribution (2) (continuous curve of Fig. 3). In addition, the characteristic fluctuation correlation time $\tau_{corr} \simeq 10^{-8}$ sec agrees with the correlation time determined from the radiation line width, $\tau_{corr} \simeq 1/2\pi\Delta\nu c$, where [2]

$\Delta\nu \sim \Delta\nu_0\sqrt{\alpha ct}$ ($\Delta\nu_0 \simeq 0.5$ cm^{-1} is the active-medium luminescence line width, and $\alpha \simeq 0.5$ cm^{-1} is the gain per unit length at threshold.

5. It is seen from the foregoing that radiation-intensity fluctuations, similar to the fluctuations of black-body radiation, occur in a laser with nonresonant feedback. This makes it possible to set up experiments on the correlation of photons (similar to those of Brown and Twiss [8]).

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[1] R. V. Ambartsumyan, N. G. Basov, P. G. Kryukov, and V. S. Letokhov, JETP Letters 3, 261 (1966), transl. p. 167; JETP 51, 724 (1966), Soviet Phys. JETP 24, 481 (1967).

[2] R. V. Ambartsumyan, P. G. Kryukov, and V. S. Letokhov, JETP 51, 1669 (1966), Soviet Phys. JETP 24, 1129 (1967).

[3] J. A. Fleck, Phys. Rev. 149, 309 (1966).

[4] V. S. Letokhov and E. P. Markin, JETP 48, 770 (1965), Soviet Phys. JETP 21, 509 (1965).

[5] A. W. Smith and J. A. Armstrong, Phys. Rev. Lett. 16, 1169 (1966).

[6] L. Mandel and E. Wolf, Revs. Modern Phys. 37, 231 (1965).

[7] R. J. Glauber, Quantum Optics and Electronics, Les Houches, 1964, Ecole d'ete de Physique Theorique.

[8] R. Hanbury Brown and R. Q. Twiss, Nature 177, 27 (1956)

CONTRIBUTION TO THE THEORY OF HOLOGRAPHIC IMAGE MAGNIFICATION

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Image magnification is attained in holography by using diverging beams. This makes a holographic microscope feasible. Usually [1] one uses for this purpose the hologram of the object itself. We call attention to another type of microscope, in which the hologram records not the object, but interference of waves from two sources. By viewing through this hologram the object illuminated by a coherent beam, it is possible to obtain a magnified image of the object. This differs in essence little from the use of a Fresnel zone plate as a lens. Such a scheme may turn out to be convenient under certain conditions.

Let us sketch briefly the theory of such a microscope. If A and B are coherent sources, then the field at the point P of a photographic plate at z = 0 will be $U(P) = U_A + U_B = \exp(ik\cdot PA) + \exp(-ik\cdot PB)$. Assume that a coherent light field s(0) with wave number k' is incident from the object 0 onto a developed hologram plate magnified m times. Then the field in a certain plane I will be

$$S(I) = \int s(O)\, e^{-ik\cdot OP}\, |U(m^{-1}P)|^2\, e^{-ik'\cdot PI}\, dO\, dP. \tag{1}$$

We confine ourselves henceforth only to the field S(I) due to the interference terms $U_A^*U_B$ or $U_AU_B^*$, assuming that the fields from $|U_A|^2 + |U_B|^2$ will turn out to be in other parts of the plane I. Then, in the narrow-beam approximation, assuming for simplicity that the object is