Natural laser-beam spatial coherence determined by spontaneous emission

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A high degree of spatial coherence was obtained in a single-mode He-Ne gas laser; the deviations of the normalized correlation function at the center of the beam from unity do not exceed several times 10^{-5}. It is shown that what actually occurs is a limiting "natural" spatial coherence determined by the spontaneous noise. The experimental data are interpreted using two models of the spatial statistics of the laser radiation: the "signal-plus-noise" model and the model of an oscillation that undergoes amplitude and phase fluctuation. A laser with a high spatial coherence can greatly extend the possibilities of investigating the scattering of light at small angles.

1. In this paper we report results of measurements, performed with a high degree of accuracy, of the normalized transverse correlation function of the field E

$$\gamma(s) = \frac{\langle E_1(r,t) E_2^*(r+s,t)\rangle}{\sqrt{\langle E_1^2\rangle}\sqrt{\langle E_2^2\rangle}} \tag{1}$$

of a single-mode He-Ne gas laser ($\lambda = 0.63\ \mu$). It was established that the value of $\gamma(s)$ differs from unity by not more than several units of 10^{-5} near the center of the beam of a gas laser with a carefully selected lowest transverse mode.

We shall show that in the experiment we have actually registered, for the first time, "natural" spatial incoherence of a laser. Knowledge of this quantity, besides being of fundamental interest, makes it possible to estimate the limiting capabilities of registering collinear scattering in light-scattering experiments, the study of the influence of weak back scattering on laser operation, etc.

2. Unlike data on temporal statistics, data on the spatial statistics of single-mode lasers are incomplete and contradictory (see, e.g., [1]). Although in analogy with temporal statistics one can speak of "natural" and "technical" broadening of the angular spectrum, these quantities are not of great interest; they result in only small corrections to the appreciable width of the angular spectrum due to the regular spatial modulation—the finite transverse section of the beam. Of primary interest in the spatial statistics is therefore a characteristic that is integral with respect to the angular spectrum, namely the spatial correlation function of the field[1)]

$$\gamma(s) = \int S(k_\perp)\cos k_\perp s\, dk_\perp, \tag{2}$$

where $S(k_\perp)$ is the angular spectrum of the random modulation of the laser beam and $k_\perp$ is the transverse component of the wave number.

3. Figure 1 shows the block diagram of the experimental setup for the measurement of the spatial coherence with the aid of a polarization interferometer[1] and a photocounting registration system. The accuracy of the measurement of $\gamma(s)$ by this procedure was discussed by us earlier[2].

The result of the experiment was shown in Fig. 2. We see that $\gamma(s)$ is close to unity practically over the entire cross section of the beam (up to the profile points where the intensity differs by a factor 10^3 from its value at the center of the beam). The measurements were performed for different excesses over the generation threshold (a quartz plate was introduced into the laser cavity). The dependence of $\gamma(s)$ on the relative losses in the resonator is shown in Fig. 3. It is interesting that although a noticeable decrease of $\gamma(s)$ is observed when the threshold is approached, the value of $\gamma(s)$ remain sufficiently high also in the superradiance regime. (The change of the character of the spatial statistics on going through the threshold can be registered by measuring simultaneously the intensity correlations—see[1].)

4. The obtained very small deviations of $\gamma(s)$ from

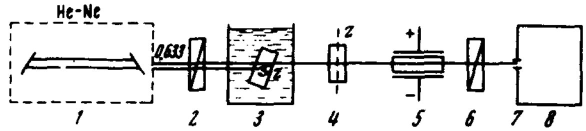

FIG. 1. Block diagram of setup: 1—laser, 2—polarizer, 3—immersed plane-parallel uniaxial-crystal plate (z axis perpendicular to the plane of the figure); 4—compensating plate similar to 3, but with the z axis in the plane of the figure, 5—phase-shifting cell, 6—analyzer, 7—diaphragm of $\sim 20\ \mu$ diameter; 8—photocounting device.

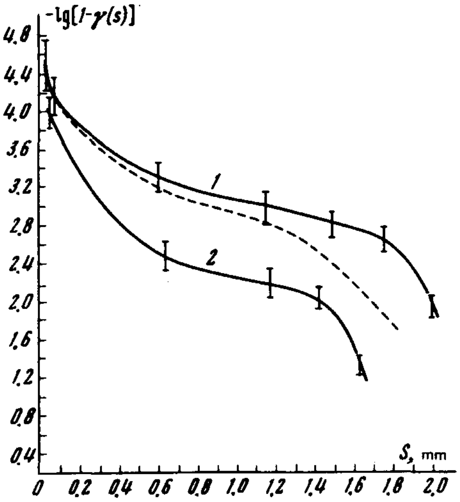

FIG. 2. The function $\log[1-\gamma(s)]$ for two laser operating regimes: 1—at minimum loss in the laser cavity; 2—at the lasing threshold. The plot of formula (5) is shown dashed.

unity should be ascribed to spontaneous emission, i.e., we have actually registered the limiting "natural" spatial incoherence. To verify this, we use first a model according to which the laser radiation is the sum of an ideally coherent mode and δ-correlated noise:

$$E(r) = E_k(r) + E_N(r), \qquad (3)$$

$I_k(r) = (c/8\pi)|E_k|^2 = I_0 \exp(-r^2/r_0^2)$. From (3) we obtain for $\gamma(s)$

$$\gamma(s) = [1 + N/I_k(s)]^{-1} = [1 + \overline{m_\alpha^2}(s)]^{-1}. \qquad (4)$$

Here N is the noise intensity. It is known that the model (3) described adequately the amplitude fluctuations, so that $\gamma(s)$ can be expressed also in terms of the mean-squared coefficient of the noise amplitude modulation $\overline{m_\alpha^2}(s)$.

The experimental value of N near the center of the beam was $N_{exp} \approx 4\times10^{-15}$ W. An estimate of the spontaneous-noise power in accordance with the formulas of[3], for the geometry of our experiment, yields a value $N_{theo} \approx 1\times10^{-15}$ W. The agreement should be regarded as perfectly satisfactory, if account is taken of the limited applicability of the results of[3] (see also[4]). For $\overline{m_\alpha^2}$ we get from our data $\overline{m_\alpha^2} \approx 3\times10^{-5}$. In experiments[5,6] in which the natural amplitude fluctuations of a single-mode laser were measured directly, the obtained values were $\overline{m^2} \approx 5\times10^{-5}$[5] and $m^2 = 10^{-4}$–10^{-6}[6]. Thus, the deviations of the spatial coherence from ideal, as measured by us, agree well with the model (3), where $E_N(r)$ is spontaneous noise. From our exact description of the experimental $\gamma(s)$ curve it is necessary to take into account also the phase fluctuations. If they are not correlated with the amplitude fluctuations, then

$$\gamma(s) = \exp\{-Ds\}[1 + N/I_k(s)]^{-1}. \qquad (5)$$

Formula (5) was used to plot the dashed curve in Fig. 2. The noticeable quantitative deviation from the experimental curve l near the edge of the beam is apparently due to inhomogeneity of the spontaneous noise over the beam cross section[7]. Experiment yields $D \approx 0.8\times10^{-2}$

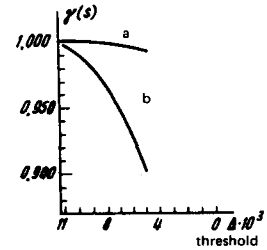

FIG. 3. Dependence of $\gamma(s)$ on the loss in the resonator for the following: a—$I_k(s)/I_k(0) = 0.1$; b—$I_k(s)/I_k(0) = 0.001$; $\Delta = \ln(T/T_{thr})$, T_{thr} is the quartz-plate transmission of which loss of generation takes place.

cm^{-1}, so that the fluctuation broadening $\Delta\Omega$ of the angular spectrum did not exceed in our experiments $\Delta\Omega = \Delta k_\perp/k_z \approx D/k_z \approx 1\times10^{-7}$, and is much smaller than the diffraction broadening ($\Delta\Omega_d = 1.22\lambda/2r_0 \approx 1\times10^{-3}$).

5. The relatively small contribution of the technical fluctuations to the value of $\gamma(s)$ measured by us is obviously connected with the strong transverse correlation of the technical deviations (the plasma fluctuations[8] were generally small). We note also that the role of the technical fluctuations in $\gamma(s)$ is "smeared out" (see above).

6. The use of lasers with large spatial coherence and the possibility of registering small changes of this coherence [$\Delta\gamma(s) \sim 10^{-8}$], which was demonstrated in the present paper, makes it possible to circumvent the difficulties (see, e.g.,[9]) of observing collinear scattering in experiments on wide scattering (the correlation radius of the scattered radiation is $r_k < r_0$). This is ensured by the fact that in the described scheme we actually subtract the incident coherent light optically, and only the noise radiation is incident on the recording device. The minimum light-scattering power that can be registered in the forward direction is determined by the spontaneous emission of the laser itself. The best sensitivity should be expected in such experiments when gas lasers with high-frequency discharge are used (see[10]).

1) A similar situation is encountered in the investigation of the temporal statistics of pulse-laser radiation, where greatest interest attaches likewise to the correlation functions. (The line width due to the regular modulation exceeds the technical and natural line widths.)

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