FIELD DISTRIBUTION AND SPATIAL COHERENCE OF AMPLIFIED SPONTANEOUS EMISSION AT 3.39 μ IN A HELIUM-NEON LASER

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An experimental study has been carried out of the field distribution over the cross section of the 3.39 μ ASE beam from a helium-neon laser with a discharge tube 4 m long and 10 mm in diameter, operated far from saturation. It was found that the beam is channeled in the active medium of the laser and the result of this is that the beam diameter becomes much smaller than the tube diameter and, at the same time, the angular divergence of the beam approaches the diffraction limit.

In contrast to generation in a resonator, the spatial distribution of the ASE (amplified spontaneous emission) field is determined by the geometry of the active medium [1-4]. Typically, the ASE of gas lasers propagates within the aperture angle D/L where D is the diameter of the active medium and L its length. However, it has been found that the divergence of the ASE beam may depart quite substantially from D/L [4-7]. We have investigated the spatial distribution of the 3.39 μ ASE in a helium-neon laser and have verified the presence of very narrow ASE beams propagating near the tube axis with an angular divergence approaching the diffraction limit.

We used a discharge tube consisting of two sections with an internal diameter of 1 cm and an over-all length of 4 m. Each section had quartz Brewster windows. Large-diameter tubes were used in order to reduce the effect of such factors as reflection from the tube walls and diffraction by the tube aperture. The absence of reflections was verified by placing stops between the tube sections. A flat mirror with a dielectric coating having a reflection coefficient of 0.98 at the wavelength of 3.39 μ was placed at one end of the tube. The radiation emitted by the tube was modulated at 600 Hz with the aid of a mechanical chopper. The detector was a Ge-Au photoresistor cooled with liquid nitrogen. The electrical signal was amplified by a narrow-band amplifier and was plotted by a strip-chart recorder. The entire detection system was checked for linearity in the intensity range under investigation.

Measurements were carried out of the amplification coefficient at 3.39 μ by passing a probe beam from an auxiliary laser operated under ASE conditions through the working tube. The axial part of the discharge was defined by stops. Under nearly optimal conditions (gas pressure 1.5 Torr, ratio of helium to neon partial pressures 6:1, discharge current 50 mA), the amplification coefficient for a weak signal was found to be 0.022 cm^{-1}. The maximum ASE power measured by the IMO-2 device was 130 μW. This means that the tube was operated far from saturation [5].

The spectral composition of the ASE was investigated with a Fabry-Perot interferometer with a baseline of 30 cm. It was found that there was a considerable narrowing of the ASE line as compared with the spontaneous emission line. The measured ASE line width was 80 mHz, which was in good agreement with the theoretical prediction [5]:

$$\Delta\nu_s = \frac{\Delta\nu_e}{\sqrt{k_0 L}}, \qquad (1)$$

where $\Delta\gamma_s$ and $\Delta\gamma_e$ are the ASE line width and the spontaneous emission line width, respectively, k_0 is the application coefficient, and L is the effective amplification length, equal to twice the length of the tube corrected for the position of the end mirror.

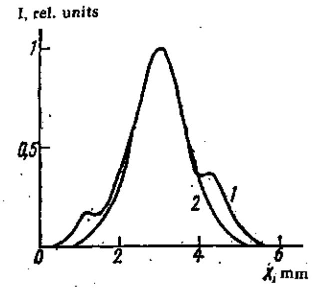

Fig. 1. Intensity distribution over the cross section of the ASE beam at a distance of 1 m from the end of the active medium.

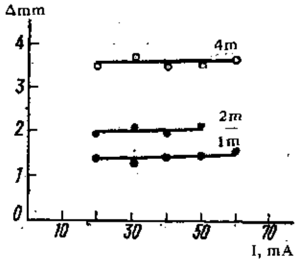

Fig. 2. Width of the ASE beam at different distances from the end of the active medium as a function of the discharge current.

The spatial distribution of the ASE field was examined with the aid of a scanning stop with a small aperture in the beam cross section. The image of the stop was projected on the receiving area of the photoresistor with the aid of a short-focus lens. The stop, the lens, and the detector were placed on the same table which could be moved by a synchronous motor. The beam profile was plotted by a strip-chart recorder. Figure 1 shows the field distribution at a distance 1 m from the end of the tube. Curve 1 corresponds to the profile obtained by scanning in the horizontal direction and curve 2 corresponds to the vertical direction. The field distribution in the former case contains additional maxima which are probably connected with parasitic reflections in the tube windows. When the distance from the end of the tube was increased to 2 m, the side maxima are less well defined and are found to disappear altogether at a distance of 4 m. We shall use the main maximum to determine the transverse side of the beam (practically the same result is obtained by using the side of the field profile in the vertical direction).

Figure 2 shows the beam width Δ measured at half maximum intensity at distances of 1, 2, and 4 m from the end of the tube for different discharge currents. It is clear from Figs. 1 and 2 that a very narrow and collimated ASE beam was produced in the laser tube. The beam is channeled near the tube axis and its output width is much less than the internal diameter of the tube. Estimates show that the divergence of the beam exceeds only slightly the divergence of a gaussian beam with the same transverse dimensions (by less than a factor of 1.5) [8]. This means that the ASE beam has a divergence approaching the diffraction limit.

The spatial coherence of the ASE beam was investigated with a modified Young's scheme [9]. We measured the contrast of the interference bands obtained by diffracting the beam by two apertures 0.5 mm in diameter and separated by between 1 and 4 mm. The apertures were placed symmetrically relative to the beam center. To ensure the overlap of the diffracted beams in a plane not too far from the diffracting apertures, we used a lens with a focal length of 200 mm. A scanning slit was placed in the focal plane of this lens, parallel to the interference bands. This arrangement differs from the classical Young scheme by the fact that the width of the apertures was not negligible in comparison with the distance between them, and also the fact that we have used a lens. Since the diffraction angles are small, the linear dimensions of the interference field are very restricted and this explains the relatively small number of bands of decreasing intensity.

The bands are illustrated in Fig. 3, which gives the intensity distribution at a distance of 50 cm from the tube. In view of the foregoing, the degree of spatial coherence $|\gamma_{12}|$ was calculated from the observed intensity distribution I(x) with the aid of the formula

$$|\gamma_{12}| = \frac{I^{\max}(x) - I^{\min}(x)}{I^{\max}(x) + I^{\min}(x)}. \tag{2}$$

This formula differs from the analogous formula given in [9] by the fact that instead of the intensities measured at different points on the interference pattern, it involves values on the maximum and minimum envelopes taken at the same values of x, $I^{\max}(x)$ and $I^{\min}(x)$. This takes into account possible nonuniformity of illumination in the interference field. It is assumed in (2) that the two apertures are illuminated in the same way. The calculated values of $|\gamma_{12}|$ were corrected for the finite slit width.

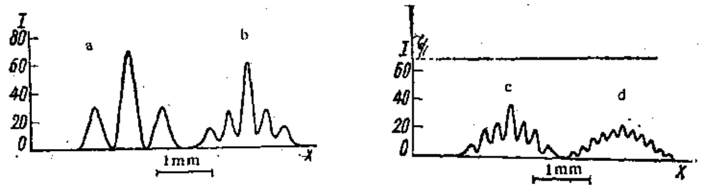

Fig. 3. Young interference bands at different separations between apertures: a) 1; b) 2; c) 3; d) 4 mm. Distance from the end of the tube 50 cm.

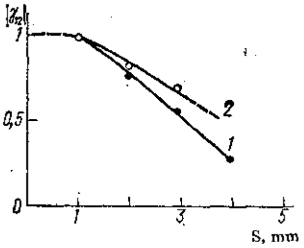

Fig. 4. Degree of spatial coherence as a function of the separation s between the apertures: 1) 50 cm from the tube; 2) 2 m from the tube.

Figure 4 shows plots of the degree of spatial coherence as a function of separation between the apertures. It is clear that the ASE beam has a high spatial coherence over its central part. As the apertures approach the edges of the beam, the degree of spatial coherence is seen to fall. Comparison of data obtained at different distances from the end of the tube shows that, as expected [9], the degree of spatial coherence increased with increasing distance from the tube for a fixed separation between the apertures.

The high degree of spatial coherence of the amplified spontaneous emission, which we have observed, is directly related to the above beam channeling effect. This behavior can be explained by the influence of the radial distribution of the amplification coefficient of the laser. Channeling of the ASE in a radially inhomogeneous active medium is accompanied by an increase in the spatial coherence of the beam, which was previously observed experimentally in the pulsed neon laser [7], the dye laser [10], and in stimulated Raman scattering [11].

In the simplest theoretical interpretation of this phenomenon [7], the beam profile in the medium can be calculated from geometric optics without taking diffraction into account and neglecting the saturation of the medium. To estimate the size of the spatial coherence region in the beam, we can use the van Cittert-Zernike theorem [9]. If we suppose that the radial distribution of the amplification factor is given by the Bessel function $k(r) = k_0 J_0(2.4r/R)$ [12], where k_0 is the axial amplification and R is the radius of the tube, and if we suppose that $k_0 L >> 1$, then calculations lead to a gaussian distribution of intensity in the emitted beam with 1/e radius given by

$$w = \frac{2\tilde{R}}{\sqrt{k_0 L}}. \qquad (3)$$

In this expression, $\tilde{R} = R/1.2$ and L is the effective amplification length. The same result is obtained by solving the wave equation for the "active waveguide" excited by spontaneous noise in the medium [13] in the region where the diffraction broadening of the beam is unimportant, i.e., for $L << w^2/\lambda$. Using (3), the last condition can be written in the form

$$L \ll L^* = \frac{4\tilde{R}}{\sqrt{k_0 \lambda}}. \qquad (4)$$

Equation (3) represents the contraction of the ASE beam in a radially nonuniform amplifying medium which, in some respect, is similar to the spectral narrowing described in [1]. It is clear from (3) that when the amplification coefficient is high, and this can be achieved in ASE lasers, the beam width at the end of the tube may be much smaller than the diameter of the tube. The size δ_{coh} of the spatiall coherent region at exit from the laser can be estimated from the van Cittert-Zernike theorem [7]

$$\delta_{coh} \simeq \frac{\lambda}{2w} L. \qquad (5)$$

The formal consequence of (3) and (5) is that when the length of the active medium reaches the value $L = L^*$, the size of the spatially coherent region defined by (5) becomes comparable with the beam diameter $2w$. The beam radius is then given by

$$w^* = \left(\frac{\lambda \tilde{R}^2}{k_0}\right)^{1/4}. \tag{6}$$

Despite the approximate character of such estimates due to the use of (3) outside its range of validity, defined by (4), they are nevertheless in good agreement with the solution of the diffraction problem [10, 13]. This shows that the formation of the spatial coherence of the ASE beam is practically complete after an amplification length $L \sim L^*$, and the beam radius tends asymptotically to a steady value for $L >> L^*$, which is in agreement with (6) [13] to within a numerical factor of the order of unity.

If we substitute the experimental values $k_0 = 0.022$ cm^{-1}, $\tilde{R} = 0.417$ cm, and $\lambda = 3.39 \cdot 10^{-4}$ cm in [4], we obtain $L^* \approx 6$ m. In contrast to [7], therefore, condition (4) is not satisfied in our experiment, and we have the intermediate case $L \sim L^*$, the analysis of which requires numerical calculations [10]. The theoretical values of the beam width obtained from (3) and (6), which are valid for the extreme cases $L << L^*$ and $L >> L^*$, i.e., 2.0 and 2.28 mm, can serve only as qualitative indicators of the narrowing of the beam due to the radial distribution of the amplification coefficient. At the same time, this gives us a qualitative explanation of the high degree of spatial coherence of the beam observed experimentally. We note that the above estimates yield beam widths that are substantially greater than the measured widths. Agreement with experiment can probably be improved by additionally taking into account the focusing effect of the active medium due to the radial distribution of the amplification coefficient [14].

We note in conclusion that the active medium in the laser must not be saturated if the above effects are to be observed. Saturation inhibits the narrowing of the ASE beam due to the reduction in the effective amplification coefficient and the modification of its radial distribution.

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