INTENSITY FLUCTUATIONS IN A GaAs LASER

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We have observed the intensity fluctuations in the light emitted by a single mode of a cw GaAs laser. The injection current was varied from a value below the threshold for coherent oscillation to a value well above threshold. We have thus been able to observe the change in noise properties of the single mode output as the laser begins to oscillate. Below threshold the mode emits random noise like a narrow-band black-body source; above threshold its noise is characteristic of a quieted, amplitude-stabilized oscillator. Our measurements of the intensity fluctuations were made with the two-detector coincidence counting technique of intensity interferometry first used successfully by Twiss, Little, and Hanbury Brown[1] and Hanbury Brown and Twiss.[2]

The observed transition between black-body and quiet oscillator behavior can be understood in terms of physical concepts which are similar to those used in describing noise in well-stabilized low-frequency oscillators. We will analyze the observations in terms of the wave interference model of intensity fluctuations used by Hanbury Brown and Twiss[2] and by Purcell.[3] Below threshold, where black-body behavior is observed, the analysis in terms of photons given by Mandel[4] could also be used; however, since we are interested in describing the transitions to coherent oscillator behavior, the wave analysis is more appropriate. It may also be mentioned that the behavior around threshold of the second-order correlation function $\langle E^{(-)}E^{(-)}E^{(+)}E^{(+)}\rangle$ introduced by Glauber[5] can be inferred from our results.

The laser used had cleaved ends and etched sides; it was 150 μ long, 10 μ wide, and had an active region about 2 μ high. It was operated cw near 10°K and was extremely stable. The output spectrum of the diode, viewed normally to a cleaved face, is shown in Fig. 1 and is seen to consist of a single family of axial modes.[6] The envelope narrowing as a function of injection level evident in Fig. 1 reflects the substantial gain present below threshold and can be used to estimate the gain.[7] The power in the mode marked "A" is shown as a function of injection current by curve A in Fig. 2. A study of this mode in the vicinity

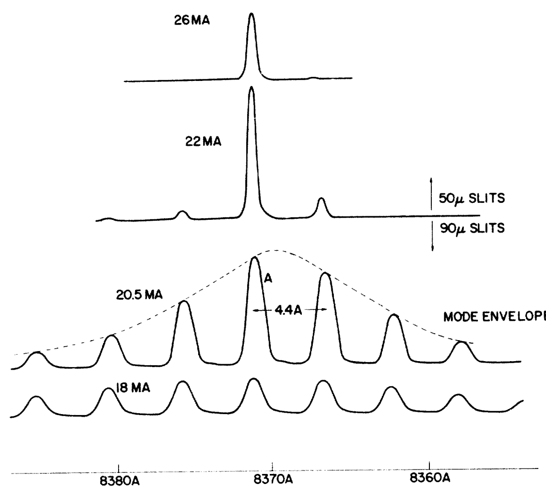

FIG. 1. Mode structure of the laser in the region of threshold. The intensity (vertical scale) is different at each current. The mode envelope at 20.5 mA is indicated by the dashed line. In all cases the widths of the peaks are instrument limited.

of threshold with a Fabry-Perot etalon of 450-Mc/sec resolution showed no structure. We believe the peak marked A to be a single axial mode at all injection levels used in this experiment. This mode was isolated with a spectrometer and it alone was used in the coincidence-counting measurements.

Commercial solid-state coincidence circuitry was used, with a coincidence resolving time of 5 nsec. The single-channel counting rates were kept (by attenuating the light if necessary) to be about 5×10^5 counts/sec, which is well below the capability of the coincidence unit. Experimentally we determined the coincidence rate under two conditions: First the rate was determined with no delay present; then a delay longer than the coherence time of the light[8] or the resolution time, whichever was larger, was inserted in one channel and the rate redetermined. The fractional decrease in coincidence rate when such a delay is inserted is called ρ. The physical significance of ρ is that it is the relative mean squared intensity fluctuation of the light source. Typical counting times necessary for a single determination of ρ were about 15 min; the number of coinci-

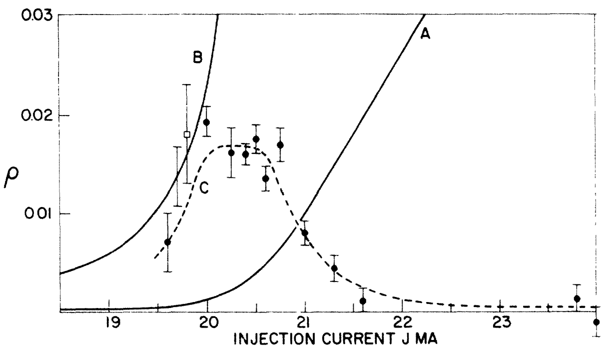

FIG. 2. The relative intensity fluctuation ρ for the strongest mode plotted against injection current J. The experimental points are solid circles with bars indicating the standard deviations of the counting fluctuations. Curve A shows the output power of the mode in arbitrary units. Curve B is the behavior of ρ for a black body predicted from the observed envelope narrowing. The accuracy of this curve is indicated by an error bar at $J=19.7$ mA. The value of ρ estimated from the measured linewidth is shown by the square. The dashed curve C is a smooth curve through the experimental points.

dences recorded in this time was about 2×10^6. Great care was taken to eliminate the effects of drifts in the coincidence circuitry. As a check we repeated the determination of the intensity fluctuations in the 4358 Å line of an air-cooled, microwave-excited, low-pressure Hg^{198} lamp obtained from Baird-Atomic, Inc. The value of ρ obtained was 0.010 ± 0.002 and corresponds to a black-body source linewidth of 860 Mc/sec, a value which is in agreement with previous determinations.[1,9] Finally, we discount the possibility that the observed effect is due to some spurious nonstationary noise for two reasons. First, we measured ρ as a function of delay with the laser operated at 20.4-mA injection current, where the coherence time of the light is unlikely to be longer than 3 nsec. No variation in ρ was detected as the delay was varied from 20 to 360 nsec. This means that there was no nonstationary noise with a correlation time greater than about 10 nsec. Second, the observed value of ρ at low injection levels is consistent with the measured linewidth and the assumption that the mode emits as a black body.

The experimental values of ρ versus injection current J are shown in Fig. 2 by the solid circles with error bars. We distinguish three regions in the curve of ρ vs J. They are $J\lesssim19.8$ mA; $19.8\lesssim J\lesssim20.8$ mA; and $J\gtrsim20.8$ mA. The boundaries of these regions are not very well defined. The first region is that for which the mode is below threshold and is emitting essentially black-body radiation. The effect of the substantial gain present below threshold is to narrow the bandwidth of the noise emission without causing any appreciable quieting. The gain-narrowed single-mode linewidth can be calculated as a function of J below threshold by using the observed envelope narrowing and the theory of Wagner and Birnbaum[7] to estimate the gain vs J; we use our previous estimate[10] of 60 000 Mc/sec for the unnarrowed width of the mode. The behavior of ρ predicted from this linewidth narrowing, the observed polarization, and the assumption of black-body behavior is shown by curve B in Fig. 2. As a check on the linewidth estimates we used a Fabry-Perot etalon to measure the actual width of the single-mode emission at 19.8 mA and obtained a value of 1300 ± 200 Mc/sec. This linewidth corresponds to the value of ρ shown by the square and error bar in Fig. 2. Finally, the measured value of ρ in this region is seen to be consistent with black-body behavior.

The behavior of ρ vs J in the third region, $J\gtrsim20.8$ mA, is also rather simply understood. Here the mode under study is emitting coherently and has the overwhelming share of the total power emitted by the axial modes. We can account for the observed behavior of the fluctuations by assuming that the field in the mode can be written as $E_0\cos[\omega t+\varphi(t)]+e_n(t)$, where e_n is a stationary noise field whose magnitude is always much less than E_0, and where $\varphi(t)$ is the slowly varying random phase of the coherent signal which is responsible for the finite width of the coherent line.[11] This random phase does not contribute anything to the intensity fluctuations. The intensity fluctuations in the total mode output in this region are due to beats between the various Fourier components of the noise e_n and to beats between the coherent signal and the noise e_n. These two mechanisms give a combined value of ρ equal to[12] $(\tau_n/2\tau_R)\times(P_{\mathrm{coh}}+aP_n)(P_{\mathrm{coh}}+P_n)^{-2}$, where τ_R is the coincidence resolving time, τ_n is the coherence time (defined according to reference 2) of the noise power P_n in the mode, P_{coh} is the coherent power in the mode, and a is a parameter determined by the shape of the power spectral density of P_n; it has the values 1, $\sqrt{2}$, and 2 for rectangular, Gaussian, and Lorentzian shapes, respectively. The physical reason for the appearance of the parameter a is that the mean squared intensity fluctuation due to beats between the coherent signal and the noise is proportional to the product of $P_{\rm coh}$ and the value of the spectral density of P_n at the laser frequency.

This expression is capable of describing qualitatively the whole of the observed ρ-vs-J curve. Below threshold $P_{\rm coh}$ is zero and the formula reduces to the well-known result for the relative intensity fluctuations of a black body[2]; this behavior has already been plotted as curve B. Above threshold, theoretical analysis of the variation of ρ vs J is more complicated; the outline of this analysis and the principal results will be given here; the details will be given in a later paper. It is first assumed that insofar as its behavior as an oscillator is concerned, the injection laser may be treated as a two-level system. A further assumption, and one which is in good agreement with observation, is that the GaAs fluorescence line is homogeneously broadened. The differential equation for the optical electric field in a single cavity mode is then written down; this may be done following the procedure used by Lamb[13] (setting all atomic velocities equal to zero). The resulting equation is nonlinear in the field strength $E(t)$ and is in fact the same as van der Pol's equation for the essential behavior of any oscillator (provided it is also assumed that the cavity mode lies at the peak of the fluorescence line, which was very nearly the case for the laser studied here). One then adds to the equation an inhomogeneous driving term[7] representing spontaneous emission noise. The response of van der Pol's oscillator to broad-band random noise has been treated in lucid fashion by Caughey.[14] The results of his analysis are directly applicable to our problem in the region where $P_{\rm coh} > P_n$. The final results of interest to us are (1) the mean squared noise power P_n in the oscillating mode decreases above threshold like $P_{\rm coh}^{-1}$; (2) the bandwidth of the noise power, i.e., $(\pi\tau_n)^{-1}$, increases linearly with $P_{\rm coh}$. Therefore in the region $J \gtrsim 20.8$ mA we expect the relative intensity fluctuations to decrease approximately as $P_{\rm coh}^{-3}$. This rapid decrease is consistent with the rapid decrease observed experimentally. (It must be recalled that the spectral density of the noise driving term is proportional to the upper-state population and changes only by ~10% as J goes from 19.5 to 22 mA, whereas the output power increases by more than an order of magnitude. At values of J much higher than used here P_n will become independent of $P_{\rm coh}$.)

Thus our results show that the proper statistical description of laser light is in fact very similar to the description of the output of any amplitude-stabilized oscillator whose performance is limited only by inevitable thermal or quantum noise.[15]

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[12]This expression follows from a calculation similar to those made in reference 2 (Appendix B) if one assumes the electric field to be a superposition of an amplitude-stabilized field and weak noise field.

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[15]Since this paper was written, L. J. Prescott and A. Van der Ziel [Phys. Letters 12, 317 (1964)] have reported single-detector measurements of noise in a gas laser just above threshold. Their results, that P_n and τ_n decrease with increasing pump power above threshold, are qualitatively consistent with the theory of reference 14 outlined above, and with our observations of ρ.