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Intensity Noise in Multimode GaAs Laser Emission

Abstract: As presently manufactured most GaAs lasers have several lasing modes when the injection current is more than 25% above threshold. This paper describes the noise properties of three groups of multimode lasers operating cw at 10°K, classified on the basis of their sub-threshold spectra. Two main types of intensity noise have been found: (1) low frequency nonstationary noise which occurs when a weak mode is lasing in competition with a strong mode, and (2) broadband stationary noise which occurs when two modes are about equal in intensity. The first type of noise is believed to arise from heat transfer processes in the diodes and dewar, while the second is probably the partition noise which must occur when a photon can be stimulated into one of a number of lasing modes. An important result of these experiments is that the total noise for all modes is very small, being comparable to that for a single mode with the same total power.

1. Introduction

We have previously studied the fluctuations in the light intensity emitted by *single mode* cw GaAs lasers.[1-3] Except in the immediate vicinity of threshold such noise is extremely small and is, in fact, the fundamental noise due to spontaneous emission in the lasing mode. As they are presently manufactured, however, most GaAs lasers lase in several modes if the injection current is more then 25% above threshold. This has several undesirable results, including an increase in the intensity noise associated with each mode. The present paper describes a study of the noise properties of several types of multimode cw lasers. Such a study is of interest for the following reasons. First, our understanding of the oscillation mechanisms in injection lasers is given a good test in trying to account theoretically for the observed types of noise. Second, the use of injection lasers for communications will depend in some measure on the signal-to-noise levels that can be obtained in the laser itself. This ratio may be seriously affected by multimode operation for certain types of communications systems.

Two main types of intensity noise have been found; the first is nonstationary, low frequency noise (a few kc/sec) which occurs when one mode is lasing weakly in competition with a second which is lasing strongly. The second type of noise is broadband, stationary noise which is probably the partition noise that must occur when a photon can be stimulated into one of a number of lasing modes. Both types of noise will be compared to shot noise in photomultipliers and to the noise generated in detectors by nonlasing narrowband ligh sources.

2. Experimental

◆ *The injection lasers*

The GaAs lasers used in these experiments were about 150 μ long and were etched down in the middle to a width of about 5 μ. The large length-to-width ratio is important in simplifying the mode structure both above and below threshold. The lasers had cleaved ends with no reflective coatings. The *p-n* junctions were in the (001) plane. The lasers were mounted in vacuum on a copper post which was in contact with liquid helium at 4.2°K. The design of the dewar is shown in Fig. 1. The temperature of the lasers was estimated to be about 10°K. At this temperature the threshold for laser action is essentially independent of temperature[4], so that even though the heat dissipated in the diode varies with injection level, threshold remains independent of the injection current.

The axial mode spacing for a GaAs cavity 150 μ long is about 4 Å and below threshold, the spectra of some of the lasers consisted of a single family of modes having this spacing (Fig. 2). In such cases, the modes can be resolved with a medium-resolution spectrometer and noise measurements can easily be made on a single mode. (A study of the mode marked A in Fig. 2 with a Fabry-Perot etalon of 450 Mc resolution showed no structure.) However, the spectrum of most of the lasers below threshold consisted of several families of modes,[5] each having the theoretical axial mode spacing. For these lasers, noise measurements cannot easily be made on single modes at or below threshold. However, for the type of lasers used here the separation of lasing modes was at least one axial mode separation and a medium-resolution spectrometer

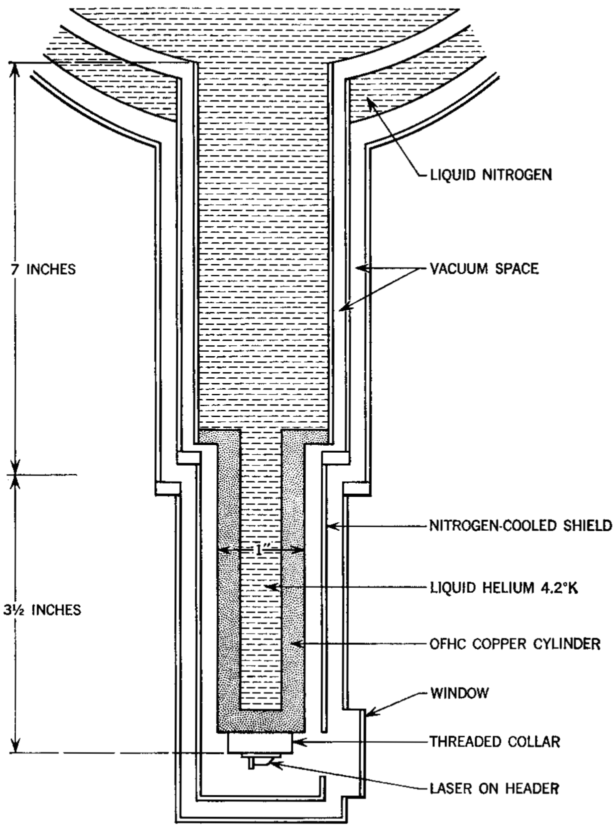

Figure 1 Mounting of the diode in the vacuum space of a helium dewar. *OFHC copper* refers to the oxygen-free high-conductivity copper used in cryogenic applications.

was adequate to resolve the modes above threshold. In the case of the correlation measurements, separate spectrometers were used to isolate the different modes.

◆ *Noise measurements*

The intensity fluctuations were measured by two independent methods: (1) the single detector technique of excess noise,[6] and (2) the coincidence counting technique of intensity interferometry.[7,8] The details of both methods have been described previously,[3] and only a summary will be given here. The first method measures the mean squared noise current $\overline{I_L^2}$ which appears in the cathode current of a single detector due to the intensity fluctuations of the laser. This noise is in addition to the detector shot noise $\overline{I_s^2}$, which is due to the discrete nature of the photocurrent. The total mean squared noise current per unit bandwidth for a detector illuminated by the laser source is

$$\overline{I_n^2} = \overline{I_s^2} + \overline{I_L^2}. \qquad (1)$$

The shot noise per unit bandwidth is[9]

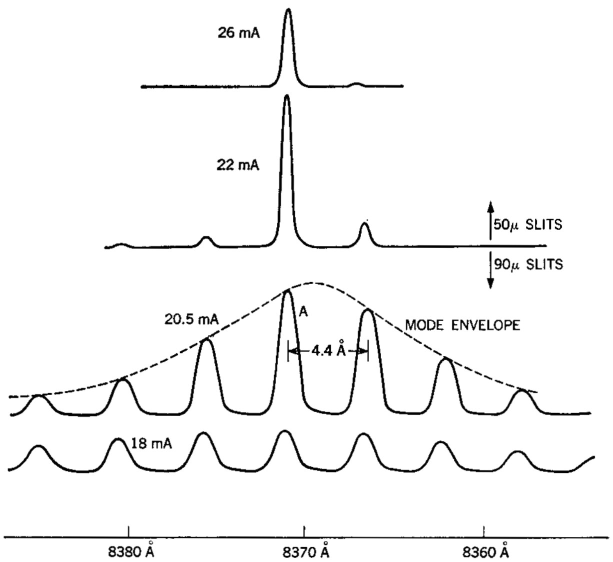

Figure 2 Spectrum of a laser having a single family of axial modes. The intensity scale is different for each current. The mode envelope at 20.5 mA is indicated by the dashed line. The width of all peaks is instrument limited.

$$\overline{I_s^2} = 2e\bar{I}_c G, \qquad (2)$$

where $\bar{I}_c$ is the average cathode current and G is the gain of the photomultiplier.*

In practice the rms noise voltage across a load resistor is measured with the detector exposed to the laser; the shot noise is then measured with a white light source (for which $\overline{I_L^2} \ll \overline{I_s^2}$) to eliminate bandwidth uncertainties. The quantity obtained is

$$\gamma = \frac{V_n^2 - V_s^2}{V_s^2 I_{dc}} = \frac{\overline{I_L^2}}{2eG(\bar{I}_c)^2}, \qquad (3)$$

where V_n is the rms voltage for the laser source, V_s is the rms shot noise voltage for the same I_{dc}, and I_{dc} is the average output (anode) current (note that $I_{dc} = G\bar{I}_c$). γ is proportional to the relative mean squared intensity fluctuations averaged over the measurement bandwidth Δf; the exact relationship depends on the nature of the fluctuations. For narrowband random fluctuations of width B (such as those for a spectral line, or the laser below threshold) the output noise is stationary, and assuming a Lorentzian shape for the optical signal, we have

$$\frac{\overline{I_L^2}}{(\bar{I}_c)^2} = \frac{2}{\pi B}\left[1 + \left(\frac{f}{B}\right)^2\right]^{-1}, \qquad (4)$$

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*The effective secondary emission noise factor[10] $(H - 1)/(\delta - 1)$ was found to be $1.00 \pm .05$ for our photomultiplier by measurement of the rms shot noise voltage in a known bandwidth. We have therefore omitted this factor in our discussion of the noise.

where f is the measurement frequency.[6] For this type of source, the relative mean squared intensity fluctuation per unit bandwidth is equal to the coherence time $\tau_n = 1/\pi B$, which is related to γ by $\tau_n = Ge\gamma$. This holds for $f \ll B$, which is normally the case in the present work. The detector bandwidth does not appear in this result because $\overline{I_L^2}$ has a uniform spectral density for $f \ll B$. The measurements of γ reported here are given in units of $(\mu A)^{-1}$ for a fixed gain of 9×10^4; the conversion factor Ge is thus 1.4×10^{-8} μC.

In the coincidence counting method, the laser beam is split into two parts, each of which falls on a separate detector. The output of the detectors is correlated by the coincidence circuitry. Fluctuations of the light beam cause an increase in the number of coincidences over the random background coincidences which arise from the finite resolving time. The number of coincidences N_c measured in a period T can be written

$$N_c = (2\tau_R n_1 n_2 + k\overline{I_L^2})T, \tag{5}$$

where n_1 and n_2 are the single channel counting rates, k depends on the detector, τ_R is the resolution time, and $\overline{I_L^2}$ is the mean square current fluctuation appearing in each detector due to the intensity fluctuations. A convenient quantity to obtain experimentally is

$$\rho = \frac{N_c - 2\tau_R n_1 n_2 T}{2\tau_R n_1 n_2 T} = \frac{k\overline{I_L^2}}{2\tau_R n_1 n_2 T} = \frac{k'\overline{I_L^2}}{2\tau_R \bar{I}_{c1}\bar{I}_{2c}}, \tag{6}$$

which is proportional to the mean squared intensity fluctuations of the source falling within the detector bandwidth ($1/2\pi\tau_R \approx 30$ Mc). Thus γ and ρ measure the same quantity, although in general for different frequency ranges.

In practice, the random number of coincidences $2\tau_R n_1 n_2 T$ cannot be calculated with sufficient accuracy from independent measurements of τ_R, n_1, and n_2; therefore, an uncorrelated number of coincidences N_{del} is measured by delaying the pulses from one detector by a time τ_d.[7]

Two kinds of noise are encountered in the lasers above threshold, and the response of the single detector and coincidence techniques to these will be briefly discussed. The first kind of noise is a random noise background superimposed on the stronger amplitude-stabilized coherent output of the laser. The bandwidth of the noise B is narrowband with respect to optical frequencies but is typically greater than 100 Mc/sec for injection lasers. The resulting noise power in the detector output has a uniform spectral density up to a frequency B. The noise is stationary, that is, its correlation function depends only on a time *interval*. For a laser with one lasing mode, a single detector measurement of this noise gives

$$\gamma = \frac{\tau_n}{Ge}\frac{P_n^2 + aP_nP_{\text{coh}}}{(P_n + P_{\text{coh}})^2}, \tag{7}$$

where P_{coh} is the coherent power and P_n the noise power from the laser, τ_n is the coherence time of the noise, and a is a factor between 1 and 2 which depends on the spectral shape of the noise. The relation between τ_n and B also depends on the spectral shape of the noise, but is approximately $\tau_n = 1/\pi B$. Eq. (7) holds for measurement frequencies less than B, which is the case for stationary noise in the present experiments.

The corresponding value of ρ for the coincidence experiments is

$$\rho = \frac{\tau_n}{2\tau_R}\frac{(P_n^2 + aP_nP_{\text{coh}})}{(P_n + P_{\text{coh}})^2} \tag{8}$$

for $\tau_n < \tau_R$, which is the case for stationary noise in the present experiments. Under these conditions, ρ is exactly the relative mean squared intensity fluctuations in the source, falling within the coincidence bandwidth, and the relation between ρ and γ is

$$\rho = \frac{2\tau_R}{Ge}\gamma. \tag{9}$$

For this type of noise N_{del} is equal to the random rate $2\tau_R n_1 n_2 T$ if τ_d is greater than τ_R. In the present work, τ_d was 17 nsec and τ_R was 5 nsec.

The second kind of noise found in the lasers above threshold is quasi-periodic in nature and hence is nonstationary. The noise power has a sharp maximum at the center frequency of the noise. In this case the value of γ depends on the measurement bandwidth and its location with respect to the noise maximum. In the present work, the nonstationary noise typically was around 1 kc/sec, which fell within one of the single-detector bandwidths used; namely, 0.1 kc/sec to 4 Mc/sec. The nonstationary noise measurements are given in terms of γ, the parameter used for stationary noise. A more natural way of recording the nonstationary noise would be in terms of a noise modulation coefficient,

$$\alpha = \frac{\sqrt{\overline{V_n^2} - \overline{V_s^2}}}{R_L I_{dc}}, \tag{10}$$

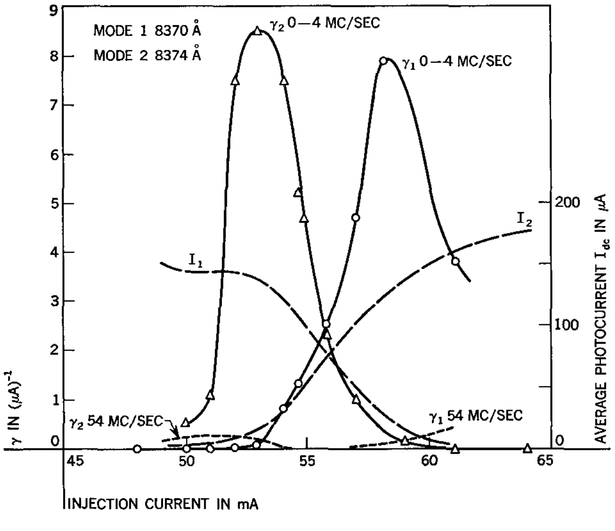
where R_L is the photomultiplier load resistor, instead of comparing it to the shot noise in an arbitrary detector bandwidth. However, since both types of noise often occur together, and the stationary noise represents a more fundamental limitation on the use of the lasers, all the single detector noise measurements are reported in terms of γ. For the nonstationary noise the coincidence method responds only to fluctuations with periods less than the delay time τ_d. Thus in the case of the 1 kc noise, the coincidence measurements give only the high-frequency tail of this noise ($f > 1/\pi\tau_d \approx 20$ Mc/sec). As previously noted, the upper frequency limit is determined by the resolution time ($f < 1/2\pi\tau_R \approx 30$ Mc/sec).

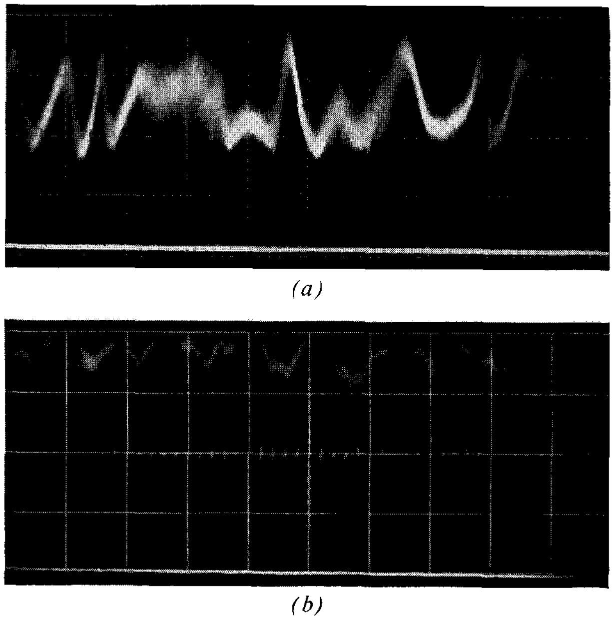
The coincidence technique can also be used to measure the correlation of the intensity fluctuations in two different modes[2,3]; this is done by shining the light from each mode on a separate detector. The coincidence rate is then either greater or smaller than the random coincidence rate depending on whether the correlation is positive or negative. A positive correlation means that on the average the intensity in both modes fluctuates up or down simultaneously while a negative correlation means that one is fluctuating up while the other fluctuates down. Again, only the high frequency noise can be correlated using this technique.

3. Results

The spectra of the lasers below threshold fell into three groups, according to the number and position of axial mode families. Diodes in Group 1 had only a single family of modes; Group 2 had, in addition, one or two somewhat weaker families nearly coincident with the main family; and Group 3 had a displacement of one or more axial mode spacings between the families.[5] The latter two varieties of mode structure presumably arose from certain common diode imperfections, whose microscopic origin is not known at present. Of the 16 diodes examined, only 3 fell in Group 1; the remainder were divided about equally between the other two groups. The noise and spectral behavior of the lasers above threshold was quite well correlated with three sub-threshold groups; hence we discuss the results in terms of these groups.

Figure 3 Single detector noise measurements in the region of a mode crossover for the laser of Fig. 2. The noise parameter γ is as defined on page 226. Values of γ for the frequency ranges 0–4 Mc/sec and 53–55 Mc/sec are shown for both modes. Threshold for this laser was about 20 mA.




(a)

(b)

Figure 4 Oscilloscope traces of the noise near a peak for a weak mode, such as mode 1 at 58 mA or mode 2 at 53 mA in Fig. 3, or mode 2 at 68 mA in Fig. 5. Sweep rate is 5 msec/div. The zero intensity position is shown by the lower trace in each oscillogram.

Group 1

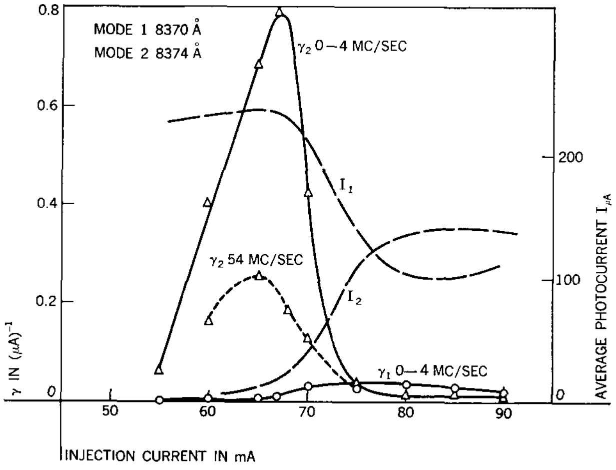
The first group of lasers exhibited only a single family of axial modes, as shown in Fig. 2. The envelope of the modes narrowed as threshold was approached, and only the strongest mode lased. This is the behavior expected for a laser with many modes under an homogeneously broadened fluorescence line.[3,10] Most lasers in this group continued in single mode operation until the injection current was two or three times the threshold value. At this point a second mode on the long wavelength side began to increase in power more rapidly than the first mode.

At higher currents the intensity of the second mode became larger than that of the first mode, i.e., a mode crossover occurred. The lasers then continued in single mode operation at currents up to 5 or 6 times the threshold value. The shift to modes at longer wavelengths is probably due to a shift in the peak of the fluorescence to longer wavelengths, which in turn is caused by heating of the diode.[4]

The mode crossover is accompanied by considerable intensity noise; this is shown in Fig. 3. The noise for each mode goes through a maximum when its power is about 1/10 that of the other mode. There are two kinds of noise at the maxima. The first is characterized by intensity fluctuations of 10 to 100% at a frequency of typically 1 kc/sec. This is illustrated by the oscilloscope traces of Fig. 4, and is clearly nonstationary noise. The second kind of noise is a weaker broadband noise covering frequencies up to at least 100 Mc/sec; this noise is stationary in character. The low frequency noise probably arises from the sensitivity of the weaker mode to vibration and temperature variations which are thought to result from the nature of the heat transfer from the laser to the He bath. The stronger mode is less sensitive to these disturbances, and so the relative effect is smaller. However, oscilloscope observations showed that the fluctuations in the two modes were comparable in magnitude but 180° out of phase. Such a correlation would be expected for two modes driven from a common pump. This point, together with the broadband noise, will be discussed below.

The noise behavior of a laser for which crossover was not complete is shown in Fig. 5. In this case the power in the two modes remained comparable above the crossover, and a large noise peak occurred only for the mode which was weaker below the crossover. In addition to single detector measurements at 0–4 Mc/sec and 54 Mc/sec, coincidence measurements of the intensity noise were made on this laser and are shown in Fig. 6. As noted in Section 2, the coincidence measurements were made with a delay of 17 nsec, and therefore will respond only to noise in the 20 to 30 Mc region. The differences among the various measurements for the 8374Å mode below 75 mA (Figs. 5 and 6) are presumably due to the complex nature of the non-stationary noise. On the other hand, the agreement among the measurements is better above 75 mA, and indicates that the noise is approximately frequency independent and stationary. In this region the noise is probably the fundamental partition noise which is expected when two modes are driven by a common pump.[11]

Figure 5 Single detector noise measurements for a laser in which the intensities of two modes become approximately equal. The spectrum near threshold (20 mA) is similar to that of Fig. 2.



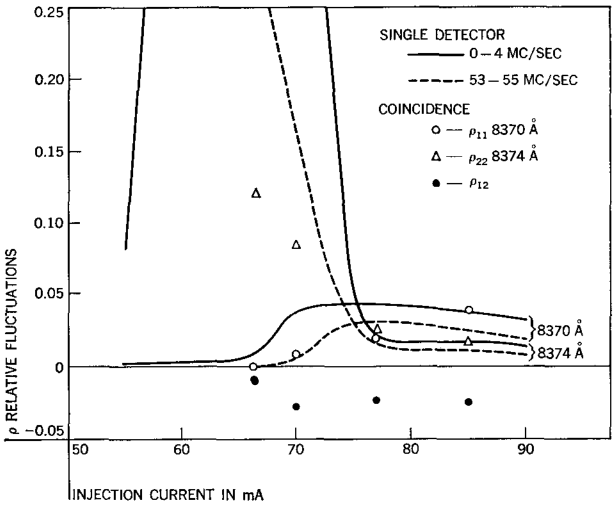


Figure 6 *Coincidence measurements of the relative intensity* fluctuations ρ_{11} and ρ_{22} for the two modes of the laser of Fig. 5, and the noise correlation ρ_{12} between the two modes. The single detector data of Fig. 5 plus some additional 54 Mc/sec data have been converted to equivalent values of ρ (using Eq. (9)) and are shown for comparison by the solid and dashed curves. If the two modes exhibited only stationary noise ($B > 100$ Mc/sec), the data for the three different noise measurements would fall on a common curve for each mode. This is approximately true for the mode at 8374 Å above 75 mA, and to a lesser extent for the mode at 8370 Å above 75 mA.

Coincidence measurements of the correlation ρ_{12} between the fluctuations in the two modes of this laser were made and are shown in Fig. 6. The negative values of ρ_{12} indicate that the high frequency fluctuations are 180° out of phase on the average. The following relation should hold for noise in two coupled modes:[3]

$$\rho_{12} = -\rho_{11}\frac{P_1}{P_2} = -\rho_{22}\frac{P_2}{P_1}, \tag{11}$$

where ρ_{11} and ρ_{22} are the relative intensity fluctuations for modes with powers P_1 and P_2, respectively, and ρ_{12} is the normalized intensity correlation of the two modes. This relation is well satisfied by the coincidence measurements at 77 mA, where the intensities in the two modes are about equal. The agreement is not as good at 85 mA, but a third mode is becoming strong here and the above relations no longer hold.

An interesting and potentially important result of the negative correlation between the intensity fluctuations in the two modes is that the net noise in the total output of the laser is very low. For the diode just described, at 77 mA the net noise for both modes was a factor of 10^4 lower than the noise for the individual modes, both at 0–4 Mc/sec and 54 Mc/sec. The corresponding value of ρ is about 3×10^{-6}, which is of the same order of magnitude as ρ for an "ideal" single mode laser of the same total power

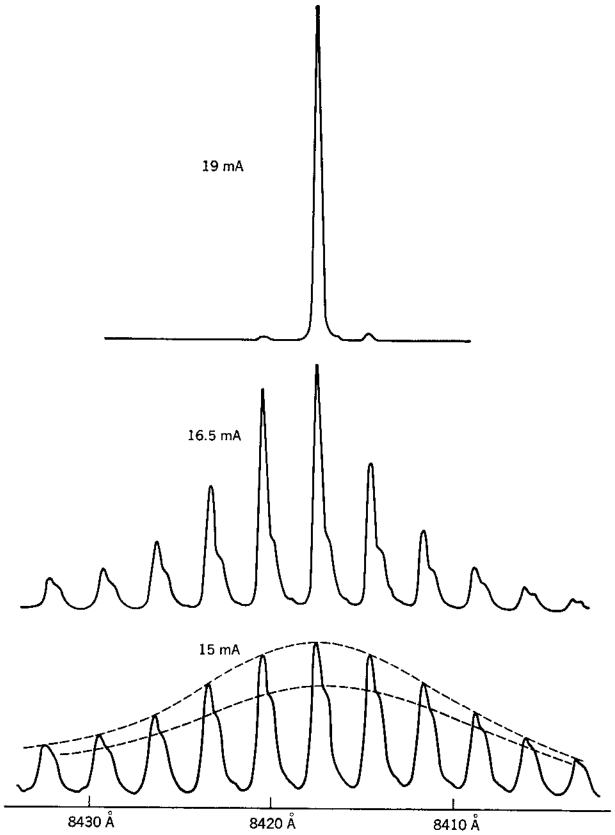


Figure 7 Spectrum of a laser having a second weaker family nearly coincident with the main family. The intensity of the weaker family has saturated at 16.5 mA. The vertical scale is different for each current.

(estimated from a typical value of ρ just above threshold and assuming $\rho \propto 1/P^2$, where P is the laser output power). This is in agreement with the results of a theoretical study[11] of multimode operation in which it was shown that the nonlinear nature of a laser oscillator stabilizes the total output but not the output of individual modes. In order to bring such a low noise above the shot noise, cathode currents greater than 1 mA are necessary, compared to 10^{-4} mA for the individual modes. In many systems applications the net laser noise will be entirely negligible.

Group 2

The second group of lasers exhibited weaker second or third families of axial modes that were nearly coincident with the main family, Fig. 7. These weaker families showed normal envelope narrowing up to currents just below threshold, where the intensities saturated. The saturation of the weaker families is expected theoretically because of their lower gain.[6] The envelope of the main family continued to narrow, and only the strongest mode of this family lased initially. Some lasers continued in single mode operation up to 2 or 3 times the threshold current. As in the previous group, a second mode usually appeared on the long wavelength side. This mode appeared to be the adjacent axial mode from the main family. There was no indication that the modes of the weaker families ever lased. The behavior of the second mode was very erratic, often switching on and off within an interval of several seconds. Thus it was difficult to make quantitative noise measurements for these lasers. It is not clear whether this behavior is characteristic of the mode structure of this group, or only of the two lasers examined for noise behavior; however, it was noted that the fluctuations in the two modes were 180° out of phase, as in Group 1, so that the total intensity was much more stable.

The behavior of the Group 1 and 2 lasers was not greatly different and the main difference between these two groups might simply be the length-to-width ratio obtained when the diodes were etched down in the center.

Group 3

The third group of lasers exhibited second or third families of modes whose envelope maximum was displaced by 3 or 4 Å or more (i.e. one or more axial mode separations) from the maximum of the main family, Fig. 8. The strongest mode of the main family lased just above threshold. At higher injection currents, a mode from the second family also lased, though not necessarily the strongest mode. Mode crossovers within the same family also occurred, with no systematic preference for shorter or longer wavelengths. In general, the mode behavior in this group was more erratic than that in Groups 1 and 2.

Noise measurements for a laser with a spectrum similar to that of Fig. 8 are shown in Fig. 9. Data is shown for the four strongest modes only. The modes at 8411Å and 8415Å belong to the main family. They show a crossover at 30 mA, with noise peaks in the weaker mode above and below the crossover similar to those in Fig. 3. The modes at 8387Å and 8391Å belong to the weak family. Coincidence measurements were made at 60 mA to see whether correlations existed among the three modes at 8387Å, 8391Å, and 8411Å. These will be referred to as modes 1, 2, and 3, respectively. The results are as follows: $\rho_{11} = +0.029$, $\rho_{12} = -0.056$, $\rho_{22} = +0.095$, $\rho_{13} = +0.0013$, and $\rho_{33} = +0.0016$. The values of ρ_{13} and ρ_{33} are zero within the experimental error of ± 0.002. The corresponding power ratios are $P_1/P_2 \approx 1/2$ and $P_2/P_3 \approx 1$. Thus modes 1 and 2 from the same family exhibit correlated partition noise, as would be expected, but mode 3 from the other family does not show partition noise and there is no correlation with the other two modes. It is concluded from these results that the two families are not driven from a common pump, but arise from two decoupled lasers within the same diode. The two lasers may simply be two filaments whose existence is favored by an imperfection in the diodes. The

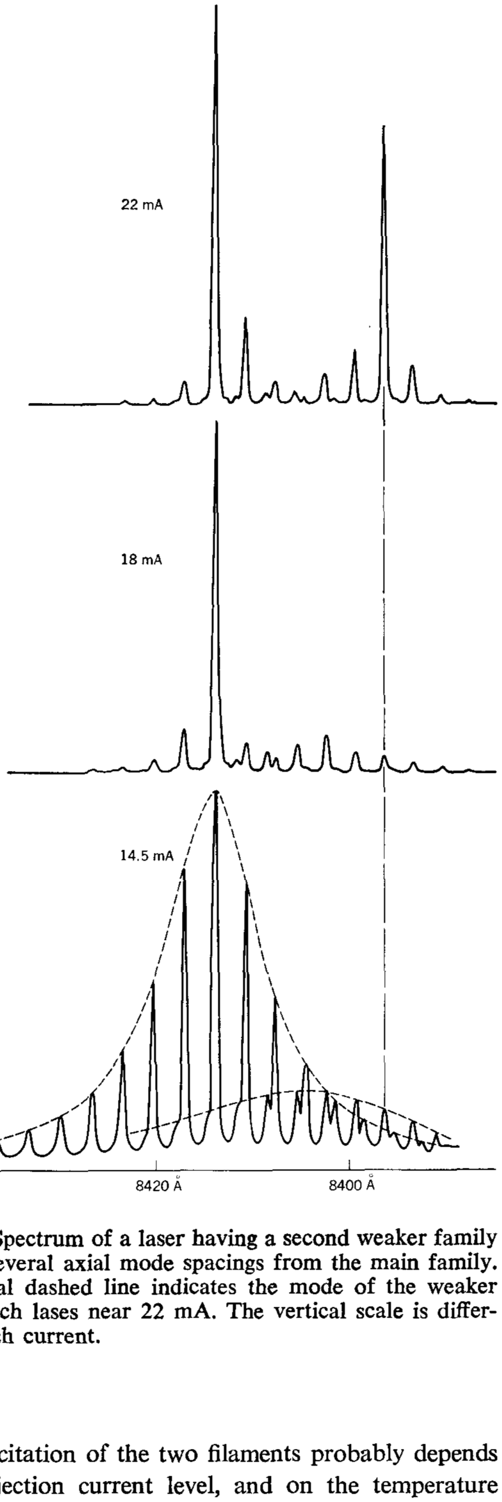


Figure 8 Spectrum of a laser having a second weaker family offset by several axial mode spacings from the main family. The vertical dashed line indicates the mode of the weaker family which lases near 22 mA. The vertical scale is different for each current.

relative excitation of the two filaments probably depends on the injection current level, and on the temperature of the diode. A further conclusion is that the net noise for the three modes is small. This was confirmed by measurements on the total output of other lasers of this group.

4. Conclusions

It has been shown conclusively that the amount and type of intensity noise which is present in the output of cw GaAs lasers is strongly correlated with the spectrum of the laser emission. The noise can vary from essentially zero in the case of a true single mode laser to very large amounts in the case of lasers with several lasing modes. It should be emphasized, however, that the noise figure of the multimode oscillator will depend on whether one is measuring the total laser output or simply the output of a single mode. The relative fluctuations in the total output are typically a factor of 10^4 times smaller than the relative fluctuations in a single mode. This fact will have several practical consequences. For example, if one wishes to construct an optical heterodyne detector using injection lasers it seems likely that the local oscillator will have to be a true single mode laser, rather than one mode of a multimode laser. On the other hand, the noise that accompanies individual modes of a multimode laser essentially disappears in a device in which the *total* coherent output is amplitude modulated. For the present, then, it appears that noise considerations, together with the lack of single-mode tunability, strongly favor the use of homodyne detection rather than heterodyne (or coherent) detection.

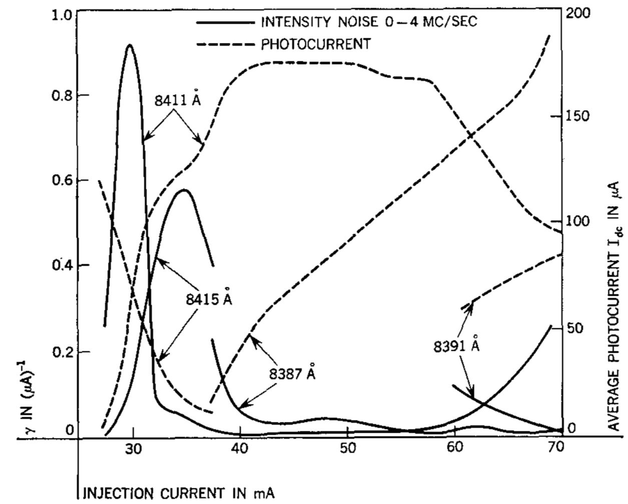


Figure 9 Single detector noise measurements of a laser with a spectrum similar to that of Fig. 8. The modes at 8411 Å and 8415 Å belong to the main family, those at 8387 Å and 8391 Å belong to the weak family.

Acknowledgments

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