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ABSTRACT

Extended measurements of laser frequency fluctuations, using improved instrumentation, have provided further verification of the Schawlow-Townes relation for the spontaneous-emission-limited line-width of a laser oscillator.

# FURTHER MEASUREMENTS OF QUANTUM PHASE NOISE IN A He-Ne LASER\*

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We recently reported the observation of spontaneous-emission-induced phase fluctuations, or "quantum phase noise", in a He-Ne 6328 Å laser operating at power levels in the low microwatt range.<sup>1</sup> Using slightly modified instrumentation, we have now extended these quantum phase fluctuation measurements over a wider range of laser powers, and have used amplitude fluctuation measurements to determine the excess noise factor appropriate to our lasers. Our new results in general validate our earlier measurements, and give further support to the Schawlow-Townes relation for the spontaneous emission contribution to the linewidth of a laser oscillator.<sup>2</sup>

The Schawlow-Townes formula predicts that the quantum phase noise contribution to the oscillation linewidth of a laser is

$$\Delta f_q = \frac{\pi h f (\Delta f_{\text{cav}})^2}{P} \times \left( \frac{N_2}{N_2 - (g_2/g_1) N_1} \right) = \alpha \frac{\pi h f (\Delta f_{\text{cav}})^2}{P} \quad (1)$$

where  $\Delta f_q$  is the full lorentzian linewidth contribution due to this noise source;  $N_2$  and  $N_1$  are the upper and lower laser level populations;  $P$  is the laser power level;  $f$  is the oscillation

frequency; and  $\Delta f_{\text{cav}}$  is the "cold" laser cavity bandwidth. The excess noise factor  $\alpha \equiv N_2/[N_2 - (g_2/g_1)N_1]$  may be determined by measuring the amplitude fluctuations in the same laser, as shown by Freed and Haus.<sup>3</sup> The audio-frequency amplitude fluctuation spectrum of the laser, measured using a photomultiplier with an appropriate load resistance  $R_L$ , may be written as the sum of a shot-noise term and an excess or quantum amplitude noise term

$$\begin{aligned}
 S(f) &= S_s + S_e(f) \\
 &= R_L^2 \left[ 2M\Gamma e I_a + 4M e I_a \eta \alpha \left( \frac{\Delta f_{\text{cav}}}{\Delta f} \right)^2 \frac{1}{1 + (f/\Delta f)^2} \right] \quad (2)
 \end{aligned}$$

In this expression  $S$  is the spectral density of the voltage across  $R_L$  (in volt<sup>2</sup>/Hz);  $M$  is the photomultiplier power gain;  $I_a$  is the anode dc current;  $\eta$  is the photocathode quantum efficiency;  $\Gamma$  is the shot noise enhancement factor; and  $\Delta f$  ( $\approx 10$  to  $30$  kHz) is the bandwidth of the amplitude fluctuation spectrum. For lasers operating at low oscillation power levels, the excess amplitude noise term  $S_e(f)$  is substantially larger than the shot noise term for frequencies less than  $\Delta f$ .

The excess amplitude noise spectrum  $S_e(f)$  was measured for our lasers, using an audio wave analyzer, at frequencies up to approximately 1 MHz. The results were in general agreement with those of Freed and Haus,<sup>3</sup> except for a small additional increase in the amplitude fluctuations at very low frequencies ( $\lesssim 3$  kHz), which we tentatively

attribute to plasma disturbances. The mean-square voltage readings  $\overline{v_n^2} = S_e B$ , where  $B$  is the analyzer bandwidth, were multiplied by the appropriate correction factor of  $1.13^2$  to account for gaussian noise in a sinusoidally calibrated average-reading voltmeter. The value of the excess noise spectrum for frequencies less than  $\Delta f$ , together with the measured bandwidth  $\Delta f$  of the excess noise fluctuations, in essence measures the excess noise factor  $\alpha$ . In fact, if the measured dc voltage  $V_a$  across the anode resistance  $R_L$  is measured at the same time as the excess noise fluctuations, then the Schawlow-Townes formula may be cast into the extremely simple form

$$\Delta f_q = \frac{\pi}{4} \frac{S_e \Delta f^2}{V_a^2} \quad (3)$$

in which all quantities are directly measurable. The measured value of this expression was used to provide the theoretical value of  $\Delta f_q$  against which to compare our frequency fluctuation measurements. Using this approach, it is not necessary to make separate determinations of the photocathode quantum efficiency or the photomultiplier gain. However, these quantities were also independently measured to guarantee that all aspects of the experiment were under proper control.

The principal change in the frequency fluctuation instrumentation was the replacement of the previous commercially available 30 MHz FM discriminator (RHG Electronics Inc. Model DF 3006) with a quadrature detector discriminator<sup>4</sup> centered at 4.5 MHz. The 4.5 MHz amplifier,

limiter, and discriminator were assembled from Fairchild and RCA integrated circuits. Two stages of preamplification and limiting were constructed from RCA CA-3013 integrated circuits. A subsequent stage consisting of a single Fairchild  $\mu A717E$  integrated circuit supplied further amplification and limiting. This stage, in conjunction with an external quadrature tank,<sup>4</sup> also provided the frequency discrimination. The narrower bandwidth and somewhat better sensitivity of this system permitted quantum phase fluctuation measurements at higher laser power levels (lower frequency fluctuation levels) than previously possible.

Our total experimental results, together with the Schawlow-Townes prediction as calibrated from the amplitude fluctuation measurements, are presented in Fig. 1. The triangular data points indicate results obtained earlier by a phase jitter technique at a specific delay time  $\tau = 167$  nsec. The square data points indicate quantum noise results obtained with the new 4.5 MHz discriminator and i.f. system. Both of these results differ by approximately a factor of two from the earlier measurements made with the 30 MHz discriminator system. The difference may be due to different limiting characteristics in the two discriminators. The Schawlow-Townes predictions, taking into account uncertainties in the evaluation, seem to be in good agreement with our overall results.

The apparent sharp increase in quantum noise below  $P = 2 \times 10^{-7}$  watts should probably, as before, be discounted. In this region the signal-to-noise detection ratio has decreased below 20 dB; hence,

all of the FM measurement techniques begin to deteriorate rapidly, in accordance with the well-known threshold properties of FM receivers. Also, due to the  $1/P$  power dependence of quantum noise, we might expect that small fluctuations in the power stabilization loop at these low levels could result in an augmented noise output.

Progress is currently being made on a high-gain He-Xe  $3.5\mu$  laser system with which we hope to observe quantum phase fluctuations in greater detail and with improved accuracy.

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- \* This study was supported by the NASA Electronics Research Center, Cambridge, Massachusetts.
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FIGURE CAPTION

1. Quantum phase noise measurements as obtained with the 30 MHz discriminator, the 4.5 MHz discriminator, and the phase jitter instrumentation. The shaded area represents the theoretically expected values based on the evaluation of Eq. (3).

