OBSERVATION OF QUANTUM PHASE NOISE IN A LASER OSCILLATOR*

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By heterodyning together two stable 6328-Å He-Ne lasers, with one laser operating at very low power, quantum phase fluctuations caused by spontaneous emission have been observed. Results, although preliminary, seem in good agreement with the predictions of Schawlow-Townes and others.[1]

Neglecting amplitude fluctuations, the beat note between two laser oscillators may be written $v = V_0 \cos(\omega_0 t + \varphi)$, where ω_0 is the mean frequency and $\varphi(t)$ the randomly varying phase. Since the instantaneous beat frequency is $\omega_0 + \dot{\varphi}(t)$, the power spectral density $G_{\dot{\varphi}}(f)$ of the quantity $\dot{\varphi}(t)$ may be determined with an rf frequency discriminator centered at ω_0, followed by an audio-wave analyzer (Fig. 1). With appropriate instrumentation one can also measure the analytically related mean-square phase jitter $\langle\Delta\varphi^2(\tau)\rangle \equiv \langle[\varphi(t+\tau)-\varphi(t)]^2\rangle$ as a function of the time interval τ.

In real lasers the random phase variation $\varphi(t)$ includes an "external" contribution $\varphi_e(t)$ due to acoustic noise, structural vibrations, and plasma disturbances, plus a usually much weaker contribution $\varphi_q(t)$ due to quantum noise. In our experiments the external disturbances occur primarily at low audio frequencies, with $G_{\dot{\varphi}e}(f) \sim 1/f^2$ [see Fig. 2(a)] and $\langle\Delta\varphi_e^2(\tau)\rangle \sim \tau^2$. The resulting beat-note power spectral density $G_v(f)$ is Gaussian with a linewidth typically $\Delta f_e \approx 3.5$ kHz in our apparatus, essentially independent of laser power level. By contrast, the quantum contribution should have a white-noise spectrum $G_{\dot{\varphi}q}(f) = 4\pi\Delta f_q$ and a phase jitter $\langle\Delta\varphi_q^2(\tau)\rangle = 2\pi\Delta_q\tau$. The Schawlow-Townes prediction is

$$\Delta f_q = \frac{\pi h f(\Delta f_{\text{cav}})^2}{P} \frac{N_2}{N_2-(g_2/g_1)N_1},$$

where f is the oscillation frequency, Δf_{cav} the "cold"-cavity bandwidth, P the laser-oscillation power level, and N_2 and N_1 the upper and lower level populations. Except at our lowest power levels, the quantum contribution to the total beat-note spectral density is considerably less than the Gaussian external contributions. The quantum contributions are, however, separable by

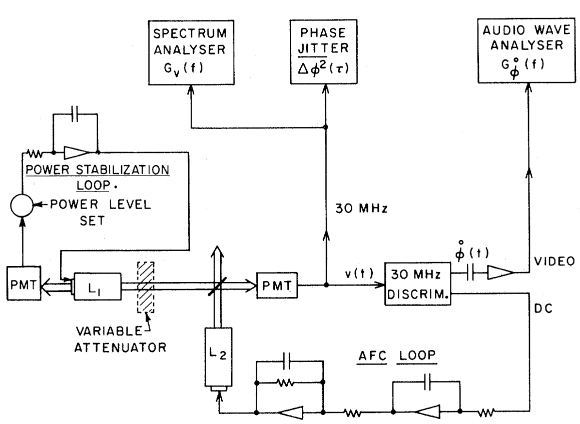

FIG. 1. Block diagram of system used to observe quantum phase fluctuations.

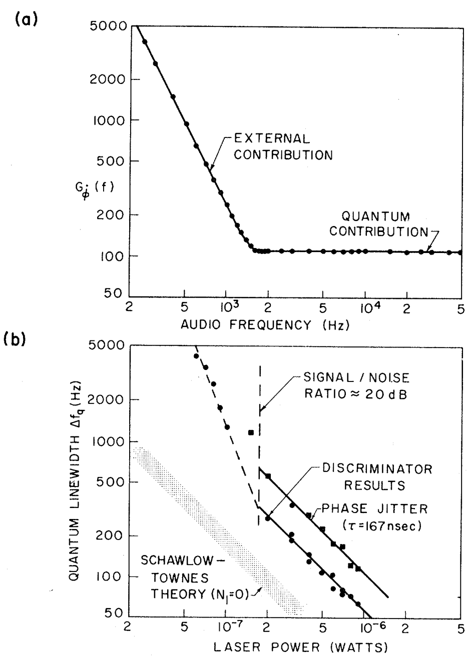

FIG. 2. (a) Typical discriminator noise output spectrum as measured by audio-wave analyzer, showing $1/f^2$ portion due to external disturbances and flat portion due to quantum noise (or, in some cases, to discriminator characteristics). (b) Quantum phase-noise linewidth contribution, as measured by flat discriminator noise level, versus oscillation power level of laser L_1. Also shown are the Schawlow-Townes theoretical result assuming $N_2/(N_2-N_1) = 1$ and the results of experimental phase-jitter measurements at a single fixed delay $\tau = 167$ nsec.

examining $G_{\dot{\varphi}}(f)$ at high enough frequencies, or $\langle\Delta\varphi^2(\tau)\rangle$ at short enough times.

The experimental apparatus (Fig. 1) is basically the same as reported earlier.[2] Laser L_1 has a relatively high-transmission output mirror (1.7%) to enlarge Δf_{cav} and thus enhance the quantum line broadening. A slow power-stabilization loop provides stable operation at low power levels by piezotuning the cavity close to the edge of its oscillation range.[3] Laser L_2 is locked 30 MHz from L_1 by a slow automatic-frequency-control loop. The signal-to-noise ratio (S/N) of the beat-note depends upon signal power P from L_1 and photocathode quantum efficiency in the usual way. Since these measurements necessarily involved low and decreasing S/N, it was necessary to verify that measured noise linewidth increases at low P did not simply represent equipment characteristics. This was checked following each measurement by operating L_1 at a higher output level, where quantum fluctuations in L_1 should be negligible, and inserting a variable optical attenuator (~30 dB) in the output of L_1 to produce the same post-attenuator power output (and hence S/N conditions) in the succeeding apparatus. Comparison of the two measurements effectively determined the quantum contribution.

The circled points in Fig. 2(b) show the measured white-noise level of $G_{\dot{\varphi}}(f)$, expressed as equivalent linewidth Δf_q, versus oscillation level of L_1. The theoretical curve is the Schawlow-Townes formula[1] taking into account the uncertainty in cavity parameters for L_1 but assuming $N_2/(N_2-g_2N_1/g_1)=1$. The offset between theory and experiment can be accounted for by assuming $N_2/(N_2-g_2N_1/g_1)\approx 3$, not unreasonable for this particular laser system. The square data points represent measurements of $\langle\Delta\varphi^2(\tau)\rangle$ at one fixed value $\tau = 167$ nsec, again converted to equivalent quantum linewidth. As also in our earlier work, we are unable to resolve the factor of 2 difference between discriminator and phase-jitter results here, and must continue to attribute it to experimental uncertainties or to some systematic error in one of the measurement techniques. We discount the apparent rapid increase in Δf_q below $P=2\times10^{-7}$ W since in this region the beat-note S/N decreases below 20 dB. At such low power levels, fluctuations in the power stabilization loop could result in an increase in observed noise because of nonlinear power dependence ($1/P$) of the quantum noise.

Our useful measurement range is uncomfortably limited at present by the vanishing quantum contribution at higher values of P and by reduction of the heterodyne S/N at lower values of P. However, we believe that the $1/P$ dependence observed between $P=2\times10^{-7}$ W and $P=9\times10^{-7}$ W most probably represents quantum phase fluctuations in laser L_1. In future experiments more detailed study should be possible by using a high-gain infrared laser transition, reducing the cavity Q, increasing Δf_{cav}, and thus greatly enhancing the quantum noise contribution.

Note added in proof.—Just as this report was completed we received the translation of a Russian Letters journal reporting very similar observations,[4] although at substantially higher power levels P and hence much lower values of Δf_q (~0.1-1.0 Hz). Our only reservations concerning the Russian results have to do with the nonideal discriminator characteristics mentioned earlier; i.e., we find that the observed inherent noise output from our real (nonideal) discriminator can have a flat spectrum that rises as ~$1/P$ due simply to decreasing S/N in the rf bandwidth rather than to any real frequency fluctuations in the beat signal. The results of Ref. 4 imply the availability of a very nearly ideal rf discriminator at $\omega_0=2\pi\times8.4$ MHz.

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[1]A. L. Schawlow and C. H. Townes, Phys. Rev. 112, 1940 (1958); for a more recent discussion, cf. M. Lax, in Physics of Quantum Electronics, edited by P. L. Kelley, B. Lax, and P. E. Tannenwald (McGraw-Hill Book Company, Inc., New York, 1966), p. 735.

[2]A. E. Siegman, B. Daino, and K. R. Manes, IEEE J. Quantum Electron. QE-3, 180 (1967).

[3]F. T. Arecchi, A. Berne, A. Sona, and P. Burlamacchi, IEEE J. Quantum Electron. QE-2, 341 (1966).

[4]Yu. N. Zaitsev and D. P. Stepanov, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 6, 733 (1967) [translation: JETP Letters 6, 209 (1967)].