Correlated Spontaneous Emission in a Zeeman Laser

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(Received 8 June 1990)

We have observed phase-diffusion noise 40% below the Schawlow-Townes limit in the relative phase of a two-mode HeNe Zeeman laser due to the correlated-emission-laser effect.

PACS numbers: 42.50.Kb, 32.90.+a, 42.50.Wm

In recent years there has been great interest in the development of high-sensitivity laser interferometers for use in the detection of gravitational waves. Ordinarily, the sensitivity of these devices is limited by quantum fluctuations that take the form of shot noise in passive interferometers and spontaneous-emission noise in active interferometers. Proposals for increasing the sensitivity of these interferometers include squeezed states for passive devices[1] and the correlated-emission laser (CEL) for active devices.[2,3] Generation of squeezed states has now been demonstrated by several groups[4,5] and the purpose of this Letter is to describe an experimental investigation of the CEL.

The CEL utilizes a gain medium with two laser transitions sharing a common lower level (Fig. 1). A coherent superposition of the upper states is created by driving a microwave transition between these levels. This superposition results in the correlation of spontaneous emission into the two laser modes and, under appropriate conditions, leads to a reduction of phase-diffusion noise in the relative phase of the two modes.

Present theory does not allow us to predict the extent of noise reduction obtainable in our particular laser system, but we can say quite generally what its signature will be. For this discussion, a useful background is to consider the phase noise in free-running and phase-locked laser (PLL) systems. The reason for examining the PLL is twofold. First, phase locking *does* occur in the CEL and so it will form the foundation of our simple CEL picture and, second, we need to know how to distinguish between correlated emission and phase locking in case only the latter exists in our laser.

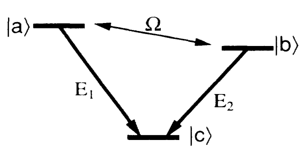

FIG. 1. CEL level diagram. Two laser transitions share a common lower level and the upper levels are coupled by an rf magnetic transition with an effective Rabi rate Ω.

It is well known that in a free-running laser the phase will undergo a random walk with mean-square phase given by $\langle \Delta\phi^2 \rangle = Dt$, where

$$D = \frac{2\pi^2 h\nu(\Delta\nu_{\rm cav})^2}{P_{\rm laser}} \frac{N_2}{N_2 - N_1} \tag{1}$$

is the diffusion rate corresponding to the Schawlow-Townes linewidth.[6] (Here we assume $t > 1/\Delta\nu_{\rm cav}$, so that shot noise can be ignored.) Typically, this linewidth is of the order of a millihertz or less and is completely masked by technical noise. Only by measuring the relative phase between two modes in the same laser is it feasible to see this phase diffusion.

Evolution of the relative phase of a two-mode PLL is described by Adler's equation:[7]

$$\frac{\partial\phi}{\partial t} = a - b\sin\phi + F(t)\,, \tag{2}$$

where a is the frequency detuning between the two modes, b is the locking strength (or range), and $F(t)$ is a δ-correlated noise term, due to spontaneous emission. This is a very general equation—it can be used to describe injection locking, laser gyrolockup, and even some electronic phase-locked loops. Equation (2) suggests a steady-state solution (lockup phase) $\phi_0 = \sin^{-1}(a/b)$ with fluctuations

$$\langle \Delta\phi^2 \rangle = \frac{D}{b\cos\phi_0}(1 - e^{-2bt\cos\phi_0})\,. \tag{3}$$

It is easy to see that at short times the PLL behaves like a free-running laser, but at long times the phase fluctuations saturate to a constant value and will appear to be "sub-Schawlow-Townes."

For the purpose of discussing the experiment, a useful model for describing the behavior of the CEL is the "geometric picture."[8] We start with a phasor diagram (Fig. 2) showing two laser fields E_1 and E_2 with relative phase ϕ. Each field fluctuates under the influence of its own driving term F_i, but we allow for a nonzero cross correlation between the terms. Using simple geometry we can write the relative phase increment as

$$\delta\phi = [\cos\tfrac{1}{2}\phi\,{\rm Im}(F_1 - F_2) + \sin\tfrac{1}{2}\phi\,{\rm Re}(F_1 + F_2)]\delta t\,.$$

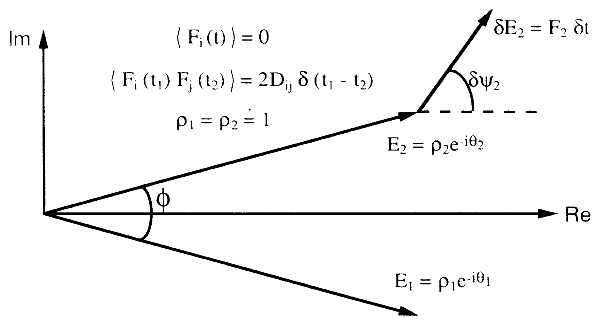

FIG. 2. Phasor diagram for the geometric picture of the CEL (Ref. 8). The laser fields E_i have a relative phase ϕ and fluctuate under the influence of F_i.

This can be simplified further by rewriting it in terms of $F_- \equiv \mathrm{Im}(F_1 - F_2)$ and $F_+ \equiv \mathrm{Re}(F_1 + F_2)$ with $\langle F_+(t_1) \times F_-(t_2) \rangle = 0$, $\varepsilon = (2\,\mathrm{Re}D_{12})/(D_{11} + D_{22})$, and

$$\langle F_\pm(t_1) F_\pm(t_2) \rangle = (D_{11} + D_{22})(1 \pm \varepsilon)\delta(t_1 - t_2)\,,$$

where the D_{ij} are defined in Fig. 2. The result is then used with Eq. (2) to yield an appropriate Langevin equation for the CEL:

$$\frac{\partial\phi}{\partial t} = a - b\sin\phi + \cos\tfrac{1}{2}\phi F_- + \sin\tfrac{1}{2}\phi F_+\,.$$

Under the condition of maximum correlation ($\varepsilon = 1$) it can be shown that $F_- \equiv 0$. The remaining F_+ term is then multiplied by zero if $\phi = 0$ and the quantum noise in the relative phase is completely suppressed. The general solution ($\varepsilon \neq 1$) has the same steady-state phase as the PLL, but the fluctuations now contain an additional term:

$$\langle \Delta\phi^2 \rangle = \frac{D}{b\cos\phi_0}(1 - e^{-2bt\cos\phi_0})(1 - \varepsilon\cos\phi_0)\,,$$

$$\langle \Delta\phi^2 \rangle = \begin{cases} 2Dt(1 - \varepsilon\cos\phi_0), & t \ll 1/b\,, \quad \text{(4a)} \\ \dfrac{D}{b\cos\phi_0}(1 - \varepsilon\cos\phi_0), & t \gg 1/b\,, \quad \text{(4b)} \end{cases}$$

where we have written $D_{11} = D_{22} \equiv D$. It is this additional term $1 - \varepsilon\cos\phi_0$ which reduces the PLL noise and is the signature of the CEL. In principle, an experiment could operate in either time limit of Eq. (4), but there are problems interpreting the data at long times. Effects that tend to increase ε also tend to increase b, making it difficult to tell whether any observed noise reduction is a CEL or a PLL effect. Limited signal-to-noise ratio makes it difficult to distinguish the ϕ_0 dependence of the CEL term from the $\cos\phi_0$ in the denominator of the PLL term. Finally, technical noise becomes a serious problem at long times. For these reasons, we have decided to work in the short-time limit where any noise reduction and ϕ_0 dependence can be safely attributed to the CEL effect. (Some measurements have been reported in the long-time limit.[9,10])

The transition we use is the 633-nm line in a HeNe laser. The natural linewidth is 17.5 MHz, collisional broadening is ~200 MHz, and the Doppler width is 1500 MHz. The upper level ($J = 1$, $g = 1.3$) is Zeeman split, 150–250 MHz, by a longitudinal dc magnetic field from a precisely controlled electromagnet. Ideally, for the CEL system, we would like the lower state to be $J = 0$; however, in the 633 line it is $J = 2$ ($g = 1.3$). (This is the main reason the present theory does not apply directly to our system. We must simply assume that correlated emission exists in our laser and then rely on the geometric picture to tell us what to look for.) The Zeeman splitting causes the laser to run in two circularly polarized modes which share a common cavity mode. The cavity length is stabilized midway between the two atomic transition frequencies by a frequency control loop referenced to an I_2-stabilized laser. Because of cavity pulling effects, the resulting laser frequency splitting is reduced to ~100 kHz. A transverse ac magnetic field at 50 kHz is applied to drive stepwise resonant two-photon magnetic dipole transitions between the $|m| = 1$ upper states. The large homogeneous linewidth makes the exact frequency of this ac field unimportant, so it is set mainly by technical considerations. At 50 kHz it is possible to generate a field strength of about 15 G—much higher than we could achieve at a frequency equal to half the atomic splitting (75–125 MHz). A windfall of this lower frequency is that we get additional (sideband injection) phase locking which allows us to vary the lock-up phase by detuning the ac field with respect to the laser frequency splitting. This sideband locking also sets a reasonable short-time limit for the system ($t < 10$ ms) before PLL effects begin to dominate.

The laser tube is enclosed in a hermetically sealed can mounted on an optical table to isolate it from the environment. The walls of the can provide mounts for the electromagnets as well as water cooling to extract the heat dissipated in them. Laser output passes through an antireflection-coated window. Feedback from external optical components is reduced by extensive optical isolation: Faraday isolators are used for all of the photodiodes and low-scatter gyromirrors are used immediately after the laser. The gyromirrors are mounted on piezoelectric transducers driven by random noise to scramble the phase of any light that does scatter back into the laser, thus reducing instabilities from "self-injection locking." The unused output from the back of the laser tube is absorbed by a black glass filter contacted to the rear mirror using index-matching fluid. The plasma discharge is run from a high-voltage power supply in conjunction with a low-noise active-current regulator. Laser output power is 50 μW per mode maximum and the free spectral range is 550 MHz.

The two laser modes are combined with a linear polarizer and the 100-kHz beatnote is detected with a photodiode. Relative-phase information is extracted from this

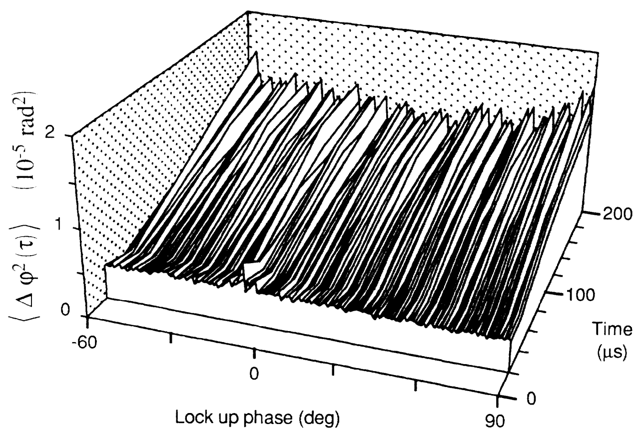

FIG. 3. Phase fluctuations as a function of lockup phase and time for an ac field strength of $B_1 = 15$ G. Computer fit yields $\varepsilon = 0.319 \pm 0.121$.

beatnote by comparing it to a low-noise phase reference. The phase reference is a quartz-crystal-based phase-locked loop, locked onto the beatnote with a 10-ms attack time constant. This long time constant allows the phased-locked loop to "flywheel" over the (fast) phase fluctuations of interest, but causes it to track out any long-term phase drift or frequency errors. Because of the high-Q nature of the quartz-crystal voltage-controlled oscillator (VCO), the phase-locked loop has a tracking range of only about 20 Hz (at 100 kHz) which can be exceeded in a few minutes. To prevent loss of lock, the low-frequency part of the VCO error signal is sent as a slow servo control to the dc magnetic field to keep the beatnote centered in the VCO range. The time constant of this loop is of the order of 1 s to ensure that there are no noticeable field changes during a data run. Comparison of the beatnote with the phase reference is made with a special analog time-interval meter which measures the phase once every cycle for up to 10^4 consecutive cycles. This fast sampling rate assures that we can work in the short-time limit and the $2\pi \times 10^{-4}$-rad single-point resolution allows us to see phase noise corresponding to a 6-mHz linewidth at 10 μs. From this phase-versus-time record we compute phase fluctuations versus time using the Allen two-point variance:[11]

$$\langle \Delta\phi^2(\tau) \rangle = \tfrac{1}{2} \langle [\phi(t+\tau) - \phi(t)]^2 \rangle .$$

Figure 3 shows phase diffusion as a function of ϕ_0 for constant ε (constant ac field). Small detunings of the ac field with respect to the free-running beatnote (measured with the ac field on but strongly detuned) change parameter a in Eq. (2) and lead to corresponding changes in ϕ_0. For a given detuning value, the relative phase was sampled for 10^3 cycles and the Allen variance calculated and plotted. This was repeated for 200 detuning values to build up a three-dimensional phase diffusion picture. Twelve of these data sets were then averaged (see Fig. 3). Both the time and ϕ_0 dependence are clearly visible in the figure. Fitting an equation of the form of (4a) yields a value $\varepsilon = 0.319 \pm 0.121$.

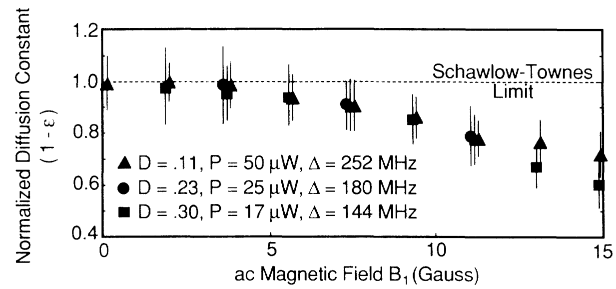

FIG. 4. Noise quenching in the CEL vs ac field strength. Data are normalized to the measured free-running diffusion constant (D). P is the laser output power per mode and Δ is the $\Delta m = 2$ Zeeman splitting.

Figure 4 shows the results of setting $\phi_0 = 0$ and varying the ac field strength. In this part, each data run consisted of measuring the phase for 10^4 cycles with the field on (CEL) and then with the field off (free run). A diffusion constant for each was calculated and a normalized diffusion constant was computed by normalizing the CEL result by the free-running result. 50 to 100 of these normalized values were then averaged together for each data point shown in the figure. Data were taken under several conditions, with different values of free-running diffusion constant, laser output power, and Zeeman splitting. Maximum noise reduction ($\sim 40\%$) was observed for the strongest ac field and the smallest Zeeman splitting.

An issue that arises is whether we are really measuring spontaneous-emission noise or simply technical noise. Technical noise is reduced many orders of magnitude by using a common cavity mode for the two transitions. Even so, at long times technical noise must finally dominate due to its t^2 dependence (the signature of frequency flicker, a $1/f$ type of noise in the laser frequency[12]). Figure 5 shows the phase noise of a free-running laser

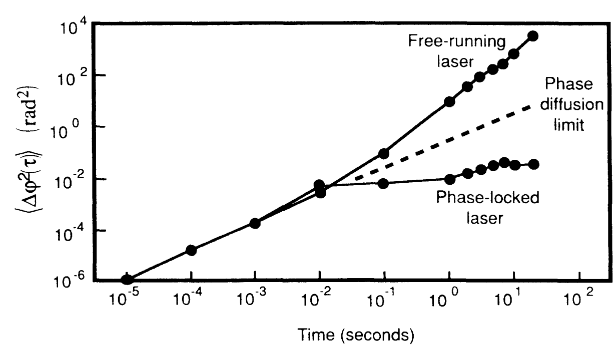

FIG. 5. Phase noise vs time for a free-running laser and a PLL. Pure quantum phase diffusion is evident in both up to 10 ms where the free-running laser starts to show the effects of technical noise and phase locking becomes effective in the PLL. Technical noise increases PLL variance slightly beyond 1 s.

and a PLL from 10 μs to 20 s. The transition from phase diffusion to frequency flicker occurs at about 10 ms in the free-running laser, conveniently similar to the time at which the phase locking begins to control the phase evolution of the PLL. At times less than 10 ms, the behavior of the two lasers is the same. The signature of the CEL would be a downward shift of the entire PLL curve, but for several reasons the effect is too small to be seen here.

Thus we see that the measured noise has the correct time dependence. We can also estimate a diffusion constant for our laser using Eq. (1). Some care must be taken when measuring the cavity linewidth because it should be done without any gain medium, but simply turning off the laser and scanning over the cavity resonance with a second laser is unsatisfactory due to possible thermally induced alignment (and hence loss) differences. We used a second HeNe laser, filled with a different isotope of Ne (^{22}Ne), to scan over a cavity resonance two orders (1100 MHz) from the one used by the Zeeman laser, thus probing just outside the gain curve. We measured $\Delta\nu_{\rm cav}=570\pm26$ kHz and $P_{\rm laser}=41\pm2$ μW per mode, resulting in $D=0.082\pm0.008$ rad/s for the beatnote. This agrees quite well with the measured diffusion rate $D=0.083\pm0.008$ rad/s taken under the same conditions.

To summarize, we have measured noise reduction 40% below the Schawlow-Townes limit in a HeNe laser due to the CEL effect. This noise reduction is in the relative phase of a two-mode laser and has potential implications for the design of optimally sensitive interferometers for gravitational wave detection. The choice may be between a passive interferometer utilizing squeezed light or an active interferometer with a CEL.

We would like to thank G. Agarwal, C. Benkert, J. Bergou, M. Orszag, W. Schleich, and M. O. Scully for many useful discussions. Dr. B. Petley also must be thanked for his useful refinements during the initial stages of the project. This research has been supported in part by the National Institute for Standards and Technology under its program of research into possible techniques for precise measurement, and in part by the Office of Naval Research and the National Science Foundation.

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