Sub-Shot-Noise laser Doppler Anemometry with Amplitude-Squeezed Light

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(Received 21 October 1996)

Amplitude-squeezed light from a quantum-well semiconductor laser with weak optical feedback from a highly dispersive grating is employed for laser Doppler anemometry. Up to 2 dB noise reduction below the shot-noise level is observed with a feedback factor of 1.5×10^{-4}. Enhanced sensitivity is demonstrated in the Doppler measurement of a gas flow velocity with an improvement in the signal to noise ratio of 1.0 dB above the shot-noise limit. [S0031-9007(97)02955-4]

PACS numbers: 42.50.Dv, 42.55.Px, 42.62.Fi

In recent years, squeezed light exhibiting fluctuations below the standard quantum limit (SQL) in one quadrature amplitude or in the amplitude of the field has been shown to enable precision measurements with sensitivities beyond the SQL [1–4]. Quadrature squeezed states of light, characterized by reduction of the mean square fluctuation in one quadrature component of the field below that of the vacuum state, have been used to improve the precision of shot-noise limited measurements of weak absorption [2] and in interferometry [3]. A frequency-tunable squeezed light source has been used to demonstrate improvement in the sensitivity of the saturation spectroscopy of atomic cesium [4] and to demonstrate fundamental phenomena in the atom-photon interaction [5]. Amplitude-squeezed states of light, featuring photon number fluctuations below those of Poissonian statistics, have been generated from semiconductor lasers [6–8], and have been recently used for nonlinear spectroscopy and dark fringe interferometry [9]. Low noise amplification has also been demonstrated using sub-Poissonian light generated by semiconductor junction light emitters [10].

In this Letter, we demonstrate the application of amplitude-squeezed light to laser Doppler anemometry with consequent improvement in the sensitivity of velocity measurements above the shot-noise limit. The amplitude-squeezed light was produced from a cooled quantum-well semiconductor laser with weak grating feedback of $\sim 10^{-3}$–10^{-4}. Up to 2 dB of photon number squeezing was observed. We have utilized this squeezed light source to achieve an improvement in sensitivity of 1.0 dB beyond the shot-noise limit for the heterodyne detection of Doppler-shifted light scattered from a gas flow containing smoke particles.

The laser Doppler technique has been widely used in laser Doppler anemometry (LDA), laser radar (LIDAR), and in light scattering measurements where an intense coherent light source is required [11,12]. Laser Doppler anemometry is a precise optical technique for the measurement of velocity based on the determination of the Doppler shift of light scattered from moving particles. The LDA technique has been employed to measure the velocity distribution of cold atoms trapped in an "optical molasses" [13] and in molecular scattering. The small Doppler frequency shifts in the weakly scattered light may be detected by an optical heterodyne technique using a reference laser beam. The velocity and density of moving particles in a fluid can be obtained from the beat frequency and beat amplitude. For the experimental arrangement shown in Fig. 1, the Doppler shift of the scattered light (dashed line directed to the detector) is given by [12]

$$\nu_D = (n/\lambda)\mathbf{u} \cdot (\mathbf{k}_s - \mathbf{k}_0) = (2nu/\lambda)\sin(\alpha/2), \quad (1)$$

with n the index of refraction of the flow medium, $\mathbf{u}$ the velocity vector of the flow with amplitude u, λ the wavelength of the laser beam, $\mathbf{k}_0$ and $\mathbf{k}_s$ the unit vectors in the directions of the illuminating and scattering (reference) beams, respectively, and α the angle between them.

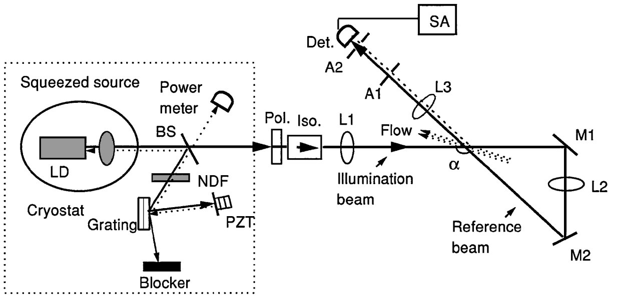

FIG. 1. Experimental setup. Squeezed source: LD—laser diode; BS—beam splitter with 94% transmission; NDF—neutral density filter; Pol.—polarizer; Iso.—optical isolators; L1, L2, L3—optical lenses; PZT—PZT-controlled mirror; M1, M2—mirrors; A1, A2—apertures. The laser beam from the squeezed source passes through a gas flow twice at an angle of α. The scattered light and the transmitted reference beam are collected by a large area pin photodetector (Det.) and the output photocurrent is amplified, and fed into a spectrum analyzer (SA).

The fundamental limitation to sensitivity of this reference beam technique is the shot noise arising from the reference laser beam [12]. The light received by the photodetector comprises a strong local oscillator (reference beam) component and a much weaker Doppler-shifted (scattered light) component. The photocurrent is $i(t) \approx \eta e[I_{l0} + 2(I_{l0} I_s)^{1/2} \cos(2\pi \nu_D t)]$, where η is the quantum efficiency of the photodetector, and I_{l0} and I_s are the photon number fluxes (intercepted by the detector per unit time) of the reference and scattered beams, respectively. The mean square heterodyne signal current at frequency ν_D is then given by $\langle i_s^2 \rangle = 2e^2 \eta^2 I_s I_{l0}$ and the mean square noise current by $\langle i_n^2 \rangle = 2e^2 \eta I_{l0} B F_0$ with B the noise bandwidth, and F_0 the Fano factor of the detected reference beam. The signal to noise ratio is then given by

$$\langle i_s^2 \rangle / \langle i_n^2 \rangle = \eta I_s / B F_0 \,. \tag{2}$$

It is apparent from Eq. (2) that an amplitude-squeezed reference beam (with $F_0 < 1$) leads to enhanced sensitivity of Doppler velocity measurements relative to shot-noise limited measurements (with $F_0 = 1$). The signal to noise ratio of Eq. (2) may be written as an upper limit of $2\eta\langle n_s \rangle / F_0$, where $\eta\langle n_s \rangle$ is the integrated photon count in a matched filter measurement. In our experiment shown in Fig. 1, both the illumination and reference beams come from an amplitude-squeezed laser source and intersect with a gas flow containing a cloud of smoke particles. The intensity of the weakly scattered light is proportional to the intensity of the illuminating beam, that is, $I_s = \beta I_{l0}$, where β is a scattering parameter. Therefore, for a given β, we can improve the signal to noise ratio by employing a photon-number squeezed reference beam as well as by increasing the optical power of the illumination beam. This sub-shot noise, weak scattering laser Doppler technique is therefore potentially valuable in situations where upper limits on permissible illumination intensities exist and where high precision is required, as in medical applications, atomic and molecular scattering, and nondestructive laser measurements generally.

When the total light scattering is very weak (corresponding to an optically thin medium), the optical loss is correspondingly small (in this experiment, less than 2%) and will not significantly degrade the squeezing of the reference beam. This is the basis of this new technique. A similar principle has been demonstrated in absorption spectroscopy with squeezed light [5,9], where the photon losses are also negligibly small. A typical heterodyne spectrum is given in Fig. 2. In the absence of scattering particles, the noise power of the reference beam (from 0.3 to 1.5 MHz) is found to be 1.0 dB below the shot-noise level [Fig. 2(a)], set by a red-filtered white light reference source and balanced detectors [7,8]. The heterodyne signal due to Doppler-shifted light scattered from smoke particles is shown in Fig. 2(b), where the signal to noise ratio is 1.0 dB above the shot-noise limit. The Doppler shift signal at 0.6 MHz corresponds to a flow velocity of 267 mm/s from Eq. (1) with $\lambda = 770$ nm, $n = 1.0$, and $\alpha = 120°$.

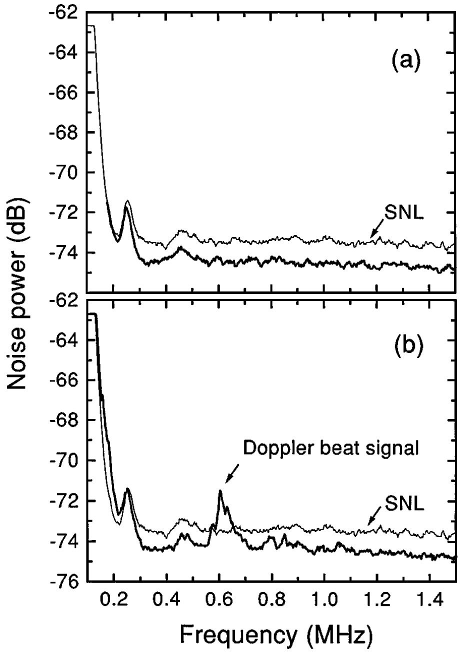

FIG. 2. Measured noise spectral densities for the transmitted reference beam with a dc detector current of 10.0 mA for (a) the gas flow free of scattering particles and (b) the gas flow containing smoke particles. The Doppler beat signal at 0.6 MHz corresponds to a flow velocity of 267 mm/s. The signal to noise ratio is improved by 1.0 dB above the usual shot-noise limit.

The experimental arrangement in Fig. 1 is a typical reference beam heterodyning configuration for laser Doppler measurements [12]. The amplitude-squeezed laser beam from the squeezed source (about 25 mW at 770 nm) passes through a polarizer (extinction ratio $>10^4$:1) and two optical isolators (total isolation ratio >60 dB), and is then focused by lens L1 (with $f = 75$ mm) onto the flow; this focused light acts as the illumination beam. The transmitted laser beam, which serves as the reference beam, is collected and focused by lens L2 (with $f = 100$ mm). The reference beam is also focused onto the flow but its focus is slightly displaced from that of the illumination beam. This ensures that the effective scattering regions are slightly different for the two beams and so avoids loss of signals by phase decorrelation [12]. The scattered light is focused with the reference beam into an aperture A1 by lens L3 and passes through an aperture A2 in front of a high efficiency pin photodetector (Hamamatsu S3994). The ac part of the photodetector current is amplified and fed into a spectrum analyzer. The aperture A1 is used to ensure that only light coming from or passing through the desired region reaches the detector.

The squeezed laser source used in our experiment was a quantum-well AlGaAs semiconductor laser with weak optical feedback from a grating in a Littman-Metcalf configuration, as shown in Fig. 1. The laser diode (SDL-5411-G1) and collimation lens were cooled down to 80 K inside a liquid nitrogen cryostat. Because of the presence of multiple subthreshold longitudinal side modes in the laser diode [14], some line-narrowing techniques such as injection locking or optical feedback from an external grating must be used in order to obtain amplitude squeezing [7,8]. In our experiment, we used a beam splitter BS (with a transmission of 94%) to reflect a small portion of the laser beam to a grating (1800 lines/mm). The first-order diffraction beam was reflected and fed back to the laser diode by a piezoelectric-translator-controlled mirror. A power meter behind the beam splitter was used to measure the feedback intensity. The maximum feedback intensity was a fraction (1.2×10^{-3}) of the output power of the laser diode. Sine the feedback beam passes the grating twice, the external cavity in this configuration is highly dispersive and therefore is effective in suppressing longitudinal side modes. This configuration keeps the advantages of low optical loss for the squeezed light output and provides frequency tunability [15]. The threshold current (3.5 mA at 80 K) was not changed significantly by this weak grating feedback. The linewidth of the single-mode laser with this configuration is estimated to be below 1.0 MHz [15], which corresponds to a coherence length of a few tens of meters, much larger than the optical path difference between illumination and reference beams in Fig. 1.

Curve *b* in Fig. 3(a) shows the measured noise power spectral density for the laser beam from the squeezed source (without the polarizer and optical isolators), with the laser diode biased at 26.7 mA giving a corresponding photodetector current of 12.0 mA. Curve *a* is the shot-noise level with the same photodetector current. The shot-noise level (SNL) was set by a red-filtered white light source. In order to decrease the effect of detector saturation in calibration of the SNL, the large-area (10 mm × 10 mm) pin photodiode was placed far away from the focus of the reference beam at A1 so that the laser beam nearly filled the detector aperture. Care was taken to check the consistency between the SNL in two identical detectors set by two white light sources and the noise calibrated by the balanced detectors with a 50/50 nonpolarizing beam splitter [14]. We found that the noise levels agreed to within 5% for dc detector current up to 15.0 mA per detector for the large beam spot described above. As an additional check, as the laser beam was attenuated 50% by using a neutral density filter, the squeezing level (2.0 dB) was reduced by 50% (curve *d* related to the SNL of curve *c*) after correction for the amplifier noise level (curve *e*). When the polarizer and optical isolators were inserted, the squeezing was degraded to about 1.0 dB as shown in Fig. 2(a) due to the additional optical losses and the interference between the main polarization component and small perpendicular polarization component [7,14].

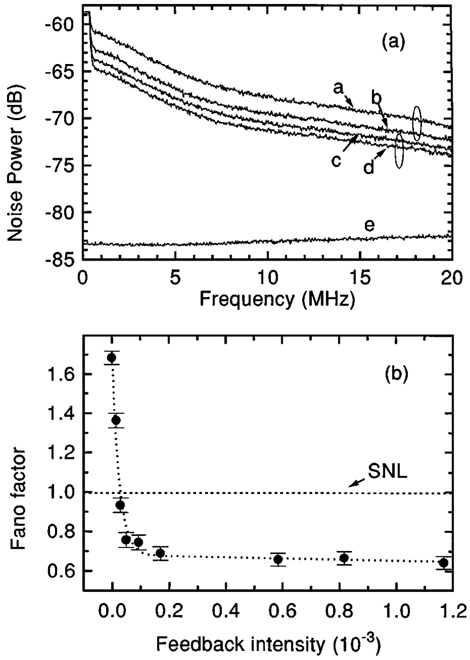

FIG. 3. (a) Measured noise power spectral densities for the output beam of the squeezed source. Curve *a* and curve *c* are the shot-noise levels with dc detector currents of 12.0 and 6.0 mA, respectively. Curve *b* is for the output beam with a 12.0 mA detector current and curve *d* is for 50% attenuated output beam. Curve *e* is for the amplifier noise level. (b) Measured Fano factor at 10.0 MHz at different feedback intensities with a 12.0 mA detector current.

The gas flow used in the experimental comprised high pressure clean nitrogen gas passing through a small chamber containing a smoke generator. As the smoke passed through the intersection region of the illumination and reference beams, the photodetector current decreased by less than 2%. In order to eliminate possible feedback of scattered light into the squeezed source, we inserted a polarizer and two optical isolators between the squeezed source and scattering region. The optical feedback due to light scattering by the gas flow was then less than 10^{-8}. Thus, the optical feedback into the laser diode was dominated by the grating feedback which was set at the maximum feedback intensity ($\sim 1.2 \times 10^{-3}$). Figure 4 shows Doppler shift signals at different nitrogen gas pressures. The flow velocities of 324, 267, and 195 mm/s were inferred from the observed Doppler shift signals in Figs. 4(a)–4(c), respectively. The detection sensitivities for Doppler signal measurements were clearly above the shot-noise level. The linewidth of the Doppler beat signal was limited by transit time, resolution bandwidth of the spectrum analyzer, and turbulence of the gas flow.

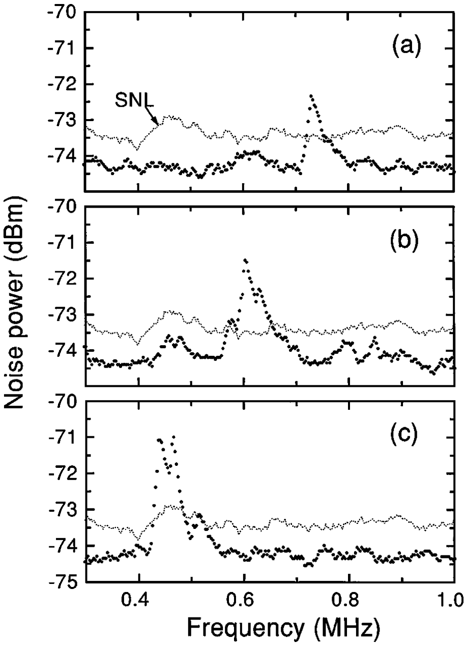

FIG. 4. Measured Doppler shift signals at different nitrogen gas pressures. The flow velocities were inferred to be (a) 324 mm/s, (b) 267 mm/s, and (c) 195 mm/s. The dc detector current is 10.0 mA. The light dotted curves are for the shot-noise levels. The spectrum analyzer was set with a resolution bandwidth of 30 kHz, a video bandwidth of 100 Hz, and a scan time of 2.0 s.

In summary, we have described and demonstrated a new sub-shot-noise laser Doppler technique, an application of squeezed light quite distinct from the interferometric and spectroscopic applications previously reported. A wideband amplitude-squeezed light source from a quantum-well semiconductor laser with weak grating feedback was employed for laser Doppler velocity measurements. Improvements in measurement sensitivity of 1.0 dB beyond the usual shot-noise limit have been directly observed. By using highly squeezed laser sources [6] or highly correlated twin beams [16,17] in a two-channel reference beam configuration, the measurement sensitivity for laser Doppler measurements could be improved to make this technique useful in practice. This sub-shot-noise laser Doppler technique is also suitable for making velocity distribution measurements of relatively small ensembles of scattering particles, such as cold atoms [13], trapped ions, or biologically active molecules.

The authors acknowledge financial support from the Australian Research Council, the Australia Commonwealth Department of Education, Employment and Training, and the University of Canberra.

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