Wideband noise characteristics of a lead-salt diode laser: possibility of quantum noise limited TDLAS performance

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The wideband noise characteristics of a PbEuSe molecular beam epitaxy diode laser have been measured up to 500 MHz. The cutoff of the frequency dependent (1/*f* type) laser noise contribution was found to be 170 MHz for this particular laser. Above this cutoff frequency the photon shot noise dominates, as was demonstrated. A noise reduction of more than 2 orders of magnitude was observed in the shot noise limited domain when compared with the 1/*f* noise dominated region below 1 MHz. This finding indicates that a similar 2 orders of magnitude sensitivity improvement can be achieved in tunable diode laser absorption spectroscopy when frequency modulation techniques are applied instead of the more conventional derivative modulation below 1 MHz.

I. Introduction

Lead-salt diode lasers emitting in the mid-infrared region have become increasingly important for high sensitivity absorption spectroscopy,[1,2] particularly in the monitoring of atmospheric trace gases.[3,4] In most of the tunable diode laser absorption spectrometers (TDLAS) a conventional derivative modulation technique has been used leading to an optical density detection limit of the order of 10^{-5} with spectra averaged over a few seconds.[3,5] Although this sensitivity is adequate for many uses, monitoring of some trace gases in clean air requires still higher sensitivity or detection speed. In attempting to improve the sensitivity and the detection speed of the present TDLAS instruments, the application of frequency modulation (FM) techniques has attracted increasing attention.[6–11]

Frequency modulation is a relatively new spectroscopic technique[12] that permits quantum limited sensitivity to be attained.[13] To achieve this ultimate sensitivity limit, the modulation frequency has to be selected sufficiently high, i.e., beyond the cutoff of the laser source noise. Both the amplitude and the frequency characteristics of this excess noise depend on the laser used.

The noise characteristics of a ring dye laser operated in the visible region were reported by Hall *et al.*[14] They found a noise reduction of more than 80 dB at modulation frequencies beyond 2 MHz when compared with a low frequency of 10 kHz. In appropriate experimental conditions, this noise reduction translates into an increased detection sensitivity of 10^4. Wong and Hall[15] demonstrated the quantum limited performance of a He–Ne laser absorption spectrometer with external modulation by an electrooptic modulator. Also, with the near-infrared GaAlAs laser diodes, frequency modulated by injection current modulation,[16–18] near quantum limited sensitivity could be achieved at modulation frequencies around 250 MHz.[19]

However, for most of the atmospheric species lead-salt tunable diode lasers emitting in the 3–30-μm region have to be used. For this type of laser, Gehrtz *et al.*[6] demonstrated that FM can also be achieved by directly modulating the injection current. So far, little is known about the noise characteristics of the lead-salt diode lasers and, therefore, the potential sensitivity improvement using FM techniques is uncertain. Previous work[20] was limited to a low frequency region up to 200 kHz which is not sufficient to evaluate the potential sensitivity improvement by going to modulation frequencies of the order of hundreds of megahertz.

In this work we report on wideband noise measurements up to a frequency of 500 MHz with a lead-salt diode laser. We identify the laser source cutoff frequency and demonstrate that the noise with frequencies above this cutoff is dominated by the fundamental

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photon shot noise. The noise reduction in this quantum limited regime relative to that of the presently used low modulation frequencies is evaluated. The measurements indicate that the detection sensitivity can be improved by more than a factor of 100 using FM instead of the common derivative technique.

II. Noise Considerations

The sensitivity of a spectrometer depends on the achievable signal-to-noise ratio (SNR). If one dissects noise according to its various contributing sources the SNR can be described as

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{(P_{1/f}^2 + P_{sn}^2 + P_{tn}^2)^{1/2}}, \tag{1}$$

The major contributions to noise are the laser source noise, excess noise ($P_{1/f}$) in the detector, the detector shot noise (P_{sn}), and the detector thermal noise (P_{tn}). The laser source noise decreases with increasing frequency and because of this dependence it is often referred to as pink or $1/f$ noise. In contrast, the shot noise and the thermal noise do not depend on frequency and are said to have a white noise spectrum. Since the frequency and laser power dependence are the key for distinguishing the different noise sources, they are discussed here in more detail.

Thermal noise arises from the random velocity fluctuations (Brownian motion) of the charge carriers in a resistive material and it is often referred to as Johnson noise.[21] The rms noise detector current is dependent on the absolute temperature T and is independent of the incident light power[22]:

$$i_{\mathrm{th}}^2 = 4k \frac{T}{R_{\mathrm{eff}}} \Delta f. \tag{2}$$

In this equation k is the Boltzmann constant, Δf is the bandwidth of the measuring equipment, and R_{eff} is the effective detector load resistance.[23]

Shot noise[24] originates from the discrete nature of photoelectron generation in a photodetector. Photons are generally Poisson distributed, and consequently, their random fluctuations are proportional to the square root of the radiation intensity. Taking into account the quantum efficiency η of the detector the rms shot noise detector current is[22]

$$i_{sn}^2 = 2e\overline{i_{dc}}\Delta f, \tag{3}$$

with

$$\overline{i_{dc}} = e\eta \frac{P_{\mathrm{laser}}}{h \cdot \nu},$$

where e is the electron charge, h is Planck's constant, ν is the light frequency, η is the detector quantum efficiency, and P is the incident light power. From this relation, the rms shot noise can be calculated if the incident light power is known.

The physical mechanism that produces $1/f$ noise is not well understood and no generally accepted mechanism for the generation of this noise has been proposed.[25] Several processes, such as contact noise, excess resistor noise, fluctuation of the work function, and laser source noise, may contribute to $1/f$ noise.[22]

An experimentally measured relation for the $1/f$ rms noise detector current is[25]

$$i_{1/f}^2 = c' \frac{i_{dc}^2}{f^b} \Delta f, \tag{4}$$

where c' is a detector constant, i_{dc} is the detector current, and b is typically 1 but can range between 0.8 and 1.5. Relation (4) shows that $1/f$ noise increases with increasing dc bias current. For photovoltaic detectors $1/f$ noise can be reduced by reducing i_{dc}. However, some dc bias current is necessary to achieve high frequency response from such detectors.

The varying dependence of the noise power contributions on dc current and thus on the laser power provides a tool for distinguishing between the different noise sources. While thermal noise is independent of i_{dc}, the shot noise power is proportional to i_{dc}, and the $1/f$ noise power is proportional to i_{dc}^2. Therefore, attenuation of the laser beam intensity by a factor of 2 with a neutral density filter will decrease the source or excess noise level by 6 dB while an observed 3-dB noise reduction will demonstrate shot noise limited operation.

The $1/f$ noise contribution is the main rationale for applying modulation techniques in high sensitivity spectroscopy. Obviously, this contribution can be evaded in frequency space by applying even higher modulation frequencies. At high enough frequencies, the total system noise is no longer dominated by the $1/f$ noise, and the frequency independent thermal and shot noise contributions determine the SNR [Eq. (1)].

The ultimate detection sensitivity is reached in quantum limited conditions, i.e., when $1/f$ noise can be neglected and shot noise is the dominant noise contribution. According to Eqs. (2) and (3), the quantum limited performance requires a minimum radiation power incident on the detector of

$$P_{\mathrm{min}} = \frac{2kThc}{e^2\eta\lambda R_{\mathrm{eff}}}, \tag{5}$$

where c is the velocity of light.

III. Experimental Setup

Wideband noise characteristics were investigated in the frequency range from 5 to 500 MHz using a PbEuSn MBE laser made at the Fraunhofer Institute for Metrology.[26] The experimental setup is shown in Fig. 1. The laser was mounted in a liquid N_2 cooled Dewar and operated at 1538 cm^{-1} using a current of 563 mA and a temperature of 85 K. The laser current was chosen to be far above the threshold of 200 mA to reduce excess noise due to spontaneous emission and to obtain higher optical output power. The laser power was determined by focusing the laser output by an $f/1.5$ BaF_2 lens on an electronically calibrated pyroelectric detector (Rs-5900, Laser Precision Systems) and it was 521 μW. Then an infrared neutral density (ND) filter was inserted in the beam and its optical density was measured to be 0.33.

The noise measurements were made by focusing the unattenuated beam on a reverse-biased photovoltaic

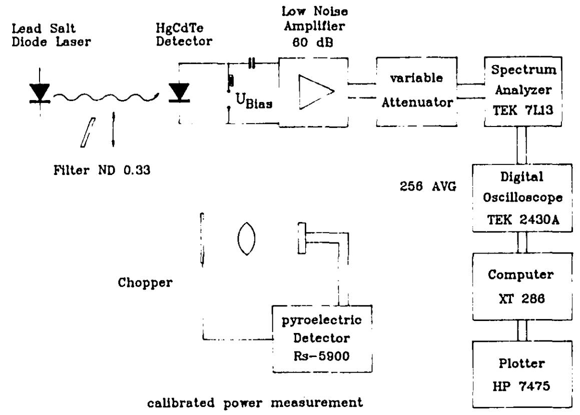

Fig. 1. Experimental setup for the investigation of wideband noise characteristics of lead-salt diode lasers: upper, determination of the noise spectra with and without an attenuator; lower, determination of the laser output power.

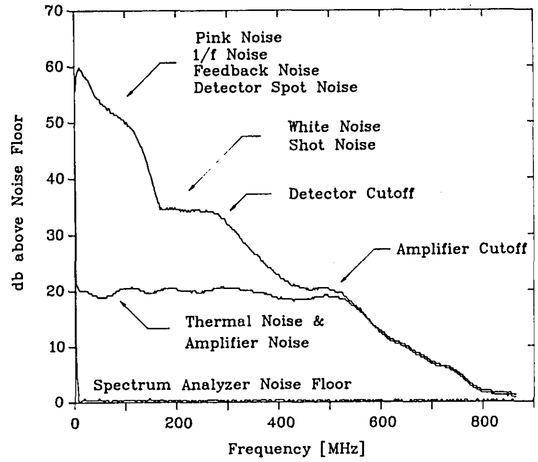

Fig. 2. Typical wideband noise spectrum of a lead-salt diode laser.

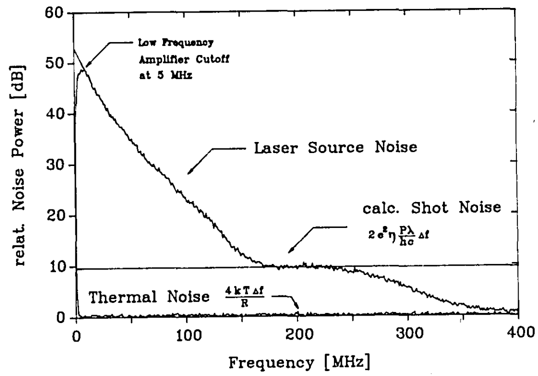

Fig. 3. Lead-salt diode laser noise spectrum measured with a spectrum analyzer with 0.3-MHz bandwidth and averaged over 256 scans. The lower trace shows the thermal noise level of the MCT detector and preamplifier combination determined with the laser switched off. The upper trace shows the noise of the laser without any modulation. The very low frequency part of this trace is linearly extrapolated to dc. The line at 9.3 dB shows the calculated shot noise level above the thermal noise. The potential SNR improvement by moving from low to high frequencies is >40 dB.

mercury cadmium telluride detector (Societé Anonyme de Telecommunication) with a quantum efficiency of 76% and a −3-dB cutoff frequency at 270 MHz. The detector output was amplified by a 60-dB low noise amplifier (Societé Anonyme de Telecommunication) with a 5–500-MHz bandwidth and analyzed by a spectrum analyzer (Tektronix 7L13). The internal calibration of the spectrum analyzer was checked by an external precision attenuator (JFW Industries). To achieve a readout accuracy of 0.1 dB, the output of the spectrum analyzer was averaged 256 times by a digital oscilloscope (Tektronix 2430A). The averaged noise spectra were transmitted to a computer for further data processing.

Great care was taken to prevent rf pickup from fm radio stations by suitable shielding and grounding of the whole setup. In the optical path of the setup two off-axis parabolas were used to collimate the laser output and to focus the beam on the detector. Reflective optics were selected to minimize feedback from the surfaces of optical components. But two BaF_2 windows at the laser and detector Dewars could not be avoided. Optical feedback noise appeared when a neutral density filter was inserted in the laser beam. This feedback could be reduced by proper adjustment of the filter.

IV. Results and Discussion

A typical wideband noise spectrum of the lead-salt diode laser shown in Fig. 2 illustrates the different noise contributions. From 5 to ~170 MHz the $1/f$ noise rendered the dominating noise contribution. This noise is attributed to intrinsic laser noise and detector excess noise as described in Sec. II. In addition, other pink noise components were observed: feedback noise due to reflections of radiation back in the laser crystal and detector spot noise due to vibration induced movements of the beam focus over the inhomogeneous detector surface. They could be reduced by suitable optical adjustment. Above 170 MHz the shot noise dominated up to ~270 MHz, the cutoff frequency of the detector. Above 270 MHz the noise was attenuated by the detector rolloff and above 500 MHz additionally by the detector preamplifier cutoff. With the laser switched off the thermal noise was not frequency dependent up to the preamplifier cutoff.

A noise spectrum with proper optical alignment is shown in Fig. 3. The frequency dependence of the detector/preamplifier combination thermal noise was recorded with the laser off (no light). Then the laser was turned on (light on) and the steplike spectrum with the pink and the white noise components was acquired. In addition to the frequency cutoff of the detector the spectrum shows the low frequency preamplifier cutoff at 5 MHz. The noise spectrum became white (frequency independent) around 170 MHz at 9.5 dB above thermal noise. This value will now be compared to the calculated relative shot noise level. According to Nyquist's theorem[27] only ohmic elements contribute to the Johnson noise current. Thus the effective amplifier input resistance of 180 Ω has to be used instead of the nominal 50-Ω high frequency impedance. With an effective load resistor temperature of 288 K the shot noise level above the thermal noise was then calculated:

$$\frac{P_{sn} + P_{th}}{P_{th}} = \frac{e^2 \eta \lambda P R_{\text{eff}}}{2khcT} + 1 = 9.3 \text{ dB}. \qquad (6)$$

This result is in excellent agreement with the actually measured value, which was 9.5 dB (Fig. 4), indicating that the dominant noise contribution is indeed the quantum shot noise. Note that the optical power of 521 μW used in this experiment by far exceeds the minimum power of 67 μW [as calculated from Eq. (5)] necessary to achieve quantum limited performance.

The above conclusion is further corroborated by a series of noise level measurements at attenuated laser power as shown in Fig. 4. Great care was exercised to calibrate the spectrum analyzer with external attenuators and frequency markers. For the noise level measurements a light on noise spectrum was first recorded at full laser power (521 μW). Then a neutral density filter was inserted in the laser beam to reduce the incident optical power by 3.3 dB corresponding to the measured optical density of 0.33. The reduced signal is displayed as the middle trace in Fig. 4. The measured attenuation in the white noise region from 170 to 240 MHz was 3.2 dB, in excellent agreement with the value of 3.3 dB expected for the shot noise dominated regime.[28] The authors want to point out that the shot noise limited frequency domain depends on laser and detector parameters. With different laser structures, increasing laser power, higher detector quantum efficiency, different detector bias current, and less contact noise, other quantum limited regions can be found and used for FM spectroscopy.

The measurements of both the noise levels and the laser power dependence clearly demonstrate that the frequency domain above 170 MHz is a shot noise limited regime. Thus an ultimate quantum limited sensitivity in a frequency modulated TDLAS system is expected at frequencies in this domain. In connection with the current discussion of the merits of different frequency modulation schemes,[9–11] we would like to point out that the quantum limitation constitutes a fundamental sensitivity limit. In theory, therefore, the ultimate sensitivity of frequency modulated TDLAS instruments should be the same regardless of the specific FM technique used.

In addition, the noise measurements shown in Fig. 3 demonstrate a considerable noise reduction of more than 40 dB in going from the low frequency region below 1 MHz (used in the present derivative TDLAS systems) to the high frequency region beyond 170 MHz. This noise reduction is smaller than the noise reduction of more than 80 dB reported by Hall *et al.*[14] for a ring dye laser running at 300 μW and frequency shift from 10 kHz to the ~$1/f$ noise cutoff of 2 MHz. The $1/f$ noise cutoff frequency of our Pb-salt laser diode is much higher, and presumably such a high cutoff could be the reason for the Eng *et al.*[20] observa-

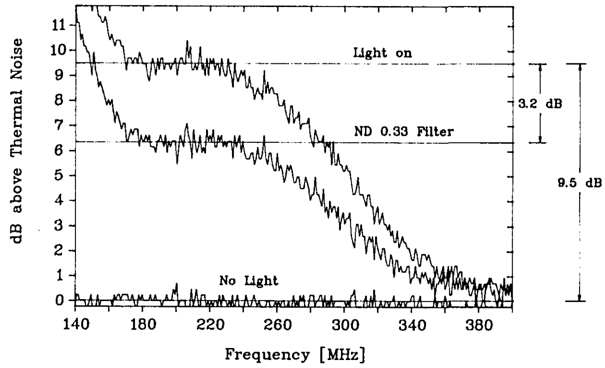

Fig. 4. Noise spectra of the same diode laser at the same operating conditions as in Fig. 3. Additionally, the noise reduction by 0.33 attenuation of the incident laser power is shown indicating the shot noise limited regime above 170 MHz.

tion of an apparently flat noise spectrum for their Pb-salt laser in the 4–200-kHz frequency range.

The noise reduction of 40 dB when the FM technique is used in the quantum limited frequency domain implies that the detection sensitivity of the present derivative TDLAS systems could theoretically be improved by more than a factor of 100. In reality, side effects such as etalon formation, pick up of high frequencies, and residual amplitude modulation (RAM) may reduce the potential sensitivity improvement. However, techniques[2] are available to cope with these problems and by applying them the ultimate sensitivity can probably be approached. Work is in progress in our laboratory to demonstrate the improved performance of a FM TDLAS system directly by measuring atmospheric trace species.

V. Conclusions

The wideband noise characteristics of a PbEuSe laser diode have been measured up to 500 MHz. At frequencies below 170 MHz, $1/f$ type noise dominated and at very low frequencies (5 MHz) it was ~40 dB above thermal noise. Above 170 MHz on the other hand, the noise was dominated by photon shot noise. This important conclusion was inferred from careful independent measurement of the noise level and of the laser power dependence. With 521 μW of incident laser power the shot noise was 9.5 dB above thermal noise and, consequently, by shifting from the very low frequencies to the shot noise limited frequency regime the noise can be reduced by more than 40 dB. These results indicate that the sensitivity of the present TDLAS instruments operated below 1 MHz can be improved by more than a factor of 100 when frequency modulation at frequencies above 170 MHz is used and when etalon effects, RAM, and other possible side effects are effectively suppressed. Such sensitivity improvements open new prospects for the construction of faster and cheaper TDLAS instruments.

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28. The expected 6-dB noise reduction in the $1/f$ region is not seen due to attenuator induced feedback noise adding to the expected 6-dB reduction.

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John told me that in Chapter 1 of his autobiography he compares the account of the Creation given in Genesis with that described as the Big Bang theory. I asked whether he had seen the concise account of the Big Bang given in a recent issue of *Modern Maturity*, a publication of the American Association of Retired Persons. He said he had seen it and had phoned several of his astronomy colleagues to inquire what the present status of the theory was. One replied, "The Hubble Constant isn't constant any more." Another said, "Even *space* is expanding." John decided to hold fast to the classic Big Bang with the remark that, "Anything that is good enough for the AARP is good enough for me!"