Laser Noise Measurements and Observation of Amplitude Squeezing in an Extended Cavity Diode Laser

F.C. Cruz, R.L. Cavasso-Filho, A.S.S. Siqueira, D.A. Manoel,
E.M. Telles, A. Scalabrin and D. Pereira
Instituto de Física "Gleb Wataghin"
Universidade Estadual de Campinas, CP.6165, Campinas, SP, 13083-970, Brazil

Recebido em 28 Outubro, 1999

We describe an experimental setup for measuring the power spectral density of amplitude and frequency noise of lasers. Results are given for an index-guided quantum well diode laser, operating at 850 nm. We show that this laser, when used at room temperature with optical feedback from a grating, exibits a reduction of the amplitude noise below the standard quantum limit.

I Introduction

The random fluctuations of the frequency (or phase) and amplitude of the electromagnetic field of a laser can play an important role in many applications of such light sources. In particular, the frequency and intensity noise of a monochromatic and tunable continuous wave (cw) laser can have a direct effect on the resolution and sensitivity that can be achieved in spectroscopy. In general, the effects of laser noise are undesirable and noise should often be controlled or reduced to acceptable levels. The knowledge of its power spectral density provides the basis for projecting servo systems that can reduce the frequency or amplitude fluctuations eventually down to the standard quantum limit (SQL) or shot-noise level.

Frequency stable lasers are also important for wavelength-division multiplexing (WDM) in optical communications [1] and are crucial elements in the development of atomic frequency standards [2] and particularly optical ones [3], where frequencies on the order of 10^{15} Hz are locked to supernarrow atomic transitions. They can also be used for precise measurements of energy differences, or frequency intervals, which can make possible very precise and accurate determination of many atomic quantities, such as Lamb shift, hyperfine constants, isotopic shifts, Landè factors, etc. On the other hand, intensity stable lasers are important also for high sensitivity trace gas detection [4], tests of the symmetrization postulate [5], optical communication [1], gravity waves detection [6] and optical interferometry [7].

In this paper we describe a setup that can be used to measure the spectral distribution of amplitude modulation (AM) or frequency modulation (FM) noise of a laser. From such measurements one can estimate the laser linewidth or choose the best modulation frequencies to be used for phase sensitive detection in FM spectroscopy [8]. In particular, this noise measurement setup will help us to project a servo system that will be used to frequency stabilize a diode or a dye laser for use in an optical frequency standard based on the high Q (10^{12}) intercombination transition of Calcium atoms, at 657 nm (10^{15}Hz) [9]. This laser should have a frequency instability on the order of the atomic transition linewidth (400 Hz) in an observation time of a few seconds. Neutral Calcium can also be laser cooled and trapped using a frequency doubled diode laser [10], tuned to the strong recycling $^1S_0$-$^1P_1$ transition at 423 nm. Our noise measurement results will be presented for this laser. It is a low threshold (18mA under optical feedback) index-guided quantum well diode laser (SDL-5422-H1), that can be operated with an injection current up to 200 mA and output powers up to 160 mW. It can be temperature tuned from nearly 845 to 860 nm, and therefore is also suitable for exciting the Cesium D_2 cooling transition, at 852 nm [11]. We show that this laser can be "amplitude squeezed", or have its amplitude noise reduced below the SQL [12], when it is used with optical feedback from an extended cavity. This opens the possibility of using this squeezed light source for spectroscopy with higher signal-to-noise ratio [13] and sub-shot-noise spectroscopy [14].

II Experimental Details

Fig. 1a shows the simplest setup for measuring the amplitude noise of a laser. The laser radiation is focused in the active area of a fast photodiode, which then converts light into electron current. It is important to avoid saturation of the photodiode by laser power. The photocurrent can then be converted to voltage and then amplified. The amplifier should be wideband and low noise, with a noise floor below the noise of the laser. We will use the term photodetector to designate the photodiode followed by the amplifier. The bandwidth, or frequency response, of the photodetector will be limited either by the bandwidth of the photodiode or the amplifier. In the ideal case, a 100% efficiency detector converts each photon into one electron. In practice this does not happen, although it is possible today to find commercial photodiodes approaching unity detection efficiency, for some wavelength ranges [15]. The time dependent fluctuations in the photocurrent, or in the amplified voltage, representing the intensity noise in the light field, are then AC coupled into a spectrum analyser, which then gives their Fourier transform.

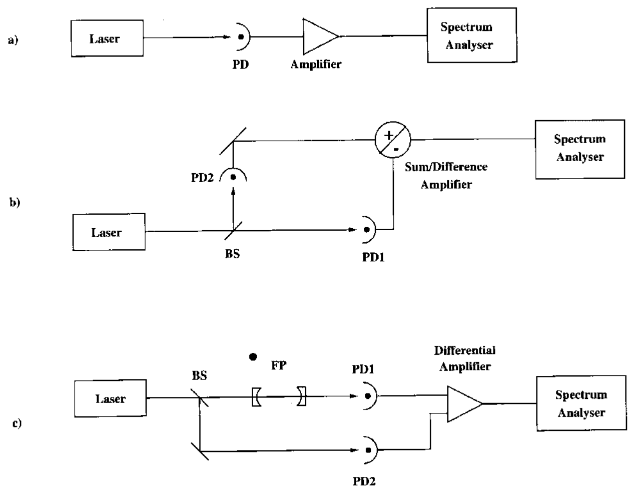

Figura 1. a) Experimental setup for measuring the amplitude or intensity noise of a laser b) Balanced Homodyne Detector. The photodetectors have a quantum efficiency of 90% at 850 nm (EG&G FND100) and the amplifier is the AD829, used as described in the text. c) Setup for measuring the frequency noise of a laser. The Fabry-Perot cavity acts as a discriminator which converts frequency into intensity fluctuations. PD: photodetector; BS: beamsplitter.

The noise spectrum of a laser usually has a 1/f behaviour, with large excess or technical noise at low frequencies, caused by environmental factors such as mechanical vibrations, electrical noise and/or thermal and pressure fluctuations. The technical noise can have discrete and high amplitude features at particular frequencies, that eventually can be identified and tracked back to their sources. For example, some electrical noise into a diode laser power supply, say at 60 Hz and harmonics, may show up in the intensity of the laser, and eventually can be eliminated after the source is identified. The fundamental noise of a laser comes from the random character of the spontaneous emission and can not be eliminated. This noise is white and is known as the standard quantum limit or the shot noise level [12]. Since the amplitude of technical noise decreases with increasing Fourier frequencies, all lasers, when operated far above threshold, tend to be shot noise limited at high Fourier frequencies, although what we call "high" will depend on the particular laser.

For a given output power, in order to determine how noisy a particular laser is at some Fourier frequency, we should determine the shot noise level for that specific power level. A reliable measurement of the shot noise level may not be easy. One method that can be employed is to use a shot-noise limited source to calibrate the shot noise level. As actual examples, one can use a battery operated LED or even a flashlamp, that illuminates the photodetector with the same optical power as the laser under investigation. Therefore a great care has to be taken in order to guarantee that both the laser and the shot noise source give the same electron current (DC level) in the photodetector. In addition, since the spectral profile of the laser and the shot noise source are not the same, and photodetectors have a frequency response, very often spectral filters are employed to narrow the bandwidth of the shot noise source, but even in this case we may argue that the shot noise source is not spectrally equivalent to the laser, and therefore the photocurrent spectral distributions will be different. Another method for measuring the laser noise, and specially the shot noise level, employs what is known as a balanced homodyne detector [12, 16], shown in Fig. 1b. In this case, the shot noise level is determined from the laser itself. Our homodyne detector consists of a 50% beamsplitter, two high efficiency detectors and a low noise amplifier that can sum or subtract the two photocurrents. We have used photodiodes with a quantum efficiency of 90% at 850 nm (EG&G FND100) and a low noise video operational amplifier (AD829) with a 3dB frequency of 50 MHz (at a gain of 20). The sum signal represents the laser noise, while the difference signal represents the shot noise level. For the difference signal, the technical noise, which is correlated at both detectors, is canceled, while the uncorrelated shot noise is not. The homodyne detector provides, in principle, a more reliable determination of the shot noise level, although great care has to be taken in balancing the two arms of the detector. To sum or subtract the signal from both photodiodes, we used an arrangement where we can switch the polarity of one of the photodiodes, together with its bias voltage. However a simpler option would be to use both photodiodes in series, and connecting the amplifier input between them. This would give the difference signal (shot noise) [16]. In this case, the sum signal (laser noise) can be measured by using either photodiode, detecting 50% of the laser power, and then multiplying the noise by a factor of two, which would give a 3dB difference in the spectrum analyser (HP8562A). We have actually used both configurations above, with equivalent results. To test the cancelation of technical noise of our homodyne detector, we have measured the commom-mode-rejection-ratio (CMRR) of the difference signal by modulating the laser injection current at some RF frequencies. This causes both amplitude and frequency modulation of the laser light. The amplitude modulation is seen by the photodetectors and shows up as a peak in the sum signal with a typical amplitude of 30 dB. We have observed that this peak is suppressed by 25 dB in the difference signal.

We have, in fact, verified that the two methods for measuring the shot noise level are in very good agreement. The determination of the shot noise level is particularly important in the observation of amplitude squeezing, since the amount of noise reduction is tipically only a few dB.

Fig. 1c shows the setup for measuring the FM noise of a laser. It basically employs the same method as in Fig. 1a, except that frequency fluctuations should be converted into intensity (amplitude) fluctuations, since a photodetector is an intensity sensitive device. For this, we use a Fabry-Perot cavity as a frequency-to-amplitude converter. This cavity does not need to have a high finesse and, in fact, low finesse ones are preferable for measuring frequency noise, and linewidths, of non-stabilized lasers. In order to convert frequency fluctuations into amplitude fluctuations, we change the cavity length, with a piezoelectric transducer (PZT), so that the laser is tuned to either side of the cavity resonance, at the half maximum point. In this region, the resonance curve is approximately linear, and we can measure its slope, in Volts/MHz, by looking at the cavity fringe in an oscilloscope and, of course, knowing the free-spectral-range of the cavity. In order to measure pure frequency fluctuations, a reference laser beam is sent to another photodetector (Fig. 1c). The signals from both photodetectors in Fig.1c are then subtracted and sent to the spectrum analyser.

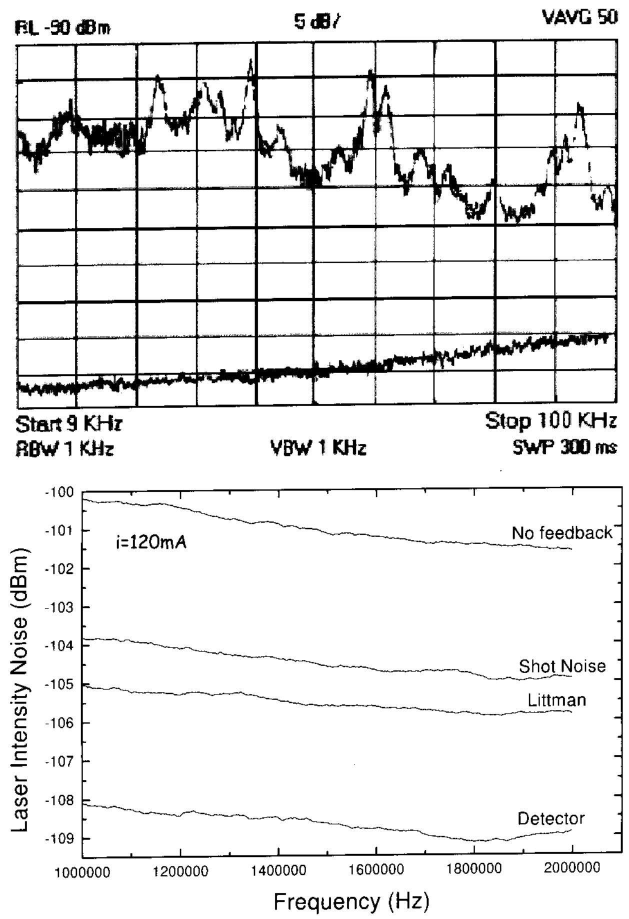

Figura 2. a) Spectral density of FM noise of the SDL-5422-H1 diode laser, from 9 to 100 kHz. Upper trace: laser noise; Lower trace: detector noise. b) Spectral density of AM noise of the SDL-5422-H1 diode laser, from 1 to 2 MHz (resolution bandwidth: 10 kHz; video bandwidth: 10 kHz.). From upper to lower traces: 1) Laser without optical feedback, 2) Shot noise level, 3) Laser under optical feedback in the Littman configuration [17] 4) Detector noise level. We can observe a reduction of the laser noise below the shot noise level when the laser is under optical feedback.

III Results

Fig. 2a shows the FM noise of the SDL5422 diode laser at 850 nm, measured from 9 to 100 kHz using another photodetector, consisting of two conventional PIN photodiodes and a lower bandwidth amplifier (≈1MHz). The laser was used in the Littman configuration [17], [10] and free-running, without any lock to an external frequency reference. Optical feedback to the laser can easily be interrupted by blocking the light incident on the mirror used in the Littman arrangement.

Fig. 2a shows that the laser, used under optical feedback (upper trace), has a large amount of technical noise, which is 20 to 30 dB above the detector noise, with some discrete and high amplitude components. We have observed that this noise decreases with increasing Fourier frequencies. The laser linewidth (free-running) was estimated by looking, in an oscilloscope, at the rms voltage fluctuations of the difference signal between both photodetectors in Fig.1c. It could also be obtained by integrating the noise power spectral density. Looking at the frequency fluctuation, in the oscilloscope, we can clearly see small amplitude and fast components, superimposed on a larger and slower drift of the laser. Those account for a measured linewidth (rms) of about 5 MHz, in an observation time of one second. Since this is dominated by the drift of the laser, about the same value is obtained if the laser is under optical feedback from the extended cavity or not. Dispersive feedback from the grating reduces the short term linewidth of the laser to the kHz level, but long term stability would have to be added by locking to a stable optical resonator or to an atomic/molecular resonance.

A similar 1/f behaviour is observed for the AM noise of the SDL5422 diode laser. Here we have used the faster photodetectors of Fig. 1b. Without optical feedback from the grating, a large amount of excess noise is observed at low frequencies, but this technical noise is only a few dB above the shot noise level, for frequencies above 100 kHz. This shows that this laser is a very low noise one and, therefore, is suitable for high sensitivity FM spectroscopy [8]. In this technique, the laser is frequency modulated usually at RF frequencies, where the laser amplitude noise is low or eventually shot-noise limited. Phase sensitive detection, at these higher frequencies, of the dispersive part of an atomic resonance, allows spectroscopy with high signal-to-noise ratio. We have seen that for our diode laser, this limit is basically reached at frequencies as low as 100 kHz.

Amplitude Squeezing

When the diode laser is used with optical feedback from the grating [10], in the Littman configuration [17], a reduction of the AM noise below the shot noise level, known as amplitude squeezing, can be observed [18]. In this case, the noise in the sum signal of the homodyne detector is lower than the noise in the difference signal. This is a manifestation of the quantum character of the light field. In order to satisfy the Heisenberg uncertainty principle, the reduction of the noise in one quadrature of the field (amplitude) below the standard quantum limit occurs at the expenses of an increase in the noise of the other quadrature (frequency).

Fig. 2b shows the AM noise spectral density, between 1 and 2 MHz, for the laser operating with and without optical feedback from the grating, at an injection current of 120 mA and an output power of 100 mW. Also shown are the shot-noise and the detector noise levels. We see that the laser noise drops below the shot noise level by as much as 1.2 dB in this frequency range. Amplitude squeezing was actually observed from a few hundred kHz to 8 MHz, without using any particular scheme for pump suppression [19]. This regime, where the injection current fluctuations are reduced by using a large impedance source, can often be easily achieved, depending on the particular current source or laser used. Amplitude squeezing has been obtained for different kinds of diode lasers and also LEDs [12]. For diode lasers, the best results are obtained with operation far above threshold, in the "pump suppression" regime [19] and at low temperatures. Larger degrees of squeezing should be obtained at high laser powers, but in this case the detection is very difficult or even impossible, since photodetectors saturate or will be damaged at high optical powers.

Since the AM noise reduction can be seen as causing a regularization in the arrival times of the photons at the detectors, any absorption or scattering of light in the optical setup, which in our case occur mainly at the grating (70% efficiency in zero order beam, 20% reflection into the first order beam and 10% losses) and optical isolator (10%), causes random removal of photons and tend to destroy the effect. Therefore squeezing clearly is a fragile effect and is very sensitive to losses in the optical setup. In fact a nice signature of squeezing would be obtained by mesuring the amount of noise reduction as a funtion of laser power attenuation, which would give a nonlinear dependence of the degree of noise reduction [20]. Unfortunately, we could not perform this test because the detector noise level, in spite of being low, is too close to the laser noise level, leaving a small range for changing the laser power. The degree of squeezing that we observe can be corrected by the detection efficiency and losses at the optical isolator, giving a total of 2.0 dB at the output of the grating, in agreement with the best values obtained so far with extended cavity diode lasers at room temperature [21].

Similar measurements to those of figure 2b, done at other values of the injection current, are being analysed now and will be published elsewhere.

IV Conclusion

We have described an experimental system for measuring the amplitude and frequency noise of a laser. Our results with this system were obtained for a commercial diode laser (SDL-5422-H1) operating at 850 nm, which we have been using to decelerate a Calcium atomic beam with light at its second harmonic.

We have observed room temperature amplitude squeezing for this diode laser, which is a reduction of the amplitude noise below the standard quantum limit, or shot noise level. This opens the possibility of using these light sources for sensitive spectroscopy with higher signal-to-noise ratio. In particular, we also intend to investigate the noise properties of the second harmonic of this squeezed laser, in order to verify if a larger degree of noise reduction can be obtained. In this direction, our next steps should also include the use of a stabilized current source [19] and operating the diode laser at lower temperatures.

We acknowledge the financial support of FAPESP, CAPES, CNPq and FAEP- UNICAMP.

References

[1] K. Hirahara, T. Fujii, K. Ishida, S. Ishihara, IEICE Trans. Electr., E**81C**, 8, (1998) 1328-1341.

[2] Time and Frequency, J.Jespersen and D.W.Hanson, Eds. Special Issue of Proc. IEEE, Vol.**79**, n.7, 1991; J.C.Bergquist, Ed., Proceedings of the Fifth Symposium on Frequency Standards and Metrology, Woods Hole, MA, Oct. 1995 (World Scientific).

[3] J.Helmcke, A.Morinaga, J.Ishikawa, and F.Riehle, IEEE Trans. Instrum. Measur., **38**, 524-532 (1989).

[4] F.Trager, Ed., Special Issue on "Environmental trace gas detection using laser spectroscopy", Appl. Phys. B, **67**, 3 (1998).

[5] M. de Angelis, G.Gagliardi, L.Gianfrani, and G.M.Tino, Phys. Rev. Lett. 76, (1996) 2840-2843; R.C.Hilborn and C.L.Yuca, Phys. Rev. Lett., **76** (1996) 2844- 2847.

[6] K.S.Thorne, in *300 Years of Gravitation,* S.W.Hawking and W.Israel, Eds. (Cambridge Univ. Press, Cambridge, 1987).

[7] M. Born and E.Wolf, *Principles of Optics*, Pergamon Press, 1986.

[8] G.Bjorklund, Opt.Lett., **5**, 1 (1980) 15-17; J.H.Shirley, **7**, 11, (1982) 537-539.

[9] P.Kersten, F.Mensing, U.Sterr, and F. Riehle, Appl. Phys. B, **68** (1998) 27-38.

[10] G.Woehl Jr, G.A.Garcia, F.C.Cruz, D.Pereira, and A.Scalabrin, Applied Optics, **38**, 12 (1999) 2540-2544.

[11] Laser Cooling and Trapping of Atoms, S.Chu and C.Wieman, Eds, Special Issue of J. Opt. Soc. Am. B, **6**, 11 (1989); H.Metcalf and P. van der Straten, Phys. Rep. **244**, 203-286 (1994).

[12] R.W.Henry and S.C.Glotzer, Am. J. Phys., **56**, 4 (1988) 318-328; G.J.Milburn and He Bi Sun, Contemp. Phys., **39**, 1 (1998) 67-79.

[13] E.S.Polzik, J.Carri, and H.J.Kimble, Appl. Phys. B **55**, (1992) 279-290.

[14] F.Marin, A.Bramati, V.Jost, and E.Giacobino, Opt. Commun. **140** (1997) 146-157; S.Kasapi, S.Lathi, and Y.Yamamoto, Opt. Lett., **22**, 7 (1997) 478-480.

[15] J.Kitching, NIST, private communication.

[16] S.B.Alexander, J. Lightwave Technology, vol.LT-**5**, 4 (1987) 523-537.

[17] M.G.Littman and H.J.Metcalf, Appl. Opt., **17**, (1978) 2224-2227.

[18] M.J.Freeman, H.Wang, D.G.Steel, R.Craig, and D.R.Scifres, Opt.Lett., **18**, 24 (1993) 2141-2143.

[19] S.Machida, Y.Yamamoto, and Y.Itaya, Phys. Rev. Lett., **58**, 10 (1987) 1000-1003.

[20] J.Kitching, A.Yariv, and Y.Shevy, Phys. Rev. Lett., **74**, 17 (1995) 3372-3375.

[21] T.C. Zhang, J.-Ph. Poizat, P. Grelu, J.-F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M.D. Levenson, and E. Giacobino, Quantum Semiclass. Optics, **7** (1995) 601-613.