Low-frequency intensity noise in semiconductor lasers

by Margaret Manson Hall

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University

Abstract:
Intensity fluctuations (intensity noise) at 25 MHz of two semiconductor lasers are studied experimentally and theoretically. At this frequency two sources of intensity noise can be examined; quantum noise and noise originating from longitudinal mode competition. This latter source of noise occurs when more than one longitudinal mode competes for laser power.

The intensity fluctuations for a free running laser diode (with no external optical feedback) and an external cavity laser (with external optical feedback) are measured as a function of injection current. An experimental value for the shot noise limit (the standard limit predicted by quantum mechanics) is also obtained, and all laser noise measurements are compared with this limit. We find that at twice the threshold injection current, the intensity noise of the free running laser is only 3.5 dB above the shot noise limit, and that of the external cavity laser 5 dB above the shot noise limit.

The ratio of the intensities of the main longitudinal mode to the side longitudinal modes is measured for both lasers, also as a function of injection current. We find that the intensity noise is decreased when the side modes are suppressed.

Single mode semiclassical and fully quantum mechanical theories are used to model the intensity noise. The two theories predict similar levels of intensity noise at low injection currents; at higher injection currents where quantum noise sources not included in the semiclassical theory play a role, the noise predictions of the two theories deviate. In particular, the semiclassical theory predicts noise below the shot noise level at high injection currents, even when the injection current carries the full shot noise.

Both theories generally predict lower levels of intensity noise than that which is measured; the single mode theories do not account for longitudinal mode competition noise. Thus we conclude that longitudinal mode competition is a significant source of intensity noise even when the side modes are suppressed below the main mode more than 30 dB. Thus a multimode theory may be necessary to effectively model the intensity noise of semiconductor lasers.

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in
SEMICONDUCTOR LASERS

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APPROVAL

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Margaret Manson Hall

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Signature Margaret M. Hall

Date July 18, 1996

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TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF FIGURES

LIST OF FIGURES--Continued

ABSTRACT

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CHAPTER 1

INTRODUCTION

Intensity fluctuations, although often small, are always present in a continuous wave (cw) laser beam. The sources of this "intensity noise" are numerous, and vary with laser type and structure, pumping level, and frequency of the fluctuations. In order to suppress the intensity fluctuations, an understanding of the noise mechanisms in the laser is crucial. An understanding of the fluctuations is also interesting from classical and quantum optical viewpoints.

An off-the-shelf semiconductor laser, operated above threshold, will have optical intensity noise 5 to 7 orders of magnitude below its cw intensity level (Fig. 1.1). As the demand for laser diodes grows, however, applications increasingly exist which require even lower levels of intensity noise. In coherent optical communications, for example, intensity noise in the local oscillator can increase the bit-error rate at the receiver.[1] The visibility of the fringe patterns from high precision interferometers and the sensitivity of spectroscopic techniques can also be augmented with a decrease in intensity noise.[2,3]

In this thesis we present intensity noise measurements for two different types of semiconductor lasers. Both of these lasers are presently employed in industrial and research projects worldwide. The fundamental quantum noise limit, predicted by the Heisenberg uncertainty principle, is also determined experimentally. All laser noise measurements are compared with this fundamental limit.

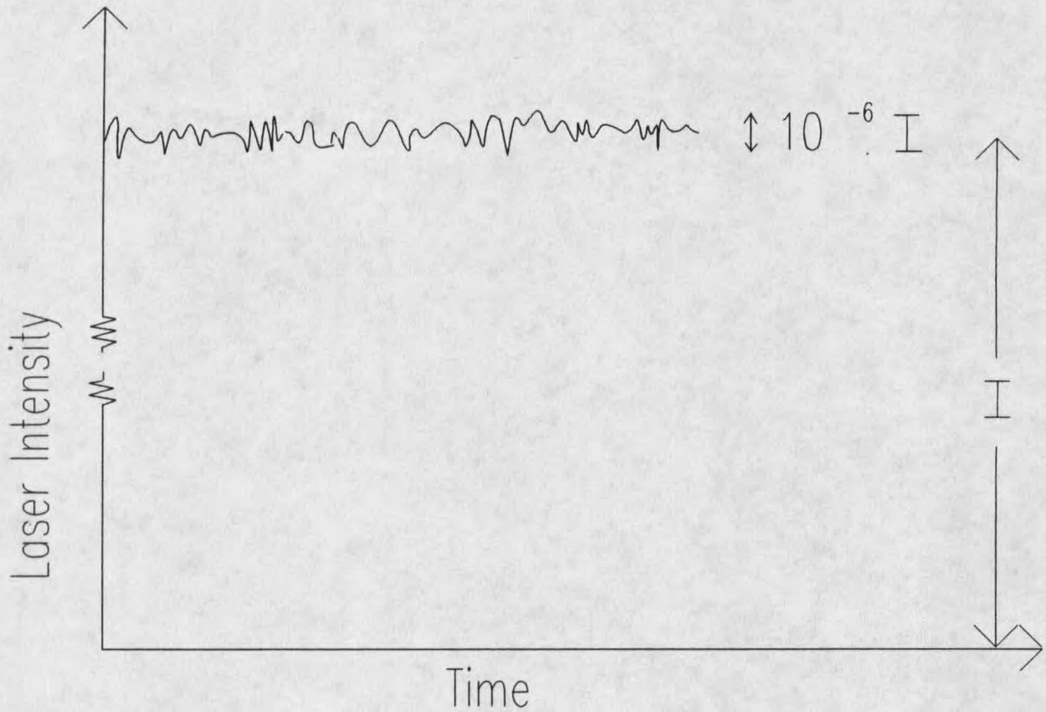

Figure 1.1. The optical intensity noise of a semiconductor laser is 5 to 7 orders of magnitude below the cw optical intensity level.

In addition, both a semiclassical and a fully quantum mechanical theoretical model of the intensity noise are used to model the experimental data. These models allow us to test not only to the accuracy of the theoretical formalisms, but also to gain insight into the sources of the intensity noise. In particular, the effects of quantum noise sources are investigated.

This thesis is organized into four chapters. In this first chapter we present background material to support and motivate this thesis project. A brief introduction to semiconductor lasers is given and the main features of the intensity noise spectrum introduced. The standard quantum limit, with which we compare all our noise measurements, is discussed. Finally, a short review of previous work done on laser diode intensity noise in the frequency range 1-100 MHz is given, with comments on the relevance of this work.

Chapter 2 is devoted to both the semiclassical and the quantum theories of the intensity noise. The third and fourth chapters discuss experiments and results of intensity noise measurements. Chapter 3 deals with a free running laser diode (with no external optical feedback) and Chapter 4 with an external cavity laser diode (with external optical feedback). We end with a short conclusion in Chapter 5.

Semiconductor Laser Basics

The simplest semiconductor laser is a forward biased p-n junction with cleaved ends (Fig. 1.2). The end surfaces act as partially reflecting mirrors and form the laser resonator. Electrons are pumped, by means of a constant dc current, into the conduction band, and "holes" are left behind in the valence band. When an electron in the conduction band decays back down to a hole in the valence band, via stimulated or spontaneous emission, a photon is generated. Typical dimensions of the laser are 300 x 200 x 100 $(\mu m)^3$, much smaller than most other types of lasers; the lasing itself takes place right at the p-n junction, in an "active region" usually only 0.5 to 5 μm thick. Most lasers today incorporate an additional layer of a slightly different bandgap material between the p and n layers. As discussed in Chapter 3, this helps to confine the carriers to a smaller region.

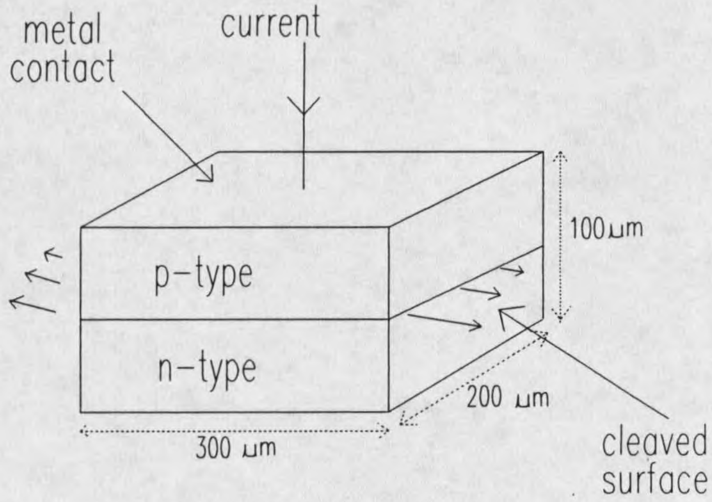

Figure 1.2. Semiconductor laser.

Because the conduction and valence bands are not discrete states, the gain profile of a semiconductor laser is exceptionally broad (Fig. 1.3). The gain profile shows the optical gain of the laser as a function of frequency (or wavelength). Due to the cavity resonances which occur when the length of the cavity L is an integral number of half wavelengths, the laser will prefer to operate at certain "longitudinal modes". The longitudinal "side modes", however, will never be completely suppressed. The doping level, laser structure, and pump level will all affect the magnitude of these side modes.

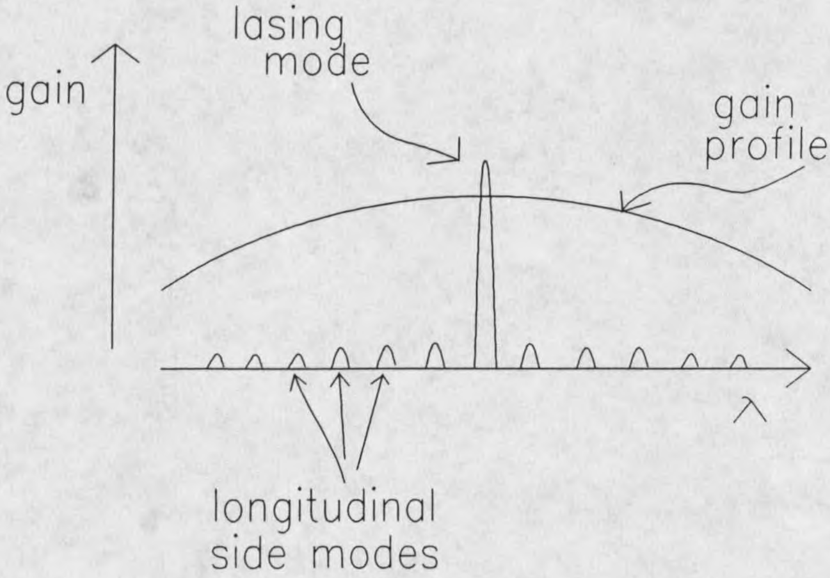

Figure 1.3. Longitudinal side modes exist due to the broad gain profile of the semiconductor laser, and the resonances of the laser cavity.

Intensity Noise Spectrum

The main features of the intensity noise spectrum of a laser diode operating above threshold are shown in Fig. 1.4. Below 1 MHz the noise is dominated by flicker noise. This noise leads to a characteristic 1/f fall-off (straight line on the log-log plot). Flicker noise is found in such diverse phenomena as the human heartbeat,[4] the relationship between intensity and pitch in music,[4] the current noise in a transistor,[4] and the intensity noise of a laser diode.[5] The origin of flicker noise is poorly understood, although chaos theory has made some progress.[6]

On the upper end of the spectrum, the noise is dominated by relaxation oscillations.[7,8]

In a semiconductor laser it takes significantly longer to pump carriers into the active region (or to create a population inversion) than it takes for photons, on average, to leave the laser cavity. These two rates, coupled with the nonlinear dynamics of the laser's exponential growth, can lead to turn on/turn off, behavior in the laser intensity. Thus a small fluctuation in either the carrier number or photon number will set up a "relaxation oscillation", which leads to a resonant condition with its peak frequency between 500 MHz and 10 GHz.

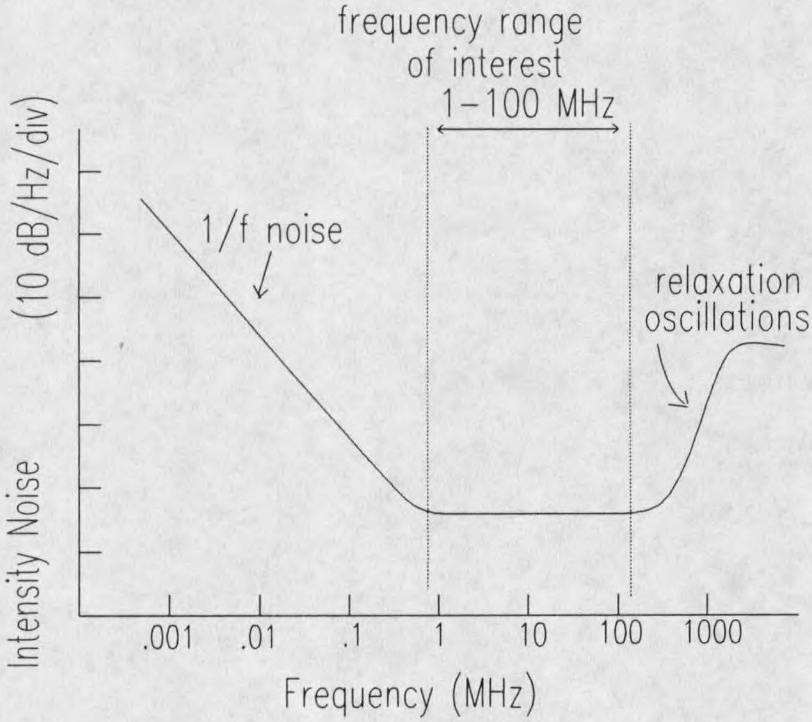

Figure 1.4. Intensity noise spectrum of a semiconductor laser.

The third regime (referred to as the low-frequency regime), and with which this thesis is concerned, is from 1 MHz to 100 MHz. Because the tail of the relaxation oscillations becomes less prominent below 100 MHz and flicker noise occurs at frequencies below 1 MHz, two other noise sources can be studied. These are quantum and longitudinal side mode noise sources, which will dominate in the 1-100 MHz range at high pump levels. (The relaxation oscillation resonance frequency will shift to higher frequencies with an increase in the pump rate.)[7]

Although recent attention has been given to the mechanisms by which longitudinal side modes can increase the intensity noise of a semiconductor laser, significant uncertainty about this issue remains. In the case of mode partitioning, whereby the main mode and its side modes trade energy amongst themselves (if at any instant the intensity of the main mode decreases, the intensity of one or more side modes increases), the total intensity noise of the laser will either remain the same or increase. If the trading of energy is complete, such that the increase in power of one mode can exactly cancel the decrease in power of the other mode or modes, the total intensity noise will remain the same.[9] If on the other hand the trading of energy amongst the modes is not complete, or if there are frequency dependent losses within the cavity, the fluctuations of the individul modes in the output beam will not not completely cancel one another. In this case the total intensity noise will increase.[10,11] Hole burning and other nonlinear gain mechanisms determine the degree of correlation between the modes.[12] A second mechansim by which side modes can add to the total intensity noise in this frequency range involves the shifting of side mode relaxation oscillations to lower frequencies.[13] This is facilitated by the coupling of the side modes to the main mode.

The intensity noise spectrum shown in Fig. 1.4 is for a laser pumped by an ideal, noise free controller (an ideal current or voltage source). Electromagnetic induction, however, from outside or inside the controller, can add electrical noise to the injection current. This in turn adds noise to the laser output. The controller must therefore be well shielded from the environment, and care must be taken to prevent "cross talk" between internal electronic components. Appendix A shows noise spectra for lasers being pumped by a well shielded battery, as well as by two non-ideal commercial controllers.

The Shot Noise Limit (SNL)

In this thesis, experimental intensity noise measurements are compared with the "standard quantum limit" for intensity noise. The standard quantum limit is the noise associated with photon fluctuations which exhibit a Poisson distribution. The variance of the Poisson distribution gives the uncertainly in the number of photons (ΔP) as[14]

$$\Delta P = \sqrt{\overline{P}}, \tag{1.1}$$

where $\overline{P}$ is the average number of photons detected in some measured time interval T. Particularly important is the coherent state of light, which in addition to possessing photon fluctuations with a Poisson distribution, also possesses photon and phase uncertainties which are at the minimum allowed by the uncertainty principle.

When photons with a Poissonian distribution impinge on a photodetector, they create an electrical current which we say is at the "shot noise limit" (SNL). The photon