Mode hopping in semiconductor lasers

by Timothy Alan Heumier

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

Montana State University

Abstract:
Semiconductor lasers have found widespread use in fiberoptic communications, merchandising (bar-code scanners), entertainment (videodisc and compact disc players), and in scientific inquiry (spectroscopy, laser cooling). Some uses require a minimum degree of stability of wavelength which is not met by these lasers: Under some conditions, semiconductor lasers can discontinuously switch wavelengths in a back-and-forth manner. This is called mode hopping.

We show that mode hopping is directly correlated to noise in the total intensity, and that this noise is easily detected by a photodiode. We also show that there are combinations of laser case temperature and injection current which lead to mode hopping. Conversely, there are other combinations for which the laser is stable. These results are shown to have implications for controlling mode hopping.

MODE HOPPING IN SEMICONDUCTOR LASERS

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APPROVAL

of a thesis submitted by

Timothy Alan Heumier

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, bibliographical style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date Dec. 7, 1992

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Tim Heumier, November, 1992

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ABSTRACT

Semiconductor lasers have found widespread use in fiberoptic communications, merchandising (bar-code scanners), entertainment (videodisc and compact disc players), and in scientific inquiry (spectroscopy, laser cooling). Some uses require a minimum degree of stability of wavelength which is not met by these lasers: Under some conditions, semiconductor lasers can discontinuously switch wavelengths in a back-and-forth manner. This is called mode hopping.

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CHAPTER I

INTRODUCTION TO SEMICONDUCTOR LASERS

Uses for Semiconductor Lasers

Due to their small size, semiconductor lasers have many applications for which other lasers would be unsuited. They are found in compact disc and videodisc players, bar code scanners, optical communications and surveying. They are also used for studies of atomic structure [1]-[3] and quantum-mechanical effects [4].

Basic Characteristics of Semiconductor Lasers

A semiconductor laser is a very small device, about as large as a grain of salt (see Figure 1). Typical dimensions are 250 microns long, 100 microns wide, and around 100 microns thick. One type of laser in wide use is the GaAs/AlGaAs laser. It is comprised of a slab of (possibly doped) GaAs sandwiched between layers of AlGaAs which serve to confine the laser radiation. This is a crystalline structure which is cleaved in manufacture so that two opposite faces are smooth and parallel. These facets, whose power reflectivity is around 0.3, form the mirrors which provide the feedback for the gain needed for laser action.

The laser is pumped by an electrical current (called the injection current) which passes through the center slab (the active region) perpendicular to its plane. The current is usually confined to a narrow strip by some means, such as a current-blocking layer. As electrons are pumped from the valence band to the conduction band (see Figure 2), a population inversion is created. Lasing occurs when the electrons undergo stimulated emission and recombine with the holes left behind in the valence band. The laser beam, emitted from both facets equally, diverges strongly because of diffraction, since the light emerges from what amounts to a slit. The diffraction is therefore greatest perpendicular to the slit, giving rise to an elliptically-shaped beam, in contrast to the round beam so familiar in HeNe lasers and others. This highly divergent beam is almost always collimated by a short focal length lens such as a microscope objective.

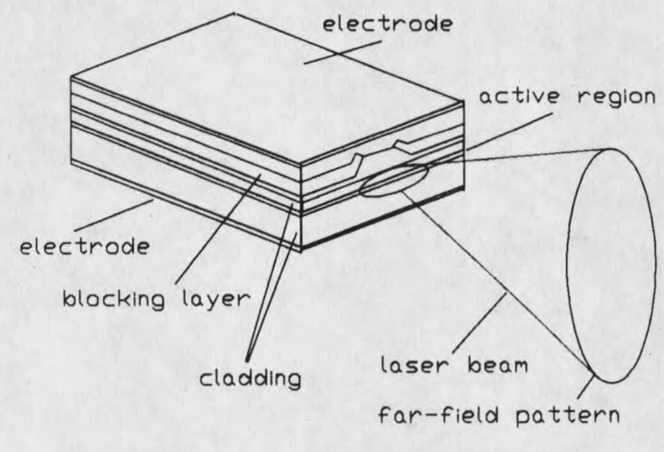

Figure 1. Schematic of typical laser diode chip. Cladding is GaAlAs, active region is GaAs. Blocking layer restricts current flow to narrow stripe through active region.

In the typical commercial semiconductor laser (or laser diode or diode laser, depending on the speaker), the crystal is mounted on a pedestal in a transistor-like package. The laser beam from the front facet exits through a glass window to the outside world. The beam from the other facet usually strikes a built-in photodiode which can be used to monitor the laser's optical power output.

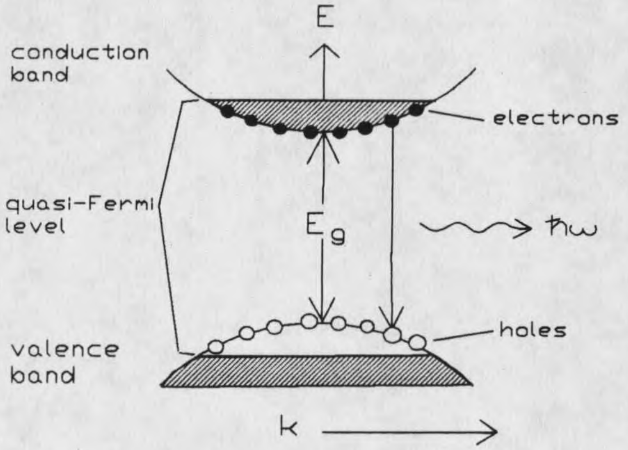

Figure 2. Simplified semiconductor band structure. Stimulated emission causes an electron in the conduction band to recombine with a hole in the valence band.

A standard measure of the performance of a diode laser is the so-called L-I curve, a graph of optical power output vs. injection current (see Figure 3). An important quantity which is derived from this curve is the threshold current. When the laser is operated below threshold, spontaneous emission dominates the optical output and the intensity is relatively low. As lasing commences, the intensity increases dramatically. The threshold current is often found by extrapolating the large-slope portion of the curve back to zero intensity, as indicated in Figure 3.

Another characteristic of laser diodes is that the output wavelength varies with temperature (see Figure 4). Each short segment represents a slight shift in wavelength caused by variation of the index of refraction with temperature and the change in cavity length due to thermal expansion. The latter causes a wavelength shift because the laser wavelengths occur at longitudinal modes of the cavity, and these modes depend on cavity length. There is an overall much greater shift of wavelength with temperature caused by the variation of the bandgap with temperature.

It should be noticed that the lasing wavelength changes abruptly at certain temperatures. Over a small range of temperature, two modes compete for the available power, and the laser may switch back and forth between these two modes. This is called mode hopping and it is the subject of this study.

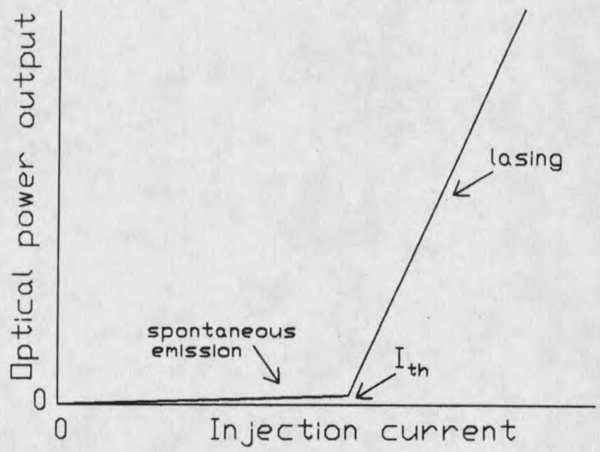

Figure 3. Graph of optical power output vs. injection current (L-I curve).

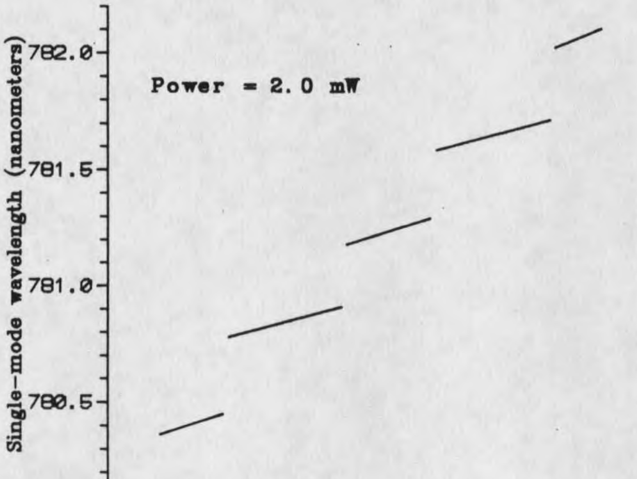

Figure 4. Graph of single-mode wavelength vs. laser case temperature. Mode hopping occurs at the discontinuities.

Motivation for Present Study of Mode Hopping

Mode hopping in semiconductor lasers is undesirable in many applications since it introduces unwanted intensity noise. A prime example is in video disk systems. Mode hopping causes variations in the location of data written to the optical disk because dispersion causes variations in beam direction, possibly necessitating the use of achromatic optics [5]. In addition, the quality of the picture derived from the disk can be degraded by mode hopping since the signal-to-noise ratio is reduced [6]. Video transmission via fiber optics also suffers from intensity noise produced by mode hopping for the same reason [7].

Mode hopping is problematical in other applications as well. In telecommunications, for example, the switching from one mode to another affects the maximum data transmission rate, since different wavelengths have different velocities in single-mode fibers with high dispersion [8]-[10]. Spectroscopy is another area which usually requires wavelength stability better than the 0.2-.3 nm variation that occurs if the laser shifts from one mode to another.

Mode hopping in semiconductor lasers has been studied by many researchers. It has been found that the externally controllable parameters of laser case temperature, injection current, and optical feedback play roles in the occurrence of mode hopping. For example, Gray and Roy [11] monitored dwell times of lasers operating in the bistable regime (complete switching between modes). They showed a qualitative map of single-mode stability as it was affected by current and temperature. Ohtsu and Teramachi [12] found a similar map in studying the power dropout probability. Linke *et al* [7] related the rate of power fluctuations of various depths to the power ratio between the main mode and the largest secondary mode (this ratio is affected by temperature and injection current). Tkach and Chraplyvy [13] found that feedback power ratios of -50 dB or less could induce mode hopping, leading to an increase in intensity noise.

The foregoing examples illustrate how problematic mode hopping is in many applications. There are, therefore, practical motivations for studying mode hopping. In addition, there are many users of diode lasers who would like to be able to know when a laser is mode hopping without resorting to spectrum analyzers or spectrographs. They would also like to be able to eliminate mode hopping without having to modify the laser or to use elaborate external optics or electronics. Finally, of course, the physicist wants to know when and why mode hopping occurs.

Statement of Research Goals

The problem faced at the beginning of this study was therefore two-fold: A non-spectroscopic means of detecting mode hopping was sought, and the conditions under which mode hopping occurs were to be studied with a view to finding a way of controlling it. Chapter II describes, for a laser operating with constant current, a simple method for detecting and quantifying mode hopping by measuring the intensity noise generated while mode hopping is occurring. In

Chapter III, it is shown that there are specific combinations of injection current and case temperature which lead to mode hopping. A stability map reveals the periodicity of these combinations. This observation leads to a method of controlling mode hopping. This periodicity and other features of the stability map are explained in Chapter IV in terms of a two-mode model, taking into account the dynamics of the mode hopping and of the detection system response. Rate equations are developed and solved, and theoretical predictions are made and compared with the experimental results. Chapter V discusses the application of these ideas and techniques to other semiconductor lasers. Finally, Chapter VI concludes the discussion with some comments regarding detection and control of mode hopping.

Chapter II

EXPERIMENTAL SETUP AND PROCEDURE

Description of Setup

Mode hopping in diode lasers was studied using the experimental arrangement shown in Figure 5. A Mitsubishi ML 4402 GaAs index-guided laser was housed in an ILX Lightwave Model 4412 laser mount. The laser mount held the laser against a 2 mm thick aluminum plate. Thermoelectric modules in good thermal contact with the plate allowed heating or cooling of the laser. The temperature of the plate (and hence the case temperature of the laser) was monitored by a calibrated thermistor. The laser mount, glass plate and photodiode were mounted on a 30 cm x 20 cm x 2.5 cm aluminum block to ensure rigidity. This block, resting on a soft foam block for vibration isolation, was placed on an optical table fitted with rigid legs. A foam-lined wooden box with temperature control covered the apparatus to provide secondary temperature buffering.

The laser case temperature and injection current were manipulated using a ILX Lightwave Model 3722 laser diode controller. The controller stabilized injection current and case temperature to <20 nA/√Hz and <5 mK, respectively.