CONSTRUCTION OF A TUNABLE EXTERNAL-CAVITY DIODE LASER WITH APPLICATIONS TO ATMOSPHERIC DIAL MEASUREMENTS

Michael Keahi Hall
Department of Electrical Engineering
University of Hawai'i at Manoa
Honolulu, HI 96822

ABSTRACT

A tunable External-Cavity Diode Laser (ECDL) prototype is designed and fabricated based on a Littman mount configuration. The ECDL is wavelength centered about the 780 nanometers (nm), the specified wavelength output of the laser diode being used. The continuous tuning range of the prototype is on the order of 10-12 nm. The ECDL prototype achieves sustained wavelength and power stability, and consistently outputs a tuned single-mode beam with a spectral width on the order of 1MHz. The ECDL prototype will serve as a "seeding" laser for a DIAL spectroscopy system to measure atmospheric constituency, as well as a testbed for the research of improved ECDL geometries and for the fabrication of future prototypes.

INTRODUCTION - LASER DIODES AND ECDLS

Diode lasers have become the technology of choice for many diverse and important applications at the forefront of experimental physics and engineering, because of their small size, low cost, high reliability, and excellent spectral and modulation characteristics. Uses of diode lasers span a very broad range of applications, including: telecommunications systems, commercial electronics, materials processing (marking, cutting, welding), non-intrusive atomic and molecular spectroscopy, process and pollution monitoring, optical ranging, and remote sensing.

Research efforts involving lasers systems require access to lasers of many distinct wavelengths and output power ranges. This can be achieved with some expense to the researcher, as the vast majority of semiconductor lasers are only available within specific wavelength regions, necessitating many lasers to be bought to meet varying applications. Additionally, researchers who use unmodified commercially available laser diodes will run into several complications. For example, an individual laser diode may not always be of the exact specified wavelength or may not be as spectrally discrete. Obviously, for compact and cost-effective designs, the strict adherence to specification will tend to falter; thus a researcher's desired wavelength may not be met and research directly suffers. Furthermore, the common laser diode has a resonant cavity such that its output wavelength is particularly sensitive to fluctuations in injection current, as well as changes in operating temperature. In fact varying these two parameters, injection current and operating temperature are the most common methods used to "tune" the wavelength of the laser diode. These methods however, only allow the output to be tuned discontinuously, which severely limits its applications and comes at the cost of overall wavelength stability and shortening of the diode lifetime. To avoid these effects the researcher must expend greater funds for higher precision laser diodes and again, for diodes of various wavelengths and power requirements.

In addition, despite their attractive features, diode lasers output relatively wide linewidths, an indication of their impure spectral composition and poor cavity quality. Cost-effective laser diodes are intended to operate at a specific wavelength and only at that wavelength, but in practice they need to be tuned by means of optical feedback to achieve the fine linewidths necessary for experimental rigor, especially for applications in spectroscopy and optical telecommunications.

External-cavity configurations enable a cost-effective laser diode to achieve such narrow linewidths. ECDLs provide a combination of extremely narrow linewidth, broad tunability, ease of use and comparatively high output powers, making them some of the most versatile lasers available. These benefits supplement the benefits of the laser diodes themselves; small size, low cost, high reliability.

ECDLs have been commercially available for approximately eight years. However, many of these systems are plagued with problems in stability, reliability, and reproducibility. Commercially available systems are also very expensive, costing as much as 1000 times that of a typical laser diode, between $30K and $50K. However, tunable external-cavity diode lasers remain a vital technology to high-tech industry, due to the diversity of their applications and attractive characteristics.

ECDL DESIGN – LITTMAN MOUNT CONFIGURATION

The Littman mount configuration ECDL consists of a common laser diode which utilizes a diffraction grating as a wavelength-tuning element by providing wavelength-selective optical feedback. This optical feedback, occurring outside the cavity of the laser diode, hence "external-cavity", is the defining feature of the ECDL systems and is what enables the tuning of the output wavelength. The external cavity is also responsible for the narrowing of the laser linewidth, a product of the dispersive nature of the diffraction grating coupled with the optical feedback provided by the feedback mirror. The external cavity is the optical path formed by laser diode, diffraction grating, and the tuning or feedback mirror. As a result of the diffraction grating physics, tuning of the Littman-type ECDL is accomplished by the translation of the feedback mirror about a circular path, where the radius is equal to the points of incidence for both the diffraction grating and feedback mirror, simultaneously. The geometry of the Littman configuration appears in Fig. 1. The heavy black lines indicate the path of beam output and feedback. The heavy dashed lines indicate the orientation of the faces of the diffraction grating and feedback mirror with respect to the one another and the pivot point. The cross-hatched triangles indicate angles.

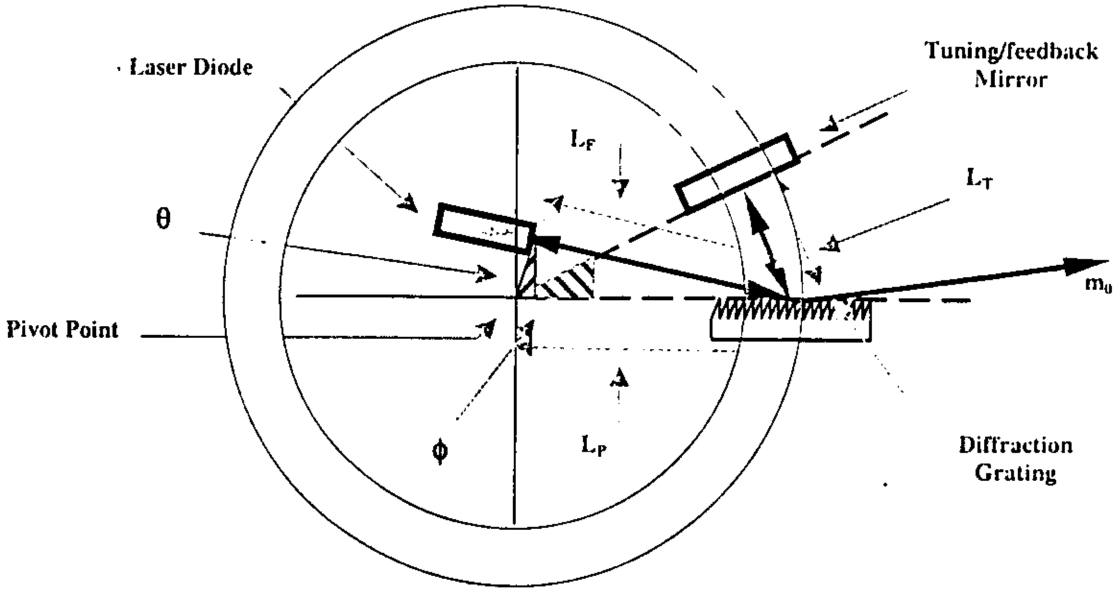

Fig. 1: Littman Configuration ECDL

The characteristic equations relating the geometry of of the external cavity to the output wavelength derived by Littman and Liu [1] are shown below in Equations 1-3. From these equations it is seen that two criteria that must be satisfied simultaneously to allow for continuous single-mode tuning: 1) the lengths of l_f and l_p must be proportionally related by sin θ as shown in Eq. 2, and 2) the angles, θ and ϕ, must be proportionally related to these lengths as shown in Eq. 3. (N is the number of half-wavelengths within the cavity, m is the output mode number and x is the separation between adjacent grating lines) Satisfying both criteria simultaneously leads to the unique geometry and pivot circle in the Littman configuration.

$$l_p = \frac{Nx}{2} \qquad \text{[Eq. 1]}$$

$$l_f = l_p \sin\theta \qquad \text{[Eq. 2]}$$

$$\lambda = \frac{x}{m}(\sin\theta + \sin\phi) = \frac{2}{N}(l_f + l_p \sin\theta) \qquad \text{[Eq. 3]}$$

FABRICATION AND ASSEMBLY

All fabrication and assembly efforts were performed by the author on the UH Manoa campus. The prototype body, tuning arm mechanism and optical mountings for the laser diode, diffraction grating, and front-surface mirror were machined using 6061 Aluminum. Appropriate physical dimensions were calculated using the characteristic equations for wavelength tuning according to the external cavity principles set forth by Littman and Liu [1]. The scale of ECDL configuration was approximated to meet the ultimate goals of the project: automation, miniaturization, reliability, and utility as a testbed for further ECDL refinements. Following fabrication of the prototype body, the ECDL components were integrated. These components include: the rotation stage for the tuning axis, the collimated laser diode assembly, the first-surface reflective mirror (to supply optical feedback), and the diffraction grating, used here as a wavelength-selective component. The rotation stage was countersunk into the machined body to serve as the tuning axis. Next, the 12 x 25 mm holographic diffraction grating with 1800 gratings/cm and the 25.4 x 25.4 mm first-surface reflective mirror were fitted into their mounts. An obsolete CD player was disassembled to obtain the non-antireflective coated collimating lens. The lens along with an inexpensive ThorLabs 2766-S01 Fabry-Perot type laser diode of wavelength 780 nm was then housed in a Jameco barrel-type lens mount. The lens mount was retrofitted to be spring-loaded to allow for fine collimation of the laser diode beam. The diode was wired to a Newport Model 525 Laser Diode Driver and the entire assembly was mounted adjacent to the prototype body for use. The configuration is shown below in Fig. 3.

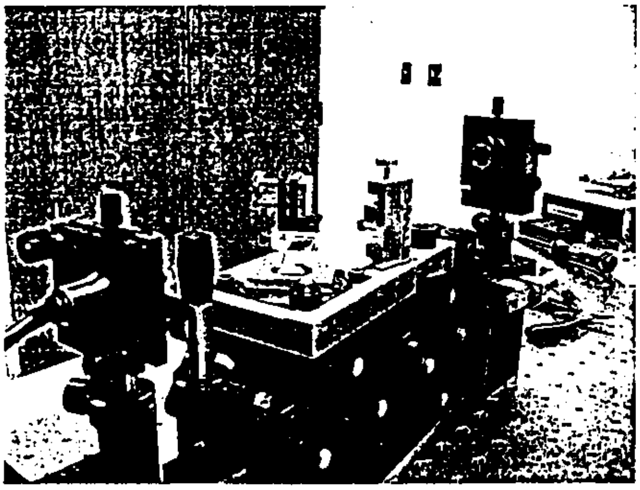

Fig. 3: The ECDL prototype. Components from left to right: mounted laser diode assembly, rotation stage and tuning arm, front-surface mirror, mounted diffraction grating, and the detector

INTRODUCTION – DIAL SPECTROSCOPY

The constructed ECDL will be implemented as a "seed" laser in a DIfferential Absorption Lidar (DIAL) spectroscopy system for general identification, quantification, and monitoring of spatial distribution of atmospheric layers. DIAL spectroscopy is an optical remote-sensing technique that utilizes LIDAR to detect and quantify atmospheric gases, aerosols, and airborne pollutants.

LIDAR is simply an acronym for LIght Detection And Ranging. LIDAR works by first emitting short laser pulses into the target medium at wavelengths specific to the gaseous molecules of interest. As the beam passes through the medium it is scattered both by air molecules and by airborne particulates in two processes, Rayleigh and Mie scattering, respectively. This scattered light, called backscatter is then detected by the receiving component of the system -- an efficient optical detector integrated within a narrow-field telescope. Based on the intensity of the backscatter, the time interval between the pulses being sent, and the backscatter being received, the molecular composition and its average spatial distribution within a given sample area can be obtained.

The DIAL approach to spectroscopy improves upon this technique in two respects. It takes advantage of the unique absorption spectra of molecules. It emits laser pulses of two different alternating wavelengths varying only by a few nanometers. One wavelength is centered on an absorption feature of the targeted gas while the other serves to provide a reference of backscatter intensity. If the targeted gas is absent along the path of the beam, the detector will see roughly equal backscatter intensities from both laser wavelengths. If the gas is present, the energy of the centered wavelength will be absorbed by the molecules, and therefore, the backscatter will be greatly diminished. The difference in backscatter intensities and return times between the two wavelengths allows DIAL systems to obtain volumetric data throughout the sample, revealing gaseous concentrations as a function of distance.

ECDLs as are ideal versus fixed wavelength lasers for atmospheric monitoring and general spectroscopy due to their previously mentioned attributes. An ECDL-seeded DIAL system can measure a greater range of gaseous molecules including trace gases and those with very narrow absorption spectra thus providing a more complete picture of atmospheric constituency.

Another impediment, the conditions of measurement, could also be overcome by implementing an ECDL in this type of spectroscopy. Though DIAL measurements themselves provide for minute adjustments to offset atmospheric aerosols, atmospheric turbulence, and competing atmospheric gas constituents such as water vapor, an ECDL-seeded DIAL system would provide, within the system itself, the ability to modify the output laser wavelengths in response to ever-present atmospheric variables: humidity, temperature fluctuations, pressure fronts, etc. In an uncontrollable environment, the elimination of even one variable contributing to error or delays would be immediately significant.

EXPERIMENTAL RESULTS

The optical output of the ECDL was characterized by an optical detector connected via optical fiber, first, through a Hewlett Packard 86120B Multi-Wavelength wavemeter and then to a PC running LABView©, the program chosen for processing and collecting experimental data. The wavemeter reported the intensity, or optical power, of the laser output over a programmed range of wavelengths.

At a diode driving current of 70 mA, the ECDL prototype demonstrated a continuous tuning range of about 10.16 nm, tuning from 774.86 nm to 785.02 nm. A greater range of tunability and shifts of this range could be achieved by subsequent adjustments to the alignment of the diode/diffraction grating/feedback mirror pathway. (This pathway constitutes the "external cavity" and is the essential feature of the Littman ECDL configuration, responsible for its advantageous attributes). The optical power remained linear through the tuning range, increasing from 0.41 mW to 0.47 mW.

Measurements of the nonintegrated laser diode were also taken to analyze the results of the ECDL prototype. Increasing the driving current of the diode from initial lasing to max recommended current, 40 mW to 74 mW, provided a discontinuous tuning range a mere 2.85 nm, from 777.46 nm to 780.31 nm. Measurements also demonstrated a "cold-start" phenomenon wherein the output power for a single wavelength would undergo a period of decrease, drifting over an output power range spanning as much as 0.5 mW before finally becoming stable.

ANALYSIS AND DISCUSSION

The first prototype proved valuable towards verifying the operating principles of the Littman ECDL configuration, as well as for gaining a solid understanding of alignment techniques and the variables that determine the limits for the tuning range and output power. The initial prototype was also extremely useful for addressing optical losses and thermal instability, which were not addressed in the technical literature, and how they might be reduced.

The overall mechanical design of this initial prototype, however, proved to be incapable of accommodating the hardware necessary automation or testing of a dual-cavity or tri-cavity. There was great difficulty in mounting a Piezo-electric transducer to the tuning arm, to allow for nano-scale translation, without prohibiting the free and level movement necessary for the tuning range mentioned earlier. For this reason accurate characterization of the laser system's tuning capabilities and its power efficiency over the entire tuning range could not be performed. The prototype was also found to be susceptible to changes in ambient operating temperature and vibration. The operational flaws of the first prototype have been documented qualitatively and quantitatively and have led to critical design modifications to be realized in the second prototype.

CONCLUSION

A tunable External-Cavity Diode Laser (ECDL) prototype has been designed and fabricated based on a Littman mount configuration. The initial prototype demonstrated the ability to utilize an inexpensive laser diode and yield a continuous wavelength tuning range of 10.6 nm while providing adequate wavelength and power stability. Among other discoveries the prototype has also proved crucial in exposing the weaknesses of inexpensive, lesser-grade optics including the salvaged collimating lens and laser diode and has revealed the variables that limit tuning range.

This project is developing new designs incorporating the conclusions drawn from the results prototype. The next prototype will be able to readily accommodate a Piezo-electric transducer for automated translation of the tuning mechanism allowing for precise characterization and miniaturization of the system for remote sensing. It will also provide for greater protection against ambient thermal and vibrational effects.

ACKNOWLEDGMENTS

The author would like to acknowledge and thank NASA and the Hawai'i Space Grant College for supporting this research endeavor and for providing UH undergraduate students the opportunity to pursue research efforts that might otherwise lie beyond feasibility. The author would also like to thank Dr. Audra Bullock for her invaluable mentorship, her continual support, guidance and insight, for the understanding and confidence found only through trial and error, and for the opportunity to discover the field of lasers and optoelectronics.

REFERENCES

[1] M. Littman and K. Liu. (1981) *Novel geometry for single-mode scanning of tunable lasers.* **Optics Letters**, 117.

[2] M. Littman. (1981) *Single-mode operation of grazing-incidence pulsed dye lasers.* **Optics Letters**, 138.

[3] P. McNicholl and H. Metcalf. (1985) *Synchronous cavity mode and feedback wavelength scanning in dye laser oscillators with gratings.* **Applied Optics**, 2757.

[4] B. Fermigier, et al. (1998) *Self-aligned external-cavity semiconductor lasers for high resolution spectroscopy.* **Optics Communications**, 73-77.

[5] S. Sivaprakasam, et al. (1996) *Mode hopping in external-cavity diode lasers.* **Optics Letters**, 411.

[6] K.C. Harvey and C. J. Myatt. (1991) *External-cavity diode laser using a grazing-incidence diffraction grating.* **Optics Letters**, 910.