Optimizing the Lasing
Quality of Diode Lasers
By Anti-Reflective Coating

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Introduction

Abstract

It has been observed that one good way to optimize the lasing quality of diode lasers in ECDL, extended cavity diode laser configuration is done by reducing the reflectance of their output facets with such Anti-Reflective (AR) coating materials as Sapphire (Al₂O₃), Hafnium Oxide (HfO₂), or Silicone Monoxide (SiO). An ECDL is a diode laser that is operated in a regime where strong feedback from one side of the chip (from an external element such as a grating) is used to control the laser’s mode [7]. It has 2 additional optical units, an adjustable mirror, and an adjustable grating mount, which makes an angle of incidence of 75 to 85 degrees with respect to the surface of the diode. There are many different designs of ECDLs but no particular design is optimum for all applications. The optical feedback power of an ECDL depends on the characteristics of the laser and reflectance of the output facet; the less the reflectance, the stronger the optical feedback, and the better the performance of the laser. Thus, we must reduce the reflectance because such a reduction in the reflectance would lead to:

- An increase in the size of the stable operation. For stable operation the laser must receive sufficient optical feedback power from the mirror and grating. Insufficient optical feedback causes unstable operation of the laser, whereas excessive feedback culminates in damage to the optical instruments of the laser.
- More usable output power.
- An increase in the tuning range of the laser, which means that the operating regime of the laser is broader, i.e. functions over a larger range of wavelengths.
The Principles of light emission in Lasers.

Figure 1. The configuration of an ECDL [7]

I. The laser mount.
II. The adjustable mirror
III. The adjustable grating

On the larger scale, the purpose of this experiment is to attempt to increase the round-trip gain of the laser, namely laser amplification as much as possible without having the laser lase. In other words, our greater goal is to achieve very low reflectances by suppressing lasing while maintaining very high optical gain.
The principles of light emission in lasers are based on electrons transiting from one energy level to another, which is known as the transition process. The transition process consists of 3 different modes: absorption, spontaneous emission, and stimulated emission. Of these 3 modes, it is the stimulated emission that gives rise to emission of laser light, i.e. coherent light. Stimulated emission occurs when photons of light with energy almost equal to absolute value of $E_2-E_1$ have incidence on electrons located at $E_2$ and the electrons move by compulsion to the $E_1$ level, where $E_1$ is energy before transition, and $E_2$ energy after transition. At this stage one observes a “population inversion”, meaning that the number of electrons after excitation on $E_2$ is larger than that on the lower level $E_1$.

Once stimulated emission occurs, the strength of the incident light should be increased to achieve optical amplification. Achieving optical amplification means having a photon with a round-trip gain greater than 1 between the 2 mirrors of the laser. Hence, the amplification will continue so long as the gain is greater than 1 in the gain medium. As the gain is incremented the amplification also increases. And one way to increase gain is to reduce reflectance of the facets of a diode laser as the formula below shows.

$$g_{th} = a_L + \frac{1}{L} \ln \left[ \frac{1}{R_1 R_2} \right]$$

(1)

Where $R_1$ and $R_2$ are the facet reflectances, $a_L$ is the loss internal to the laser, and $L$ is the length of the laser. This formula clearly illustrates that coating the output facet of a laser
whose result will be a smaller value of either $R_1$ or $R_2$, indeed leads to an increase in the
threshold gain, $g_{th}$.

When the net laser amplification between mirrors, taking into account any
scattering or other losses, exceeds the net reflection loss at the mirrors themselves, one
observes laser oscillation to which physicists refer as the threshold of the laser. What
goes on is that the highly reflective mirrors (one is 100% reflective, the other is partially
transmitting but mostly reflective) and internal gain inside the cavity permit any energy
inside the cavity to recirculate and reverberate many times, extracting energy from the
laser medium on each bounce so that the recirculating wave also builds up to very large
amplitudes inside the cavity [2]. This build-up and coherent reinforcement lead to a very
large increase of internal circulating energy. When such coherent oscillation occurs, an
output beam that is both highly directional and monochromatic can be coupled out of the
laser, either through a partially transmitting mirror on one end or by some other technique
[2]. At this moment one observes the lasing of the laser.

**Diode laser.**

The operation principles of a diode laser are basically the same as a common
HeNe laser, it has the same basic elements: (I) suitable optical feedback elements that
allow a beam of radiation to either pass once through the laser medium (as in a laser
amplifier) or bounce back and forth repeatedly through laser medium (as in a laser
oscillator); (II) a pumping process to excite atoms, molecules or ions into higher energy
levels; and (III) a laser medium, which stimulates the emission of an amplified photon.
What sets a diode laser different from a common a HeNe laser is: first, a diode laser is
much smaller than a HeNe laser; the entire length measures to be 200µm. Second, unlike most common lasers whose gain medium is gaseous concentrations of molecules, atoms, or ions, a diode laser has as its gain medium a semi-conducting forward biased photodiode. It is this semi-conductor diode and the structure of the laser that determine its wavelength. For instance an AlGaAs diode laser uses two cleaved facets as reflection mirrors, both placed at one end of the active layer, which is the amplifying medium of the laser. The beams go in every direction within the active layer until they match the direction of the laser’s “Fabry-Perot” oscillator. Here, one must bear in mind that laser oscillation never happens without optical feedback. If the matching occurs, the selected beams end up being confined between the facets and oscillation commences. The active layer (Al\textsubscript{y}Ga\textsubscript{1-y}As) is sandwiched between a positive and negative layer of Al\textsubscript{x}Ga\textsubscript{1-x}As.

And when one adds forward directed bias, electrons and holes will be injected from the positive and negative layers. Carriers will be confined to the active layer and create “population inversion” [5]. As a result, a high gain will be obtained. In this way, stimulated emission will be performed effectively and light will remain in the active layer for light has a characteristic that it gathers where the refractive index is highest, and the
active layer has a higher index of refraction than the surrounding levels. (Figure 3. The internal structure of a diode laser [5])

Last, unlike most common lasers, which are limited to fairly sharply defined discrete frequencies that depend on the transitions of the specific atoms employed in the laser and [therefore] to fairly narrow tuning ranges that depend on the line widths of these atomic transitions a diode laser, especially in the near infrared can offer instantaneous amplification bandwidths of order 200 angstroms [2]. In other words diode lasers have a higher tuning range than what has been referred to as “common lasers” here.

General characteristics of diode lasers

In this section I will touch on a few general characteristics that the diode lasers possess. The most important property to note about diode laser is that since they operate as forward-biased diodes, their operating characteristics are strongly temperature dependent. Therefore, one has to treat the injection current of the diode carefully the injection current is dependent on temperature and attempt to measure it with great accuracy because the laser diodes tend to overheat rapidly in the absence of proper cooling systems.

Another important measure of a laser’s operating characteristics is the pumping rate, which equivalent to injection current (I) above threshold (I_{th}) normalized to threshold value [7] as indicated by formula 2. If the laser functions within regular parameters, the laser’s output power, relative amplitude noise, and other characteristics improve with pumping rate.

\[ R = \frac{I - I_{th}}{I_{th}} \]  

(2)
One can illustrate the main property of a diode laser best with a plot of output power vs. injection current. The behavior that defines the interaction between the output power and injection current of a diode laser is quite characteristic and easily distinguishable as the two plots below indicate.

**Figure 4.1. The output power vs. Injection current**

Figure 4.1 represents the output power vs. injection current plot of a Mitsubishi ML64110R laser diode, whose threshold current is 68 mA for lasing at 25°C. The fact that the graph is inverted should not be attributed to any peculiar property of the laser. The inversion originates from negative polarity of the setup used to test the diode. As one can easily see, at first, when we increase the injection current, the output power is incremented very slowly, but when the current arrives at a certain value, we observe a total change behavior; the output power starts to go up much faster, and the dependence of power on current becomes linear. This may not look so obvious on figure 3.1 due to
the discrepancies in the data, which result from the extreme heating of the laser. However, the plot clearly shows that the threshold occurs at 70 mA, which is acceptably close to the specified 68 mA despite the deviations caused by the heating of the laser.

![Graph of Power vs. Current (mA)](image)

Figure 4.2. The output power vs. Injection current

Figure 4.2 describes the output power and injection current behavior of another Mitsubishi ML64110R diode laser, which we mounted on the sample holder plate in the vacuum chamber and wired it up to the electric feed through. The threshold occurs again at roughly 68-70 mA, but this time we observe a plot free of deviations, which is due to diode being cooled by the aluminum plate upon which it is placed. Hence, in both diodes we observe the behavior that we expect and can verify that they function properly and are suitable for the task.
Experimental Procedure

Before I go any further, I must admit to the reader that we did not get to experiment at all in this brief 10-week period, therefore, the reader should be aware of the fact that the conclusion of this experiment is not based on our own experimentations but is derived from research performed by other sources and on the hopes that if we had started to experiment everything would have worked as we expected, which is not always the case.

There are three common techniques that one can employ to coat lasers, all of which are based on traditional dielectric coating methods. Those three well-established techniques are:

1. Thermal evaporation
2. Electron beam deposition
3. RF sputtering

The common coating materials, as I mentioned earlier, used to coat lasers are sapphire (Al$_2$O$_3$), Hafnium Oxide (HfO$_2$), and Silicone Monoxide (SiO).

Thermal evaporation is usually performed with SiO and as one can tell from the terminology, it involves evaporating SiO and coating the output facet of the diode with the rising vapor. Although one can achieve reflectances below $10^{-3}$ with this method, which is convenient because the equipment required for this procedure is relatively simple, we avoided the use of it due to a challenging and intricate property that it has. Changing the oxygen pressure of SiO also culminates in a change of the oxygen composition in the film (SiO$_x$), hence a change in the index of refraction form 1.6 to 2.0.
The apparent index of refraction of SiO can also change over time depending on how frequently and how much the laser is exposed to and operated in air.

Another simple technique with which we decided to proceed is e-beam deposited Al₂O₃ or/and HfO₂. One applies this coating using a standard electron beam evaporation source. Both of these materials work well as optical coatings. Al₂O₃, sapphire is a synthetic hexagonal crystal form of aluminum oxide. It is very hard, strong and resistant to moisture and chemical attack. Its useful transmissive range extends from 50nm to 6µm. Figure 4 displays the transmission range of a layer of sapphire 1mm in thickness. It seems that its transmission peaks at values that go from 0.5 to 6.0µm. Sapphire also exhibits resistance to radiation, and has high thermal conductivity and stability with a thermal expansion coefficient of 8.4x10⁻⁶/°C (20-500°C) and a density of 3.97 gm/cm³.

The procedure is as follows: the operating wavelength is to be 780 nm, where rubidium transition form 5s to 5p occurs. We place a graphite container full of sapphire into the vacuum chamber. This chamber is in direct contact with a tube of electrons that we shoot at the graphite container. Since graphite has high thermal conductivity, the
surge of electrons causes it to heat. As the container becomes warmer, the sapphire begins to evaporate. Then, the gaseous sapphire rises up in the vacuum chamber and hits the laser diode, which in turn is coated.

There are many combinations to apply this coating technique. One may just choose to proceed with simply sapphire coating or can use a two-layer coating constituted by $\text{Al}_2\text{O}_3$ of roughly $\lambda/2$ and $\text{HfO}_2$ of $\lambda/4$ in thickness. In theory, one can usually tell how thick of a coating layer the facet needs and the coating can be done accordingly. However, most diode lasers nowadays are manufactured with a single layer on both their facets that are approximately $\lambda/2$ thick in most cases. But, there is no guarantee that the coating material used on the facet is characterized, and thickness is specified by manufacturers. As a result, we have no idea how thick our coating layer should be. It might be less than $\lambda/4$ or more than $\lambda/2$. Since we have neither the desire nor the eagerness to spend time identifying the unknown coating and its thickness, the best and easiest way to observe the coatings is to monitor the change in the threshold current [the current at which laser oscillation begins] of the laser while it is being coated. The amount of reflectivity and the threshold current are inversely proportional, this implies that the lower the reflectance, the higher the threshold current. Our task is to monitor the threshold current until it reaches a maximum where we will have achieved lowest reflectance. Since, we are not sure how thick the layer is supposed to be; it is quite possible that when we start coating the reflectance may go up and then drop. As we coat the diode further the amount of reflectance is lessened and the lowest reflectance is attained when we observe the maximum value of the threshold current. Figure 5 well illustrates the increase in the threshold current as the laser is coated. Here, the bold curve
represents a laser without a layer of coating and its threshold occurs at approximately 38mA, whereas the lightly colored curve represents a diode laser with a Al₂O₃+HfO₂ coating on its facet and clearly its threshold (68mA) is greater than that of the laser without coating.

Figure 6. The threshold current with and without coating [7]

If we adhere to meticulously careful measurements we may be able to obtain reflectances as low as 10⁻⁴ or 10⁻⁵.
**Experimental Apparatus**

The bell-jar vacuum, its instruments and the “can-opener” constitute the apparatus for this experiment. The “can-opener” as the name connotes is an inexpensive tool that is very similar to a real can opener. Its function is to remove the caps from the diodes. When doing this one must treat the diode gently and not apply too much pressure on the “can-opener” for it might crush the cap and damage the optical instrument in the diode rather than cutting through the cap. Once the cap is removed and the laser is tested for the correct output power vs. injection current behavior as depicted in the previous section, we are ready to place the laser in the vacuum chamber and commence running the experiment.

The behemoth of this experiment or the main piece of apparatus is the bell-jar vacuum chamber consisting of an aluminum spool piece (main body) and an aluminum (Appendix A) top plate 1” thick, and 18.5” in diameter. The spool piece has an inner diameter of 17.75” and is roughly 17” tall. To provide a hermetic seal we use 2 O-rings, one placed in a groove on the bottom surface of the top plate and the other on the bottom part of the spool piece. Both O-rings are made from viton, which exhibits high degrees of hardness, can withstand excessive heat and corrosive chemicals and has a temperature range from –20F to 400F. It is very important to note that both O-rings and the grooves must be maintained very carefully and be free of cracks and/or scratches. The O-rings must also be the right size for the groove. (Appendix B) Otherwise the seal would not hold. When one obtains the suitable O-rings and inserts them in grooves, the following task is to pump down the vacuum chamber to see how low the pressure gets and whether or not the vacuum holds.
This procedure basically involves setting up the vacuum chamber, sealing it and connecting it to mechanical pump, which is to pump it down. No vacuum instruments are needed at this stage for we are only concerned with how good of a vacuum medium the chamber creates. After multiple attempts that resulted in failures and modifying the O-rings a few times, (Appendix C) we achieved the lowest pump-down pressure, 190 millitorrs, which is not very close to the pressure at which our experiments are to be run. (The experimental pressure is on the order of $10^{-6}$ torrs). The chamber also did not seem to hold any pressure lower than 2000 millitorrs, which suggested the presence of leaks on the surface of the chamber as we had expected from the beginning. After detecting the leaks (Appendix D), which were mostly clustered on the welded seals on the inner surface of the bell jar, the chamber was sent to the OSU Physics Main Machine Shop for welding.

The current status of the bell-jar is unclear. It has been re-welded twice. However, it has not been leak-tested after the second re-welding. It may still leak.

The chamber has a few instruments, which assist and track the coating procedure and transmit data. These instruments are attached to the top plate, because such an arrangement facilitates the separation of the top from the main body without damaging the instruments. The instruments are:

1. **A shutter**, which is a sheet of metal suspended approximately 8” from the top and controlled by a knob on the outer surface of the plate. It prevents the sapphire vapor from hitting the diode when coating is no longer desired and need to be ceased.
2. **A sample holder plate** that holds the laser diode in place. Its main function is to provide a stable base to set the laser, and keep it from heating excessively. The diode laser is to be placed on the bottom surface of the plate and oriented downward to face directly the graphite container containing sapphire.

3. **An electric feed through**, which is basically a series of wires that one uses to transmit information back and forth and power the diode. Three of these wires are connected to the three pins of the diode. A thicker wire of brownish color extends from the top piece to the sample holder to which it is attached.

4. **A thermocouple**, which is the thick brown wire. Its function is to measure the temperature in the chamber, which will go up to approximately 3000K.

5. **A thickness sensor and monitor**, which measure the thickness of the coating. The monitor is the box that displays the information acquired by the sensor. We place the sensor on the bottom surface of the sample holder plate and orient it downward the same way as the diode at the same elevation. It is imperative that both the diode and sensor be positioned the same way at the same height so as to receive the same amount of sapphire. Otherwise the diode may have a different thickness from what the thickness monitor indicates, hence, inaccurate data. The sensor is attached to its own electric feed through that is connected to the thickness monitor, creating the necessary medium for information transmission from the sensor to the monitor. The way the sensor operates is based on a quartz crystal contained in it. This crystal begins to resonate when the sensor is activated. As the coating gets thicker, the resonance frequency of the sensor...
decreases, and the thickness monitor monitors the changes in the frequency and displays the thickness of the layer on the sensor.

Then in the big picture, we have the sample holder holding the diode and partially cooling it. The diode is connected to our data recorders by an electric feedthrough, which allows us to keep track of the current, the power and etc. going through the diode. The thickness is monitored by a thickness monitor receiving data from a thickness sensor attached to the sample holder. The thermocouple, which is in contact with the sample holder records the temperature in the chamber. And when we wish to cease coating we simply turn the shutter in such a way that it blocks the rising sapphire. If everything goes as it seems on paper and functions properly we should be able to obtain some interesting results not long after the experiment commences.

Figure 7. The vacuum instruments
Data, Data Analysis, Results

Unavailable so far.

Conclusion

Although we did not have the opportunity to run this experiment at all, it is clear to me what would have happened had we actually coated the laser. The most likely scenario would be an increasing reflectance at first, and then we would possibly begin to observe a decreasing reflectance as we continued to coat the laser. The threshold would have first dropped and reached a minimum, then started to increase until it reached its maximum value, which would of course be greater than the threshold value of the laser prior to coating.

Considering that we only have a high vacuum, and experience and skills of undergraduate students, the lowest reflectance we might have achieved would be about 1%. It is unfortunate that I have neither the data to display nor the numerical figures to corroborate my argument, but this setback is only temporary for we are indeed very close to completing our setup. I believe my research group will begin the experiment soon after I leave the program, and will acquire the type of data described in this paper.
Appendix

A) The standard material to use for high vacuums or any kind of vacuum is stainless steel, because it is more resistant to chemical attack and temperature effects. The reason as to why we are using an aluminum piece must solely be ascribed to the fact that our piece is free because we borrowed it whereas ordering a stainless steel piece of those dimensions costs thousands of dollars. Hence, although we use it now, I strongly recommend against the use of aluminum.

B) According to the technical specifications stated in “Building Scientific Apparatus: A practical guide to Design and Construction” (see bibliography for further details) the groove has to be 10% wider than the O-ring and have 70% of its depth. For instance if one uses O-rings 0.15” in cross sectional diameter, the groove has to be 0.165” wide and 0.105” deep. Failure to fulfill both these specifications will result in the O-ring moving excessively or not moving enough to provide a good seal, or in metal to metal contact, which will all culminate in the same horrendous scenario; failure to seal the vacuum and leaks.

C) The pump down procedure was quite painful. Every time we attempted to pump the chamber down, it always seemed to refuse to collaborate and was never pumped down at the first attempt, nor did it manage to hold the pressure inside. Most of the time we had to resort to the use of C-clamps to clamp the top and bottom plates onto the spool piece, 4 clamps onto the top and for onto the bottom plate, to enable the vacuum to pump down. The initial 1/8” O-rings were also replaced by oversize 0.210” O-rings. In addition to all these modifications we also employed a vacuum sealing material,
Q-sealant on the other surfaces of the vacuum along the welded lines. Or modifications eventually yielded pleasing results; we ceased to use C-clamps to trigger sealing and achieved a pressure 190 millitorrs, a decent value considering the conditions under which we work and the instruments that we have.

D) To detect the possible leaks on the chamber, we employed 2 methods, one method is fairly cheap and easy but effective, and the other involves the use of a very highly technological instrument namely the helium leak detector. Initially we resorted to the cheap procedure, which involves pressurizing the vacuum (after clamping it down of course), and spraying the welded assembly lines with a substance called “Snoop”, which is similar to soap water in content. Snoop bubbles when it is in contact with air, and this facilitates greatly the detection of small leaks. At the end of this procedure, which we did repeatedly we located many leaks, which were all clustered on the welded assembly lines that connect the lips to the cylindrical body that form the spool piece.

The second method was done to confirm our findings and pinpoint the location smaller leaks. We used a high-tech ultra sensitive helium detector to test the piece. Basically, what went on during this procedure is that the detector has a helium-pump, which we utilized to pump helium into the chamber. Once the vacuum was full of helium, we just probed a sensor on the compromised parts of the vacuum and looked for leaks. The function of the sensor is to trace helium, and display an output signal (a loud and annoying noise in this case) indicating that it has detected helium. It is connected to the detector, and can also be adjusted to a desired sensitivity. I am pleased announce that the findings of the helium detector concurred with those performed with Snoop detector.
Bibliography

1. **Building Scientific Apparatus: A Practical Guide to Design and Construction.**
   John H. Moore, Davis C. Christopher, and Michael A. Caplan.


