External-cavity frequency-stabilization of visible and infrared semiconductor lasers for high resolution spectroscopy

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We have shown that external cavity stabilization can be a straightforward and powerful technique for converting diode lasers of poor spectral quality into useful tools for high precision laser spectroscopy. The method requires an anti-reflection coating on one facet of the diode laser but, contrary to popular belief, this is not difficult and does not require any specialized equipment. We describe a coating procedure which can be used with standard commercial diode lasers. We have demonstrated the external cavity method using diodes at a variety of visible and infrared wavelengths. Details are given for a visible laser centered at 670 nm.

1. Introduction

Diode lasers are attractive sources of coherent light from atomic physics because they are cheap, small and robust. There are, however, some respects in which commercial diode lasers are not ideal for atomic spectroscopy. These include stringent requirements on the stability of temperature and injection current, difficulty of continuous tuning, a linewidth that is typically a few tens of MHz and extreme sensitivity of optical feedback [1]. Further, when a device first becomes available at a new wavelength, the spectrum is often very poor, exhibiting several longitudinal modes, each with a linewidth of several hundred MHz. The first visible diode lasers, which operated at 670 nm provide a typical example. These lasers were gain-guided with a spectrum consisting of several modes. They were followed more than a year later by index-guided devices which run on a single mode but still have the other problems listed above. A similar evolution is now in progress with 660 nm diodes which can give access to two atomic transitions of great interest: the Balmer-α line of hydrogen and the extremely narrow intercombination line of calcium [2]. Since many applications require narrowband single-mode radiation, our development of simple techniques which render such devices monochromatic and stable is of general interest.

It has been recognized for a long time that the spectral properties of a diode laser can be improved by using optical feedback to increase the effective quality factor of the cavity. One approach is to use weak feedback from a high-finesse resonant reflector [3] and this has been quite widely adopted because it does not require any modification of the diode laser. On the other hand, this method still requires excellent control of the diode temperature, diode current, and of unwanted optical feedback and does not work well with diode lasers which operate naturally on several modes. We have exploited a different approach, external cavity feedback [4,5], which uses strong feedback in conjunction with an anti-reflection coating on one facet of the laser. Although the external cavity method has some significant advantages over the weak feedback approach, it has not been widely adopted because the anti-reflection coating is generally regarded as a job for experts. In this paper we first describe a simple method for coating commercially packaged diode lasers and then give details of an external cavity design that is suitable for a wide range of visible and infrared diode lasers. As an example, we discuss the performance of a 670 nm visible diode laser modified in this way.
2. Anti-reflection coating

In order to ensure that the external cavity controls the spectral properties of the laser it is necessary to anti-reflection coat the output facet. The first step is to expose the laser by removing the top of the package using a parting tool in a lathe. Surprisingly, when the top of the package flies off, it does not usually damage the laser; we have lost only one laser out of more than 50. The coating is applied by evaporating a thin film onto the exposed output facet of the laser using a resistively heated thermal source (it appears that the discharge associated with electron-beam heating of the source damages the diode unless it is carefully shielded [6]). Of the materials which can be evaporated thermally, SiO (refractive index 1.9) is convenient and leads to an adequately low reflectivity (≈ 1%) for a quarter-wave layer. Moreover, films of SiO have good stability and adhere well to cold substrates.

The SiO is contained in a special boat (R.D. Mathis Co.) which is baffled to prevent sudden eruptions of the SiO onto the diode and which is directly heated to 1250 K by passing a current of 250 A through it. The pressure in the coating chamber must be low to obtain films of low reflectivity and good stability because the composition of the evaporated layer is affected by residual gases. We obtain good results with a base pressure of $3 \times 10^{-7}$ Torr.

The diode is mounted in a holder approximately 30 cm away from the boat. Electrical feedthroughs in the vacuum chamber allow us to pass current through the laser and to monitor the light output using a photodiode (most packages include a photodiode which monitors the light emitted from the back facet). After heating and outgassing the boat, we open a shutter and the deposition begins. The correct thickness of the evaporated layer cannot be gauged with sufficient accuracy using a standard crystal monitor. Instead, we monitor the decrease in reflectivity directly by observing the corresponding decrease in the intra-cavity power of the laser. We occasionally increase the injection current in order to keep the laser just above threshold, and when the reflectivity passes through its minimum value, the signal on the photodiode goes through a minimum and we close the shutter. Since the power emitted from the coated front facet is considerably higher than emerging through the back facet into the photodiode $^1$, one has to be careful not to destroy the laser even when the photodiode reading is quite modest. Typically, the deposition takes three minutes. The boat is then allowed to cool and the vacuum system is backfilled with dry nitrogen. Although we have used a commercial vacuum deposition system for our coatings, we could equally well have used any small vacuum system, such as an atomic beam apparatus, with suitable electrical feedthroughs.

In fig. 1 we show the output power versus injection current ($L/I$ characteristic) for a gain-guided 670 nm diode (NDL3200 manufactured by NEC) before and after coating. We have found that this curve is a convenient and sensitive measure of the quality of the coating; deterioration appears as an increase in the slope accompanied by a decrease in the threshold. If the coating is carried out as we have described, it is typical to find no change in the $L/I$ characteristic even after the diode has been operated for several months. Some lasers, usually higher power devices, have a partial anti-reflection coating of Al$_2$O$_3$ ($n = 1.65$). In that case, the minimum of reflectivity due to an additional layer of SiO is not so low and

\[ P_{c}/P_{u} = \left( \frac{1 - R_c}{1 - R_u} \right)^{1/2}, \]

where $R_c$ and $R_u$ are the coated and uncoated reflectivities respectively.

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$^1$ The ratio of powers is given by $P_c/P_u = \left[ (1 - R_c)/\sqrt{R_u} \right]/\left[ (1 - R_u)/\sqrt{R_c} \right]$. 

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![Fig. 1. $L/I$ characteristic of NDL3200 laser diode before and after anti-reflection coating.](image-url)
the tunability of the laser is adversely affected as discussed in the following section.

3. Cavity construction and operation

We illustrate in fig. 2 our design for a general external cavity laser which we build on a base of invar of quartz. One end of the 12 cm long cavity is formed by a Littrow-mounted diffraction grating (1200 lines/mm, blazed for 750 nm) glued to a piezoelectric crystal and held by a commercial mirror mount. The other end of the cavity is the uncoated backfacet of the laser diode. The diode is rigidly mounted on a heat sink whose temperature can be adjusted using a Peltier cooler. A short focal length (4.5 mm) plastic lens collimates the laser output light and a fine thread in the mount allows us to adjust the distance between the laser and the lens. Light is coupled out of the cavity using a beam splitter. Although the packaged laser is hermetically sealed, there seems to be no problem associated with running the diodes in air. In the interests of stability, however, we do cover the whole cavity with a lucite box to exclude draughts.

When this cavity was used with the multi-mode, gain guided diodes at 660 nm and 670 nm we could not obtain stable, single-frequency operation without the addition of an intracavity etalon (1 mm thick, reflectivity 85% on a commercial mirror mount), even when the cavity length was reduced to only a few centimeters. In the absence of this etalon the laser usually operated on a few adjacent external cavity modes. It was not normally required for any of the infrared diode lasers we used provided that the cavity length was made short enough – typically a few centimeters.

In order to align the cavity, the laser injection current is set to a value a little above the threshold of the uncoated diode. The laser and lens are moved transversely until the light falls near the center of the grating and are then fixed in place. The output beam from the diode is polarized parallel to the plane of the junction and is often elliptical. If the diode is mounted with the plane of the junction vertical (parallel to the lines of the grating) more lines are illuminated by the spot and the resolution is improved. Alternatively, if the junction is horizontal, fewer lines are illuminated but the reflectivity of our grating is then higher because of the polarization of the light [7]. Of course, both high resolution and high reflectivity are desirable, but in practice we find that the red diode operates better with its junction in the vertical plane. The distance between the diode and the lens is adjusted until the size of the strip of light returning from the grating is slightly less than the diameter of the lens, then the grating is rotated to direct the return beam back into the laser. The resulting increase of intracavity power appears on the photodiode. Now the injection current can be cautiously increased while rocking the vertical tilt of the grating until lasing occurs. A fine adjustment of the distance between the laser diode and the lens is usually needed to optimize the output power. Finally, if the etalon is to be used, it is now placed in the cavity.

The laser wavelength can be tuned coarsely over a range of about 20 nm simply by rotating the grating. The residual reflectivity of the coated facet leads to small gaps in the tuning curve (typically 100 GHz every 500 GHz) which can usually be filled in by making small changes to the diode temperature or injection current. The size of the gaps is larger if the reflectivity of the output facet is higher, as in the case of diodes that are partially anti-reflection coated by the manufacturer. If the etalon is being used, the laser makes 100 GHz etalon mode-hops when the grating is rotated and 1.2 GHz longitudinal cavity mode-hops when the etalon is rotated. The laser frequency can be scanned continuously over about 1.2 GHz by moving the grating with the piezoelectric translator, and much larger scans are possible if the etalon is simultaneously rotated to prevent mode-hops.

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**Fig. 2.** Schematic diagram of external cavity laser.

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*We use an inexpensive grating from Edmund Scientific but we expect that more expensive gratings would work equally well.*
We usually pass a constant current through the Peltier junction in order to cool the diode. This lowers the threshold, improves the mode quality and prolongs the lifetime of the laser. Lowering the temperature also moves the whole gain curve to shorter wavelengths which may be an advantage for some applications. The external cavity laser is very much less sensitive to variations of the diode temperature because the diode itself is only a small part of the cavity. As a result, no temperature stabilization is required. Similarly, the variation of frequency with fluctuations of the injection current is so greatly reduced that ordinary laboratory current supplies can be used. Our supply consists of a car battery, a variable resistor and some protection components.

The external cavity laser has one other significant virtue. It is extremely insensitive to back reflections of the output beam and therefore normally requires no optical isolation from the rest of the apparatus.

4. Performance

The method described above is very general. We have demonstrated it with the following laser diodes: Hitachi HLP1400 and Mitsubishi ML3401 near 830 nm; Panasonic LN9705 near 805 nm; ML4402E and ML4102 near 780 nm; NEC NDL3200, Toshiba TOLD9200 and TOLD9211 near 670 nm; TOLD9220 near 660 nm.

Most recently, we have tested our method using a Phillips OF4999 laser diode. At a temperature of 5 °C we observed a 1 mW output of single-mode radiation at 630 nm. This is the shortest wavelength of single frequency output obtained from diode lasers to date.

Here we give typical parameters for NDL3200 which was the first red diode to be commercially available. It is interesting for applications in atomic physics because it can be tuned to the resonance line of Li, but the unmodified diode runs on several modes, each with a linewidth of several hundred MHz.

The external cavity forced the diode to operate in a single, narrow mode. We typically chose to cool the laser to 0 °C at which temperature the wavelength was coarsely tunable from 600 nm to 675 nm by rotation of the grating. Examination of the light with an optical spectrum analyzer showed no secondary modes with the etalon installed in the cavity (see fig. 3). Using an uncoated glass block as an output coupler, a total power of 3 mW was distributed over four output beams. With a coated beam splitter we were able to obtain power in excess of 6 mW in the strongest of the output beams. At this level the manufacturer’s power rating is exceeded and presumably the lifetime of the laser is reduced, but we note that the price of a new diode is comparable with that of a few grams of laser dye!

When two such lasers were mixed, we obtained the heterodyne spectrum given in fig. 4, which shows that...
the linewidth of the laser is less than 50 kHz in a sampling time of a few milliseconds. On a longer scale the acoustic jitter of the cavity increases the linewidth to a few hundred kHz but this can readily be suppressed by feedback to the piezoelectric crystal on which the grating is mounted. If greater servo bandwidth is required, a crossover network can be used to send the higher frequency components of the error signal to the injection current. In this way we have locked the laser to a transmission peak of a stable cavity whose linewidth was 35 MHz wide. The residual error signal indicated that the total laser jitter relative to the cavity was reduced to less than 30 kHz.

For this diode the normal variation of frequency with temperature is of order 100 GHz/K. When installed in the external cavity this was reduced by a factor of 100 which eliminated the need for active temperature stabilization of the diode. The dependence of frequency on injection current was similarly reduced to approximately 40 MHz/mA in the external cavity laser.

An experiment [8] recently undertaken to study the Stark shift of the 671 nm resonance line of Li demonstrates the value of this laser as a practical tool for atomic physics. The measured spectrum of this transition is shown in fig. 5 in which the natural width and the residual Doppler width contribute 6 MHz each to the observed linewidth of 12 MHz. During the course of this experiment, two external cavity diode lasers were separately servo-locked to a Li atomic beam for hours at a time while electric-field-dependent changes in the heterodyne frequency were measured with an accuracy of a few hundred hertz.

5. Conclusion

We have demonstrated a simple method for modifying standard commercial laser diodes to obtain widely tunable, narrow-band, single-mode light by anti-reflection coating the output facet and operating the diode with strong feedback from an external cavity. The method is inexpensive, easy to reproduce and applicable to a broad range of laser diodes.

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References