4. SEMICONDUCTOR DIODE LASERS*

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4.1 Introduction

This chapter deals with the technology of applying semiconductor lasers to scientific and technical fields. Diode lasers are prevalent in many applications because of their well-known attributes: high reliability, miniature size, relative simplicity of use, and relatively low cost. These factors are important, but the use of diode lasers in technical fields is also increasing because of their unique capabilities, such as: tunability, high efficiency, useful power levels, reasonable coherence, and excellent modulation capabilities. Volumes of information are already available on the technology of semiconductor lasers [1–8]. Their application to scientific fields has been discussed in a few review articles [9–13], and at least one special issue of a journal focused on the spectroscopic detection of atoms and molecules using diode lasers [14]. As in any rapidly advancing field, this information becomes outdated quickly and will need to be supplemented with current journal publications. We will concentrate here on the basic laser characteristics and general principles of operating single-frequency, tunable, diode laser systems.

4.2 General Characteristics of Diode Lasers

A wide variety of diode lasers are now commercially available. These range from low-power/high-speed communications lasers to high-power/wide-stripe devices that run multimode (both spatial and temporal) and are used mainly for pumping solid-state lasers. For most scientific applications it is much easier to use

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single spatial-mode lasers, and we will concentrate on these devices here. In addition to the usual Fabry–Perot type lasers, distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers are now commercially available at some wavelengths. These lasers have a more complex resonator structure that incorporates an optical grating fabricated within the semiconductor chip. Bragg reflection from the internal grating provides wavelength-selective optical feedback that forces single-longitudinal-mode operation at a wavelength within the reflection bandpass of the grating.

Figure 1 gives a rough sketch of the current (1995) distribution of commercially available continuous wave (CW) single spatial-mode semiconductor lasers. There are gaps in the wavelength coverage (and actual availability) and significant differences in performance across this distribution. Some typical characteristics of semiconductor lasers are outlined in Table I. More details can be found in manufacturer's catalogs and an excellent recent handbook [15].

Another family of semiconductor lasers (outside the scope of the present chapter) is based on group IV–VI elements (most common are Pb-salt lasers). These lasers span the wavelength range from 3.3 to 30 μm and operate at cryogenic temperatures. The lead-salt lasers have not experienced the same degree of commercialization as the room-temperature devices, primarily because they are much more expensive and they have poor mode quality and relatively low output powers (≤ 5 mW). However, high-quality devices using Sb-based semiconductors that operate at wavelengths that range from ~2 to 4.5 μm have been developed [16]. These promising new devices, unfortunately, are not yet commercially available.

4.2.1 Tuning Characteristics

Often of paramount importance for scientific applications are the tuning characteristics of a laser. A diode laser's wavelength is determined by the semiconductor material and structure, and is a function of both temperature and carrier density. For a typical single-mode laser the wavelength increases monotonically with increasing temperature and then suddenly jumps to another mode at a longer wavelength. Although this jump is most often to the next cavity mode (~0.3 nm cavity mode spacing), it is not at all unusual for one or several modes to be skipped. The tuning range of each mode is typically on the order of 25% of the mode spacing, but might vary by a factor of 5 or more. Subsequently decreasing the temperature causes the operating wavelength to shift downward with similar behavior, but hysteresis will be observed at the mode transitions. Details of the tuning characteristics are available in the general references [1–8] and [17].

Operating a simple diode laser at the wavelength of an atomic or molecular transition usually requires iterative selection of injection current and temperature settings. However, for any given laser the optimum tuning to a specific wavelength cannot always be achieved. Possible alternatives include trying several lasers or
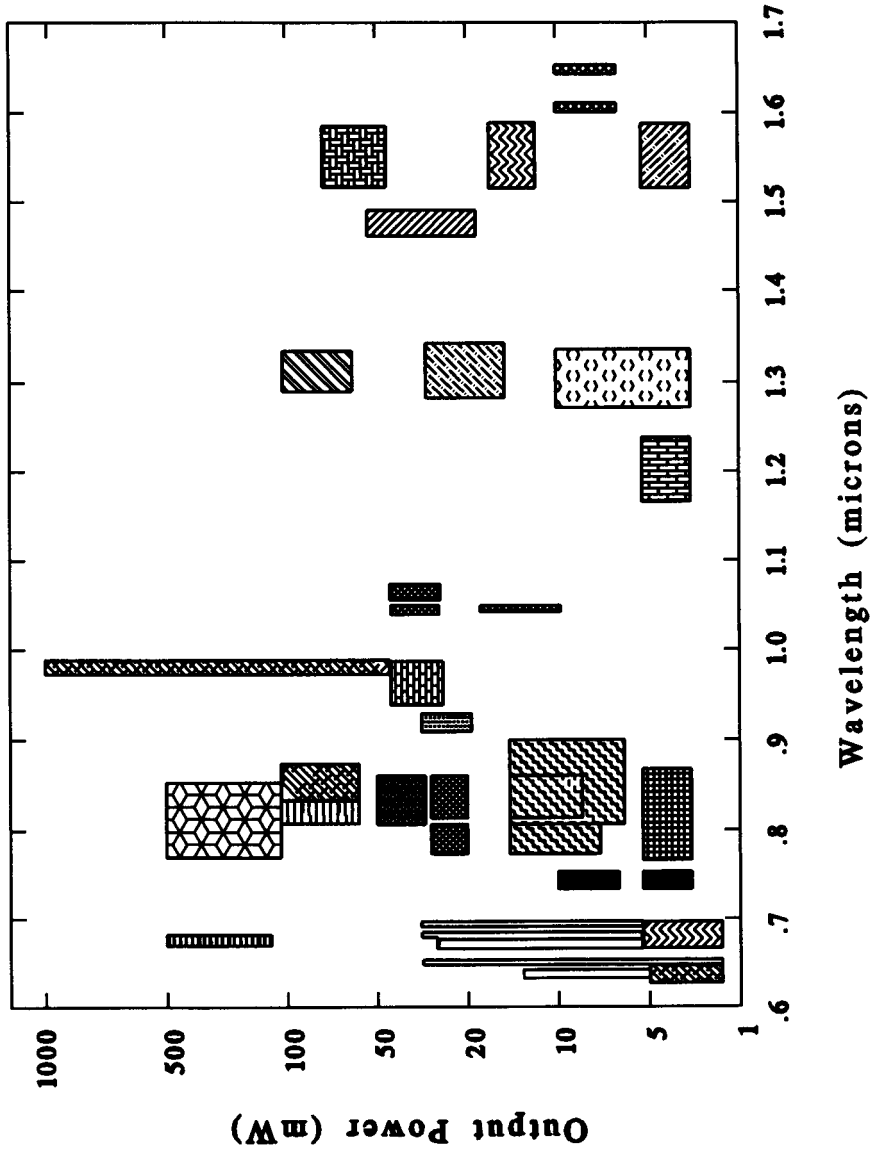
FIG. 1. Power vs. wavelength of commercial single spatial-mode CW room-temperature semiconductor diode lasers. Much of this information has been taken from various literature sources and manufacturer's catalogs and has not necessarily been verified.

TABLE 1.   Typical Semiconductor Laser Parameters[a]

Semiconductor	$(Al_xGa_{1-x})_yIn_{1-y}P$	$Al_xGa_{1-x}As$	$Ga_xIn_{1-x}P_yAs_{1-y}$	MOPA
Wavelength	635–670 nm	750–850 nm	1.3–1.5 μm	670, 780–850, 980 nm
Output power (mW)	3–30	5–200	3–100	500–1000
Far-field divergence FWMI (degrees)	8 × 40	11 × 33	30 × 35	0.3 × 35
Waveguide mode dimensions (μm)	4 × 1	3 × 1	1.25 × 1	1 × 100
Astigmatism (μm)	~10	1–5	1–5	~500
Threshold current	30–90 mA	20–60 mA	20–50 mA	~0.5 A
Operating current	50–120 mA	50–200 mA	40–120 mA	~2.5 A
$I_2 = I_1 e^{(T2-T1)/T0}$	$T_0 \approx 100$ K	$T_0 \approx 150$ K	$T_0 \approx 60$ K	
Slope efficiency (mW/mA)	0.5–0.7	0.7	0.2	1
Refractive index	3.1–3.5	3.3–3.6	3.2–3.5	3.3–3.6
Frequency vs. injection current (GHz/mA)	~5	~3	1	
Frequency vs. temperature				
Large-scale (nm/K)	~0.2	~0.25	~0.3	
Small-scale (GHz/K)	~30	~30	~10	
Gain bandwidth (nm)	20	30	50	20
Typical linewidth (MHz)	200	5–20	100	
Alpha factor (α)		3–6	4–8	

[a]These values are representative examples and can vary significantly with structure and composition. The data applies to index-guided single spatial- and spectral-mode Fabry–Perot lasers. Much of this information has been taken from various literature sources and manufacturer's catalogs and has not necessarily been verified.

using optical feedback techniques to control the wavelength. Extended-cavity lasers (Section 4.3) allow tuning to any wavelength within the gain curve of the laser. Another option is to place a small mirror near (~100 μm away) the laser's facet, forming an etalon that acts as a mode selector [18]. An attractive alternative (but improbable for other than a few standard wavelengths) is to find a monolithic DBR laser that operates at the desired wavelength.

4.2.2 Output Power

A typical output power vs. injection current (*P–I*) curve for a CW diode laser is shown in Fig. 2. The slope of the *P–I* curve above threshold gives the laser's slope-efficiency (in mW/mA). Semiconductor lasers operate as forward-biased diodes with the voltage drop fixed by the bandgap and an additional series resistance of about 2 to 50 Ω. As expected for a semiconductor diode, the laser's

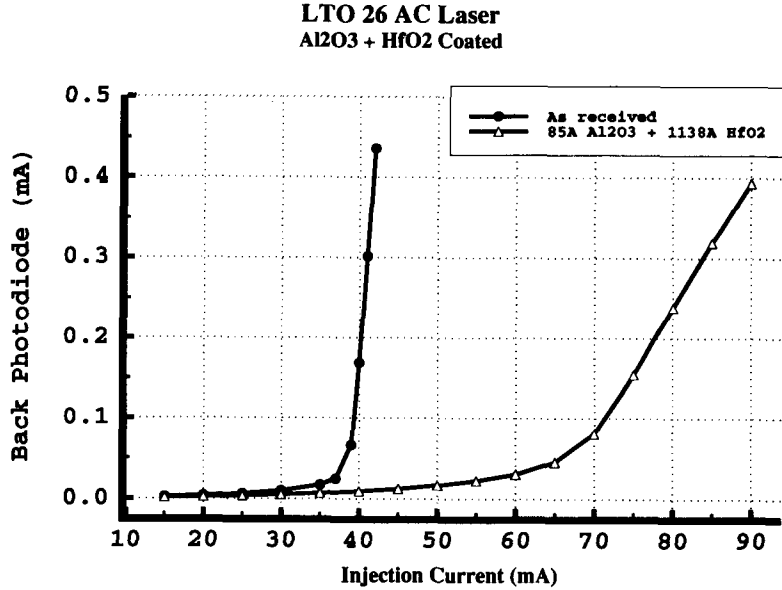**LTO 26 AC Laser**
Al2O3 + HfO2 Coated

FIG. 2. Output power vs. injection current for a typical AlGaAs diode laser operating near 780 nm. The vertical axis is photocurrent from the photodiode that monitors power out of the laser's back facet. The solid dots show the $P-I$ curve of the standard commercial laser as received ($I_{th} \approx 38$ mA), while the open triangles show the $P-I$ curve of the laser after we coated the front facet with an antireflectance (AR) coating ($I_{th} \approx 68$ mA). As fractionally more power is coupled out the front facet, the slope efficiency of the back facet power is decreased.

operating characteristics are strongly temperature-dependent. Using a simple model for a diode laser [3, 5] gives a threshold gain of

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

and a total output power above threshold of

$$P_{total} = \frac{\eta_i h\nu (I - I_{th})}{e \, g_{th} L} \ln\left[\frac{1}{R_1 R_2}\right], \qquad (2)$$

where R_1 and R_2 are the facet reflectances, a_L is the loss internal to the laser, $h\nu$ is the photon energy, I is the injection current, I_{th} is the threshold injection current, η_i is the internal quantum efficiency, e is the electron charge, and L is the laser length. The threshold will vary with temperature as $I_2 = I_1 \exp [T_2 - T_1)/T_0]$, where

T_0 is a characteristic temperature for the laser. A more precise theoretical treatment allows parameters in these equations to depend on wavelength, carrier density, semiconductor material, and laser structure. If the injection current is increased to excessively high values, the P–I curve becomes sublinear, with the output power eventually decreasing due to gain saturation, heating, or damage resulting from high optical powers on the facets. Operation at overly high currents shortens the lifetime and can seriously damage or destroy the laser. An important measure of a laser's operating characteristics is the pumping rate, $R = (I - I_{th})/I_{th}$, which is the injection current above threshold normalized to the threshold value. Generally in the safe operating region of temperature and current, the laser's characteristics improve with pumping rate: the power increases, the linewidth decreases, and the relative amplitude noise decreases.

Recent advances in diode laser technology have produced impressive results in high-power devices based on tapered amplifier designs. By starting with a narrow-stripe single-mode waveguide and then expanding the width of the waveguide out to larger dimensions, the output power can be increased while retaining single spatial-mode operation. Thus, monolithic master-oscillator/power-amplifier (MOPA) systems can be integrated into a single semiconductor chip [19]. The increase in power obtained with tapered amplifiers scales roughly as the ratio of the widths of the output to input waveguide dimensions. Single spatial-mode devices with watt-level output powers are now appearing on the commercial market. Obviously, high-power devices will open up many new possibilities. Of particular interest will be their use with nonlinear optical materials to access other spectral regions.

4.2.3 Beam Quality

The spatial mode produced by diode lasers depends on the laser structure and the collimating optics. Since the output beam diverges rapidly from the small semiconductor waveguide, a high-numerical-aperture lens is needed to collect the light into a collimated beam. Beam quality is not always what we might hope for, but at least in the case of single-mode lasers it can be corrected to be nearly cylindrically symmetric Gaussian. Output beams are typically asymmetric, with a larger divergence in the direction perpendicular to the junction (see Table I). Well above threshold, most are strongly polarized with the electric field parallel to the junction. The modes can also have astigmatism, which manifests itself as the apparent axial separation of the source of rays in the planes parallel and perpendicular to the junction. Astigmatic distances for Fabry–Perot lasers are generally in the range of 1 to 10 μm, while for tapered amplifiers the astigmatism can be ~1 mm, about half the length of the chip. Left uncompensated, this aberration may degrade the beam quality and result in an aberrated far-field intensity distribution. A cylindrical lens can be used to correct the astigmatism, while the asymmetry in

divergence is often corrected with a pair of anamorphic prisms that are oriented to angularly magnify the smaller divergence and hence produce a nearly circular beam [20]. Alternatively, a cylindrical telescope can be used to correct the angular asymmetry. In addition, there are sometimes small changes in the spatial mode parameters with large changes in the pumping rate R.

4.2.4 Laser Amplitude Noise

An important attribute of semiconductor lasers is that they typically have much lower amplitude noise then other tunable laser systems. For example, a single-mode laser operating well above threshold might typically exhibit amplitude fluctuations that approach the shot-noise level for frequencies above ~1 MHz. The noise does increases toward lower frequencies with an approximately $1/f$ dependence. A common measure of the amplitude noise is the relative intensity noise: RIN $= \langle \Delta P^2 \rangle / \langle P \rangle^2 \approx [2 \cdot \Delta f S_p(f)]^2 / \langle P \rangle^2$, where Δf is the detection bandwidth, $S_p(f)$ is the spectral density of the power fluctuations, and $\langle P \rangle$ is the mean power. In general, RIN will decrease with increasing pumping rate. If the laser is operated in a multimode regime, the amplitude noise may be much more pronounced, especially when there are only a small number of modes oscillating. Optical feedback can also cause increased amplitude noise.

4.2.5 Optical Feedback

The effects of optical feedback on diode lasers can be profound and depend on a number of factors: the amount of feedback, the facet reflectance, the pumping rate R, and the distance from the laser to the source of feedback (feedback time delay). In some regions of this multidimensional space, the feedback can narrow the linewidth and stabilize the laser's wavelength, while in other regions optical feedback causes such instabilities as erratic mode jumping and coherence collapse [5, 21–24]. In general, optical feedback (even small amounts $P_{\text{feedback}}/P_{\text{out}} \leq 10^{-5}$) from uncontrolled sources should be avoided. For many applications this simply means tilting optical elements to avoid direct reflections. In other cases we are forced to use Faraday isolators, which unfortunately tend to be bulky and expensive for wavelengths less than 1 μm. In some of the next sections we discuss ways to use optical feedback to advantage.

Even though the terminology used to describe diode lasers is inconsistent and imprecise, it may be useful to review some of the nomenclature. For some reason the description "solitary laser" has come to mean a semiconductor diode laser that has not been modified by external effects such as optical or electronic feedback. "External cavity laser," on the other, hand describes a system that lases only because of optical feedback from external optical elements [25]. The name "extended-cavity diode laser" (ECDL) has come to mean something between these

two cases; that is, when the laser 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. Sometimes the nomenclature and jargon are more confusing than useful.

4.2.6 Laser Degradation

When properly protected from electrical damage, semiconductor diode lasers are reliable and long-lived. However, there are variations from laser to laser and some variations of laser characteristics with time. Quite a lot of research has been done on the degradation of laser diodes (there is even a book on the subject [26]). However, we still lack detailed understanding of some aspects of laser aging, such as the change in laser wavelength with time. Some characteristic modes of laser degradation are now recognized, including "dark line defect" and facet degradation (which can be caused by gradual photochemical effects or catastrophic optical damage, COD). There seems little that users can do about these changes other than providing good electrical protection and a clean environment for lasers whose facets are open to the air. High currents and high temperatures will increase the rate of degradation. When treated properly, modern lasers have very long natural lifetimes (~10,000 h), but unnatural lifetimes can be quite short!

4.3 Extended-Cavity Lasers

Tuning the wavelength of diode lasers and narrowing their linewidth can be accomplished using some form of dispersive optical feedback [27]. Designs that employ relatively high optical feedback power, $P_{feedback}/P_{out} \gtrsim 0.05$ (which is the power fed back into the laser's waveguide mode relative to the output power without feedback), can have a large tuning range and be very stable. In addition to broad tuning, extended-cavity lasers typically have much narrower linewidths than solitary lasers (fast linewidths ~50 kHz as opposed to ~20 MHz). Diffraction gratings are the most commonly used dispersive feedback element, although intracavity etalons, prisms, and birefringent filters have also been used successfully.

Good-quality commercial extended-cavity diode laser systems are now available from a few manufacturers, but distribution in terms of power and wavelength are still somewhat limited. Because of special requirements or cost constraints, users may find it desirable to build their own extended-cavity systems. This can be done relatively simply, as described in a number of papers [7, 12, 28, 29] and as we outline below.

4.3.1 ECDL Construction

There are many good designs for extended-cavity lasers, but no particular design that is optimum for all applications. In Fig. 3 we see five different configu-
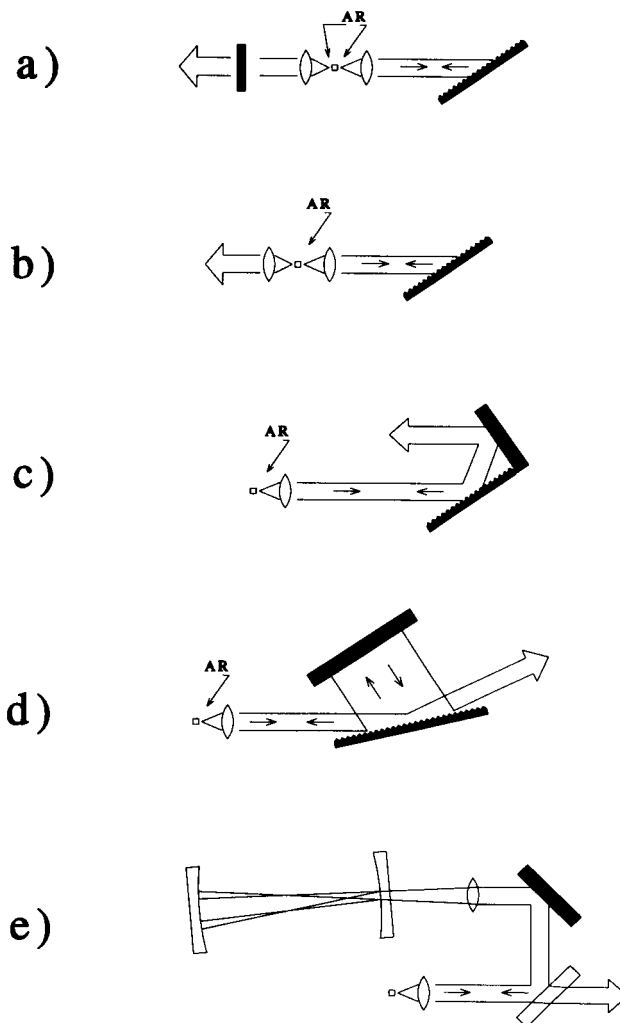
FIG. 3. Various optical feedback configurations. The first design (a) is a two-sided external-cavity design, (b,c) are single-sided extended-cavity designs in Littrow configuration, (d) is an extended-cavity laser that uses a grating in a grazing-incidence configuration, and (e) is a resonant optical-locking configuration using a confocal Fabry–Perot cavity. Design (b) is appealing because there is no movement of the output beam when the grating is rotated to tune the wavelength, and it can also be optimized to deliver high output power. On the other hand, it has the disadvantage that it requires a special laser package (or a rather severe modification of standard laser packages) to gain unobstructed access to both facets. In present usage, the two most common tunable laser designs are (c) and (d) because they are relatively easy to implement using commercial lasers.

rations of optical feedback that can be used to control diode lasers. For optimum performance many of these designs require good antireflection coatings on the output facet of the chip (see Section 4.5).

When designing a laser cavity, it is important to remember that the diffraction efficiency of typical gratings has a strong polarization dependence. For beams polarized perpendicular to the rulings we expect high diffraction efficiency, while for beams polarized parallel the efficiency can be significantly reduced. In the Littrow configuration (Fig. 3b,c), the number of grating lines covered by the laser mode is constrained by the focal length and numerical aperture of the collimating lens, the orientation of the laser spatial mode, and the line spacing and corresponding cutoff wavelength of the grating. Since the beam from a laser waveguide is normally polarized in the direction parallel to the junction, in the far field the laser beam is polarized along the narrow dimension of the spatial mode. When the laser's asymmetric mode is incident on a diffraction grating, there is a compromise between high resolution and high diffraction efficiency. The user has very little freedom of design, which means that the resolution is sometimes not as high as we would like. In some cases it can be advantageous to use a half-wave plate between the laser and the grating to decouple the polarization (hence diffraction efficiency) from the spatial mode orientation. An alternative approach is to use prisms to expand the small direction of the spatial mode [20, 24, 30]. With the one-sided Littrow configuration (Fig. 3c) there is also the disadvantage that the beam moves as the laser's wavelength is tuned. A remedy to the problem of beam movement with tuning (present in the Fig. 3c configuration) is to use a mirror mounted with its surface perpendicular to the grating surface so as to form a retroreflector. Rotating both the grating and mirror together leaves the output beam direction unchanged, although there will be some beam displacement if the axis of rotation is not defined by the intersection of the grating and the mirror. This arrangement is not easily compatible with long continuous scans.

Even with these limitations we often use the standard Littrow configuration (Fig. 3c) because of its simplicity, and most of the time it works reasonably well. For many applications (atomic physics in particular) large tuning ranges are not very important. In practice one can achieve continuous scans of ~2 to 10 GHz by simply arranging the grating pivot point so that the grating angle tunes synchronously with the laser's frequency as controlled by the extended-cavity length. Coarse tuning can be accomplished manually with a fine pitched screw. A typical 800-nm system might consist of an 8-mm focal length collimating lens (N.A. = 0.5), an 1800-line/mm grating in Littrow configuration with a cavity length of about 5 cm. In a typical Littrow system we normally orient the laser mode so that the larger dimension is orthogonal to the direction of the grating rulings. This orientation gives better resolution and better output power than the opposite orientation.
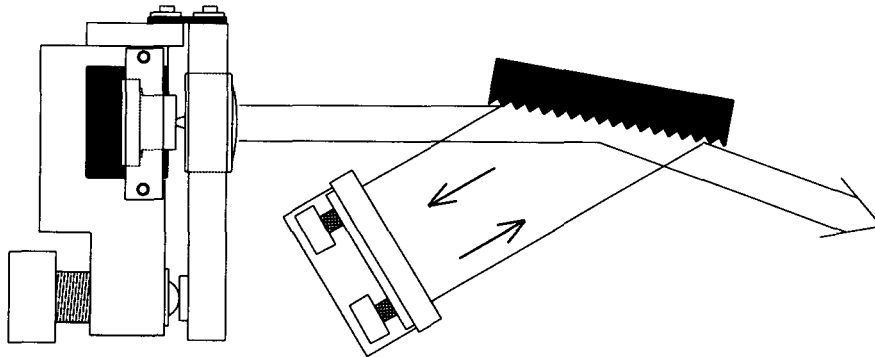
FIG. 4. Diagram of a simple grazing-incidence grating-tuned extended-cavity diode laser. This extended-cavity system is constructed of three basic units: the laser mount, the grating mount, and the feedback mirror. The diode laser, Peltier cooler, and collimating objective are all integrated together in a stable laser mount that uses a flexure and fine-pitched screw for precise focus adjustment. The feedback mirror and the angle of the grating are adjusted relative to laser beam direction to provide just enough optical feedback power for stable single-mode operation.

The grazing incidence arrangement (Fig. 3d) as proposed by Harvey and Myatt [31] was shown to have the important advantages of significantly higher spectral resolving power and no movement of the output beam when the laser is tuned. This design, implemented with diode lasers by Harvey, is often called the Littman (or Littman–Metcalf) configuration because they introduced the use of grazing-incidence gratings to control dye lasers [32]. Good discussions of the grazing incidence design have also been given by Day [33]. A simple mechanical layout for a grazing-incidence grating-tuned ECDL is shown in Fig. 4.

In designing all of these systems we need to address a few basic requirements. We need to precisely align the laser cavity, to tune the wavelength, and to precisely control the laser chip temperature and extract excess heat. Care must be taken to ensure a stable thermal and mechanical structure by using good materials and kinematic design principles. Ironically, ECDLs provide narrow spectral line-widths, but they are also much more susceptible to external perturbations than were the solitary lasers that we started with! For stable single-frequency operation, ECDLs need to be isolated from vibrations and pressure fluctuations. A useful principle to keep in mind in this design is: *if something can move, it will*. Allowing a large dynamic range of motion competes directly with stability.

The simple optomechanical design sketched in Fig. 4 is an example of a versatile system that satisfies most (but never all) of our basic requirements. It consists of a copper baseplate (not shown) that acts as a rigid backbone for the laser resonator and at the same time serves as the heat sink for the temperature

control system. A commercial laser is mounted in a small copper fixture that bridges the Peltier cooler and attaches to the laser base mount (also copper). The base mount is then rigidly attached to one end of the baseplate. The collimating lens is connected to the laser base mount by a stiff spring-steel flexure that is clamped in place using locating pins and multiple screws. The lens is mounted in an eccentric ring that is clamped in place after initial coarse alignment. The transverse alignment can be set accurately enough with careful hand alignment and visual inspection of the beam direction and shape. In the example of Fig. 4, the eccentric on the lens mount is used to adjust the vertical height of the lens, while the horizontal position is set by the transverse displacement of the laser on the base mount. Critical adjustment of the focus is done with a high-quality fine-pitched screw that translates the lens against the restoring force provided by the flexure. We typically use 6.3-mm diameter screws with 3.1 threads/mm (1/4-80 screw). The lever arm from the flexure pivot point (Fig. 4) gives further drive reduction. This simple design tilts the lens slightly as it is translated for focusing; however, this is not a serious limitation because the lens can be set very close to the optimum position before it is clamped in place. In constructing this system we tolerate the thermal expansion of copper in order to have the good thermal conductivity and low mechanical Q. For very-high-frequency stability the cavity length can be controlled with a PZT. For some high-power lasers we use water cooling in the laser base mount. The water can be circulated without pump vibrations by using a simple thermal syphon.

One of the requirements for stable operation of ECDLs is to return sufficient optical feedback power to the diode laser waveguide mode. The optimal feedback power depends on the characteristics of the laser and, in particular, the reflectance of the output facet. Typically feedback power ratios ($p_{feedback}/p_{out}$) of from 5 to 50% are appropriate. In grazing-incidence systems the feedback mirror and the angle of the grating (relative to the laser beam direction) are adjusted to provide just enough feedback power for stable single-mode operation (typical incidence angles for the grating might be ~75–85°). Good-quality high-numerical-aperture objectives (N.A. ~ 0.5) are recommended for the collimating lens. In most cases it is not necessary to correct for the laser's astigmatism for the laser to function properly in extended-cavity mode. However, the output beam will have some aberration if only spherical optics are used. Objectives lenses specifically designed for diode laser collimation often assume that there is a thin window between the laser chip and the lens. For best mode quality, the lens design needs to take into account any window on the laser mount.

4.3.2 Alignment

The optical alignment of extended-cavity lasers requires precision, but with practice alignment can be accomplished in a simple common-sense manner. Infra-

red-sensitive cards that fluoresce in the visible are extremely useful when working with near-IR lasers. Electronic IR viewers or CCD cameras can also be used. For the initial alignment, the objective lens is carefully centered on the laser's output so that the beam propagates in the same direction as the unperturbed laser emission. The beam should appear roughly collimated over a distance of several meters. The grating is then positioned so that the first-order diffracted beam returns to the laser (taking care that the grating blaze is toward the lens). A card with a small aperture held in front of the lens is useful to roughly position the returned beam on the outgoing beam. Fine tuning of the focus and alignment will then be necessary to obtain stable single-mode operation.

The method that we use most often to align ECDLs was derived from work describing the output power-vs.-injection current characteristics of ECDLs [21, 34, 35]. The method is simple and requires only monitoring the output power as a function of the swept injection current. Following the coarse alignment procedure described above and with the laser operated near threshold, a triangular ramp is applied to the injection current. Monitoring the output power of the ECDL with a large-area photodiode and an oscilloscope (synchronized to the triangular wave) yields a classic diode laser $P-I$ curve with no optical feedback (see Fig. 2). When there is feedback from the extended cavity, there will be abrupt discontinuous changes in threshold behavior. Iterative adjustment of the focus and extended-cavity alignment will result in oscilloscope traces similar to those in Fig. 5.

4.3.3 Tuning

The maximum tuning range of an ECDL depends on the design of the cavity and on the detailed characteristics of the diode laser chip. Factors that affect the tuning include: the facet reflectances, the degree to which the spectral broadening is homogeneous, the side-mode suppression ratio, the pumping rate R, the spatial mode control (how well the mode is index guided), and the propensity for nonlinear coupling between modes (for example, four-wave mixing). As users, the facet reflectance is almost the only parameter that we have any control over. If the reflectance of the laser facet that faces the grating is very low ($<10^{-4}$), the maximum tuning range can be as large as the laser's gain curve (approximately ±20 nm for AlGaAs lasers and even larger for InGaAsP lasers). Continuous single-mode scans over many nanometers require very low facet reflectance and synchronization of the tuning of the grating passband with change in cavity length.

4.4 Electronics

The electronics required to operate semiconductor lasers are relatively straightforward and can be very simple if we do not require precise tuning. Since the
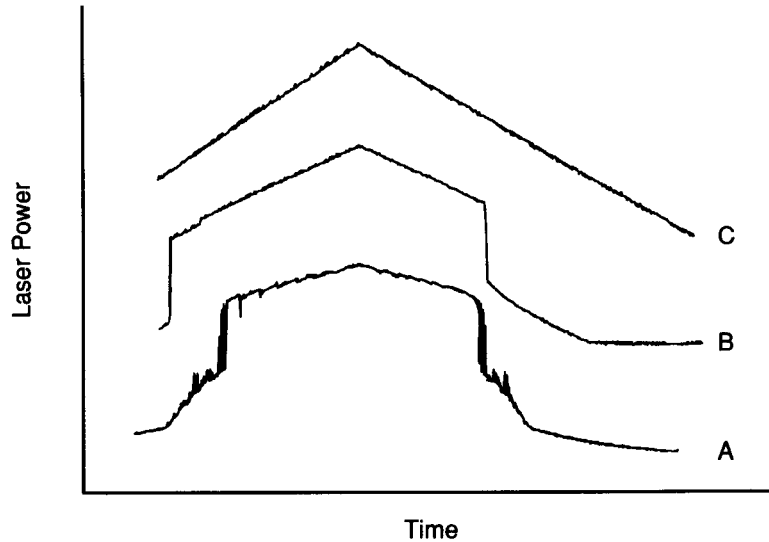
Time

Fig. 5. Output power of ECDL vs. injection current, which is swept near threshold with a triangle wave. Three different *P–I* curves are shown for different cavity alignments; the curves have been offset vertically for clarity. The horizontal axis (labeled here as time) is synched with a triangle wave ramp, with maximum injection current corresponding to maximum output power. The characteristic features of the *P–I* curve are a good indicator of the quality of the extended-cavity alignment. As the focus of the collimating lens and feedback from the grating are aligned, the output power increases in abrupt steps. The rounded corners and noise on curve A corresponds to poor cavity alignment and are indicative of multilongitudinal mode operation. Curve B shows the type of abrupt jumps that are indicative of single-mode operation. Curve C is near-optimum alignment, where the injection current has very little effect on the laser's frequency and no mode jumps are apparent.

laser's output power and frequency depend sensitively on temperature and injection current, we need to control both with some precision. The typical laser parameters in Table I can be used to estimate the stability and noise performance that will be required of the current source and temperature controller for a given application.

4.4.1 Current Sources

The most important requirement of current sources used for diode lasers is that they **MUST BE FREE** of electrical transients that can seriously damage the laser. CW narrow-stripe lasers require an injection current of about 20 to 200 mA and have a forward voltage drop of about 2 V. In contrast, some of the high-power devices—such as wide-stripe lasers, MOPAs, and diode laser arrays—might re-

quire a few amperes of injection current. The simplest diode laser current supply is just a battery and a current-limiting resistor (or potentiometer). In practice we usually want to do more than just turn the laser on, and so the current source becomes somewhat more complicated. A number of good diode laser current sources are now commercially available. These range from simple integrated circuit chips that are designed for low-cost consumer electronics to very elaborate microprocessor-controlled systems. If a laboratory with a limited budget is planning on operating a significant number of precision diode laser systems, it can be cost-effective to produce some simple circuit boards for current sources and temperature controllers. Following this approach, we have found a few general principles to be useful.

- When possible do not put the AC-to-DC power converter in the same box with the current source electronics; very good filtering and regulation of the DC supplies are also important.

- It is important to keep the diode laser current path, both to and from the laser, independent of other signal and return paths.

- Pay careful attention to avoiding spikes on startup, shutdown, and even power failures. Before endangering a valuable laser, time is well invested in testing for transients (under all conceivable operating conditions) with an inexpensive imitation laser load (such as 10 LEDs in parallel and these in series with a 1 Ω current sensing resistor to ground; you can also use one or more rectifier diodes in place of the LEDs).

- To protect against damage caused by transients and operator errors, it is important to attach some passive protection near the laser chip (a typical protection circuit is shown in Fig. 6). Protection circuits can also have adverse effects, such as slowing down modulation response and increasing thermal instability due to diode leakage current. This last effect can be eliminated when necessary by controlling the temperature of the protection diodes by placing them on the laser heat sink.

- Watch for potential ground loop problems, particularly when connecting multiple cables between the laser, current source, sweep source, temperature controller, optical table, detectors, oscilloscope, etc. Our approach has been to keep the laser heat sink at ground potential but to isolate it from all other grounds (including that of the box that we use to enclose the laser), except at the laser current source where there is a common ground.

- Look for other useful hints and examples in catalogs supplied by the laser manufacturers.

An example of a good-quality diode laser current source is in Fig. 6. Other examples can be found in the literature [36, 37]. This circuit is designed to have good stability, low noise, and modulation capability.
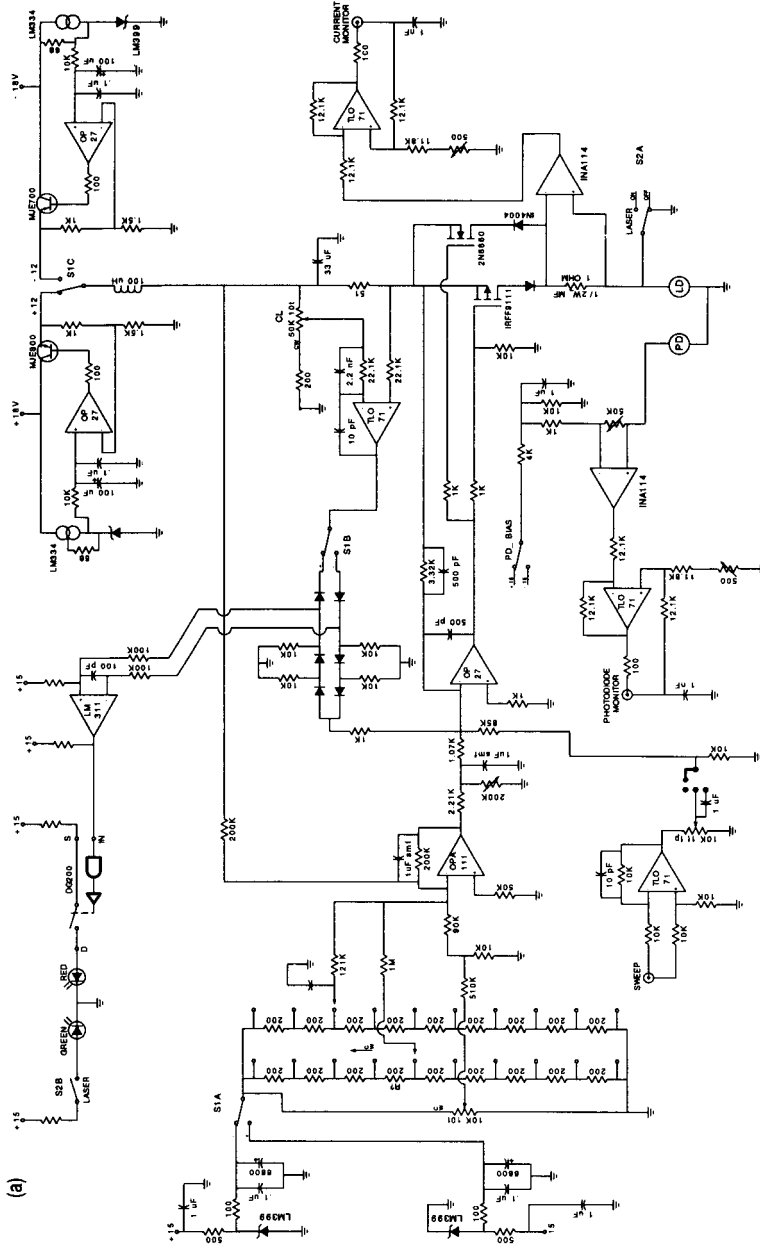
FIG. 6. Diode laser current source (a) and laser protection circuit (b). The operation of the current source is based on a summing amplifier that balances the voltage drop across a sense resistor (R_s) with a voltage supplied by a precision variable-voltage reference. To keep the diode laser mount at ground potential, the sense resistor is placed between the summing amplifier output and the supply rail. A typical modulation (sweep) input is also shown as a signal that adds to the summing amplifier input. A variable current limit (CL) sets the maximum current that can be supplied to the laser (a red LED indicates that the current limit is reached). A three-pole switch (S1A–C) changes the source polarity. Photodiode bias polarity is set by PD-BIAS. When the laser is off, a short (S2A) is connected across the laser. The laser protection circuit is located at the laser mount and consists of a simple low-pass filter and clamping diodes.
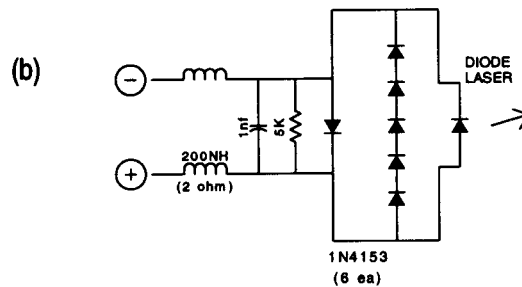
(b)

DIODE
LASER

1nf

6K

200NH
(2 ohm)

1N4153
(6 ea)

FIG. 6b

4.4.2 Temperature Controllers

The high sensitivity of diode laser wavelengths to temperature (~30 MHz/mK) places stringent requirements on their temperature control. For fixed-wavelength operation, solitary lasers require better temperature stability than ECDLs. With ECDLs the temperature stability is more of a concern because of thermal expansion of materials than it is because of the temperature sensitivity of the laser's gain. In practice the most difficult task in maintaining temperature stability is not the electronics, but rather it is the design of the thermal environment. A stable thermomechanical environment will reduce problems associated with such important, but often less obvious, perturbations as: beam-pointing stability (remember the angular magnifying properties of the short-focal-length collimating objective) and fluctuations of even the small optical feedback that is invariably present. Putting ECDLs in hermetically sealed containers greatly improves both thermal and optomechanical stability.

Important tradeoffs have to be balanced in designing temperature control systems for diode lasers. For instance, we would like to have the thermistor very close to the laser to accurately measure the laser's temperature, but we also want the thermistor close to the thermoelectric transducer so that the time delay in the servo is small and the loop can have fast response and high gain. These considerations indicate that a very small thermal mass should be used to support the laser. But the mount should also be mechanically stable and have a large thermal mass so that rapid temperature fluctuations (outside the loop bandwidth, e.g., from moving air) do not perturb the laser's temperature. For practical reasons we would also like the entire system to be relatively light and compact. Obviously, compromises are in order.

Figure 7 depicts an example of a temperature controller that uses a Peltier cooler to control the temperature of a diode laser; others can be found in the literature [12, 29]. An excellent analysis of the use of Peltiers in temperature control systems has been provided by Van Baak [38]. As with current sources, there are some basic design principles that are useful in constructing thermal control systems:
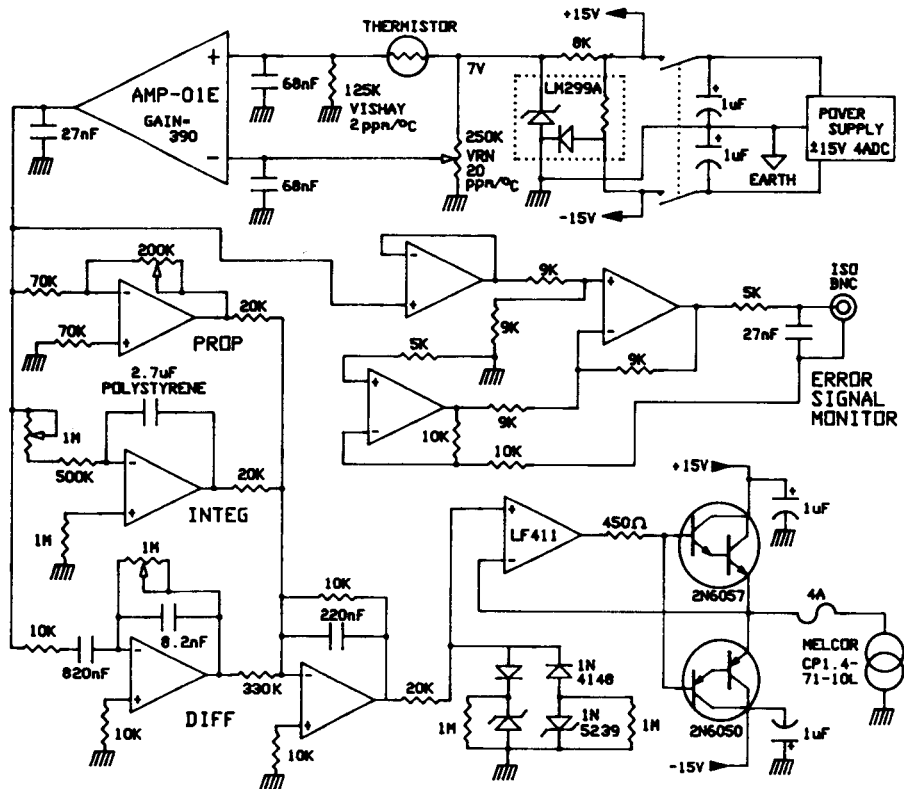
FIG. 7. Diode laser temperature controller. A precision thermistor (nominal value 125 kΩ) is used in a resistance bridge to sense the laser's temperature, and a Peltier (thermoelectric) cooler is used for cooling or heating. The servo-loop is a PID (proportional integral differential) control that processes the error signal and then sends it to a driver amplifier which provides sufficient power to run the Peltier cooler (typically a few volts and a few amperes). This circuit is from reference [36].

- Two-stage thermal control can be very effective in improving the stability of ECDLs. One controller is used for the extended cavity and the other for the laser chip.

- Thermistors should be buried in holes below the surface (& 5 mm) to avoid perturbations from temperature differences with the surrounding air.

- High-thermal-expansion materials (e.g., plastics, aluminum, copper) require better temperature control to maintain mechanical stability and alignment. Invar and fused silica can be useful for some components.

- The combined thermomechanical properties of the materials and construction must be considered. This includes the dynamic response of the material used within the thermal control loop (aluminum, copper, and silver have large coefficients of thermal diffusivity, which is good for control systems, but they also have large coefficients of thermal expansion, which is bad for mechanical stability).

- Peltier coolers are not very efficient, so a relatively large thermal reservoir may be required to dissipate excess heat.

- Watch out for thermal drifts and emfs in the electronics. Even good-quality resistors and capacitors can have significant temperature coefficients. Potentiometers can be particularly troublesome.

4.5 Optical Coatings on Laser Facets

Operating a diode laser in an extended-cavity configuration works best if the reflectance of the laser's output facet is very low. ECDLs are inherently coupled cavity systems and are known to have operating regions of stability and instability [21–23]. By reducing the reflectance of the output facet the performance of the ECDL is improved: the size of the stable operating region (in temperature, current, and feedback power) is increased, the usable output power is increased, and, most importantly, the laser's tuning range is increased.

In Eq. (1) we see the strong dependence of the laser threshold current on the reflectance of the facets. This is illustrated in Fig. 2, which shows the $P-I$ curves of a laser before and after the output facet is antireflection (AR) coated. Almost all commercial lasers come from manufacturers with coatings already on the laser's facets. These coatings serve two purposes: first, they protect the facets from degradation, and, second, they adjust the facet reflectance to optimize the output power. Since the early days of diode lasers, Al_2O_3 coatings have been used to reduce facet degradation and increase the lifetime of diode lasers. We typically find that commercial low-power (P . 10 mW) AlGaAs lasers have single-layer coatings on both facets that are approximately $\lambda/2$ in optical thickness. In most cases we do not know with certainty what coating material has been used. Empirically we often (but not always) find that the laser coatings have an index of refraction of about 1.60, which is consistent with e-beam vapor-deposited Al_2O_3. Higher-power lasers (& 15 mW) typically have a similar coating on the output facet, except that the thickness is approximately $\lambda/4$ (which results in a reflectance of a few percent). The back facet of the high-power lasers typically has a multilayer coating with a reflectance of 90% or more.

Most commercial lasers can be improved for use in extended-cavity configurations by reducing the reflectance of the output facet. The majority of laser manu-

facturers are not interested in putting special coatings on diode lasers for those users who need a few inexpensive lasers. In order to transform general-purpose lasers into ECDLs, we have found it advantageous to develop some simple coating capabilities in our own lab. Fortunately, the equipment needed to coat diode lasers is readily available from the optical coating/semiconductor industry. For example, inexpensive (can opener–like) tools are available for removing the caps from the standard hermetically sealed semiconductor packages. Otherwise, all that is really needed is a simple vacuum coating system with electrical feedthroughs.

Our coating techniques are based on traditional dielectric coating methods but are directed toward the specific problem of modifying the facet reflectance of semiconductor lasers. We generally use common coating materials (e.g., Al_2O_3, HfO_2, SiO) and well-established techniques (thermal evaporation, electron beam deposition, and RF sputtering). If one does not want to spend time characterizing the unknown coatings on the lasers and carefully calibrating thickness monitors, it is easiest to do the coatings by monitoring the change in threshold while the laser is being coated. During the coating process the laser injection current is ramped through threshold with a repetitive triangular sweep and the power out of the back facet is monitored. Many lasers already have a monitor photodiode behind them that can be used for this purpose.

Diode laser coatings have been studied in detail, and good-quality AR and mirror coatings have been developed. Some very useful information can even be found in the published literature, but often details are lacking because they are proprietary in nature. The lowest-reflectance coatings that have been reported on diode lasers range from 10^{-4} to 10^{-5}. These results have often been achieved by laboratories working on optical amplifiers, in which case it is necessary to suppress lasing altogether while maintaining very high optical gain.

Two relatively simple AR coatings that work reasonably well on commercial lasers are: (i) thermally evaporated silicon monoxide and (ii) e-beam-deposited HfO_2 and/or Al_2O_3. Either of these coatings can achieve reflectances below 10^{-3}, even on commercial lasers that already have some coating on their facets. Silicon monoxide is convenient because the equipment required for thermal evaporation is relatively simple. It also has the useful (but challenging) property that changing the oxygen pressure in the coating chamber changes the oxygen composition (x) in the film (SiO_x), and hence the index of refraction from about 1.6 to 2.0. With all coatings, but with SiO_x in particular, the apparent index of refraction of the coating can change over time as the laser is exposed to and operated in air.

An AR coating that we use regularly for semiconductor lasers is a dual coating of Al_2O_3 and HfO_2. We apply this coating using a standard electron beam evaporation source. Both of these materials produce good-quality optical coatings that are compatible with most of the commercial lasers that we have tested. To reduce the facet reflectance of commercial lasers we first add Al_2O_3 (when needed) to bring the laser's base coating thickness to approximately $\lambda/2$, and then we put

down a $\lambda/4$ layer of HfO_2 (deposited index approximately 1.89). The optical thickness of coatings is monitored by watching the change in laser threshold while the laser is being coated. This particular two-layer coating is relatively easy to monitor because the threshold reaches an extremum at or near the proper thickness for both layers.

4.6 Diode Laser Frequency Noise and Stabilization

We draw a clear distinction between two aspects of laser frequency stabilization. The first concerns the reduction in the drift and low-frequency fluctuations (jitter) of the laser's center frequency, and the second concerns the faster fluctuations that are responsible for the "fast linewidth" of the laser. The general aspects of frequency stabilization of lasers are addressed in other chapters (Zhu and Hall, Chapter 5 in this volume) and elsewhere. We will concentrate here on those aspects particularly relevant to diode lasers [5–7]. An excellent discussion of the subject is given by Telle [39].

First, the optical cavity of a solitary diode lasers is very small and the facet reflectance is not very high, which means that the Q of the resonator is low and the resulting linewidth of the laser is relatively large (typically 10–200 MHz). In addition, a number of physical processes affect the spectral width of diode lasers. These include carrier density and temperature fluctuations, pump fluctuations, and spontaneous emission. These effects can be amplified by the strong coupling between the phase and amplitude of the lasing field. This coupling causes the linewidth of diode lasers to be increased above the fundamental Schawlow–Townes limit by a factor of $(1 + \alpha^2)$, where α (typically 3–10) is the ratio of the change in the real to the imaginary part of the susceptibility of the gain medium.

4.6.1 Electronic Control

An inexact but useful rule of thumb for frequency control servo systems is that the bandwidth of the servo needs to be somewhat greater than the linewidth of the laser before the servo can actually reduce the laser's linewidth. Solitary lasers have linewidths that are typically tens of MHz wide, which means that it is difficult, but not impossible, to achieve servo-loop bandwidths that are high enough to narrow the linewidth. Even though the frequency of the laser light responds on nanosecond time scales to changes in the injection current, other factors limit the loop response time. Very fast electronics must be used, and the physical size of the system must be small to minimize propagation delays. It is necessary to compensate phase shifts in the transfer function of injection current to laser frequency and also the time delays inherent in the frequency discriminator (for example, a Fabry–Perot cavity).

150 mW laser

Extended Cavity Laser

Crystal

Blue out

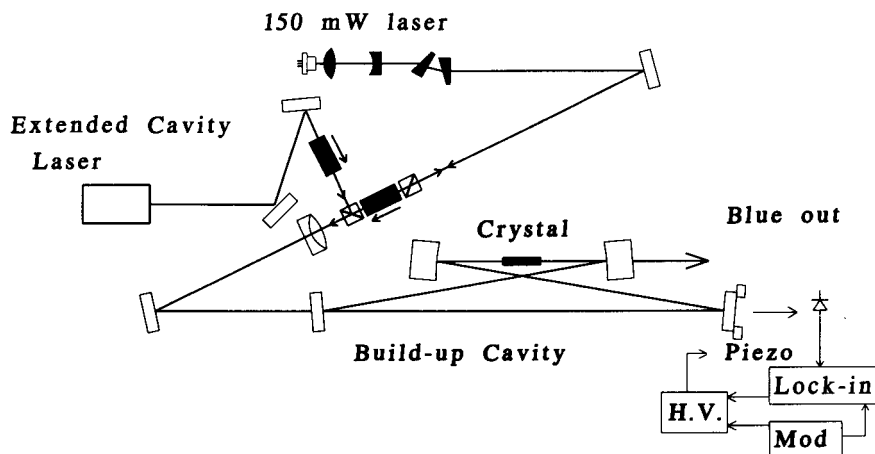**Build-up Cavity**

Piezo

Lock-in

H.V.

Mod

FIG. 8. Frequency-doubled diode laser. In this system a grating-tuned ECDL provides tuning and high spectral purity, which is then used to control the frequency of a higher-power diode laser by injection locking. Injection about 5 mW from the ECDL into the slave laser provides about 150 mW of tunable output power. The spatial mode of the slave laser is asymmetric ($\theta_\perp/\theta_\parallel \sim 3$) and has a small amount of astigmatism (about 3 μm); these are corrected by using an anamorphic prism pair and a cylindrical lens. After spatial mode correction and passing through an optical isolator, there are about 105 mW remaining in the beam that is incident upon the ring buildup cavity that contains the $KNbO_3$ crystal. The combined mode matching and coupling efficiency of this beam into the ring is about 75%. Usable blue output powers as high as 45 mW are obtained in a good stable spatial and temporal mode near 425 nm.

4.6.2 Optical Control

Resonant optical feedback from a confocal cavity (Fig. 3e) can be used to narrow the linewidth and simultaneously stabilize the center frequency of diode lasers [2]. With this method optical feedback occurs only in the narrow spectral windows defined by the confocal Fabry–Perot resonances. When the solitary laser's frequency is tuned within the optical capture range of a Fabry–Perot resonance, the resulting resonant feedback causes the laser to lock its frequency to the nearby cavity resonance. The laser's fast linewidth is thus reduced by a factor of about 1000 (to <10 kHz), and the center frequency is then automatically stabilized to the cavity resonance. This system does not require modification of the solitary diode laser and typically operates in the weak feedback regime, $P_{feedback}/P_{out}$. 10^{-3}. A limitation of this optical locking technique is that the tuning range of the laser is still restricted to those wavelengths accessible by the solitary laser alone. Although no active control is needed to optically lock a laser to a

cavity, electronic servos will be necessary for stable long-term operation at a specific frequency.

4.6.3 Combined Optical and Electronic Control

As with most tunable lasers, the lasing frequency of ECDLs is controlled by a mechanical system (the grating angle and cavity length) that is susceptible to perturbation and drift. Active frequency stabilization can be done using some sort of frequency reference (such as a Fabry–Perot cavity or an atomic resonance) and an electronic control system. The error signal from the frequency reference is processed by a loop filter and fed back to control the laser frequency. The main feedback path is usually to a PZT that controls the laser cavity length. The frequency stability that can be achieved using only a PZT loop is usually adequate for most applications, but when linewidths less than about 50 kHz are needed it is relatively easy to use an additional feedback loop to the injection current (or to an intracavity modulator) to further narrow the laser linewidth. These additional feedback paths have higher servo bandwidths because they are not limited in speed by having to move the mass of a mirror or grating. With servo bandwidths of ≥ 1 MHz it is even possible to phase-lock a diode laser to a reference laser source.

4.7 Extending Wavelength Coverage

Present technology is now reasonably good at controlling the spectral characteristics of diode lasers, but these lasers may not be available at the wavelengths that we require (Fig. 1). Fortunately, new wavelengths are on the horizon. There are promising research results with blue lasers using ZnSe and GaN, and the Sb-based IR lasers also have great potential. In the meantime, we can use the existing diodes and nonlinear optical techniques to extend wavelength coverage.

Good results have been reported by using diode lasers and difference-frequency generation (DFG) to produce single-frequency tunable infrared light [40]. The chalcopyrite crystals $AgGaS_2$ and $AgGaSe_2$ and periodically poled lithium niobate are well suited to this application because they have large nonlinear coefficients and they phase match for diode laser wavelengths. In fact, it appears that almost the entire spectral region between 2 and 18 μm could be covered by using these crystals and diode lasers as the input.

In the opposite wavelength direction there is a need for good tunable lasers in the blue and UV based on solid-state sources. Fortunately, nonlinear crystals such as $KNbO_3$, KTP, $LiNbO_3$, BBO, and $LiIO_3$ can be used for second-harmonic generation (SHG) and sum frequency mixing of diode laser light [41]. With these techniques and materials the region between 200 and 500 nm is accessible. For example, the SHG system developed in our lab by C. Weimer is diagrammed in Fig. 8. This system uses $KNbO_3$, which is a particularly good example because it

has a large nonlinear coefficient, and it noncritically phase matches for AlGaAs diode laser wavelengths. Starting with an injection-locked 150 mW diode laser, this system produces more than 40 mW of tunable light near 425 nm. An analogous system that uses angle phase matching in $LiIO_3$ produces about 200 μW of 405 nm light for an input power of 40 mW at 810 nm.

From recent publications and conference proceedings we can anticipate that higher-power lasers will soon be available in many wavelength regions. As the technology improves we will be able to incorporate these lasers and MOPAs with various nonlinear optical materials to greatly extend useful wavelength coverage.

Acknowledgments

References

Given the length and general nature of this chapter, we provide only a very basic list of references that might serve as a starting point for further study.

1. Kressel, H., and Butler, J. K. (1977). *Semiconductor Lasers and Heterojunction LEDs*, Academic Press, New York.

2. Casey Jr., H. C., and Panish, M. B. (1978). *Heterostructure Lasers, Parts A and B*, Academic Press, New York.

3. Thompson, G. H. B. (1980). *Physics of Semiconductor Laser Devices*, Wiley, New York.

4. Yariv, A. (1989). *Quantum Electronics*, 3rd edition, Wiley, New York.

5. Petermann, K. (1988). *Laser Diode Modulation and Noise*, Kluwer Academic, Dordrecht, The Netherlands.

6. Yamamoto, Y., ed. (1991). *Coherence, Amplification, and Quantum Effects in Semiconductor Lasers*, Wiley, New York.

7. Ohtsu, M. (1992). *Highly Coherent Semiconductor Lasers*, Artech House, Boston.

8. Zory, P. S., ed. (1993). *Quantum Well Lasers*, Academic Press, Boston.

9. Camparo, J. (1985). *Contemp. Phys.* **26**, 443.

10. Ohtsu, M., and Tako, T.'(1988). In *Progress in Optics*, Volume 25, E. Wolf (ed.), Elsevier, Amsterdam.

11. Lawrenz, J., and Niemax, K. (1989). *Spectrochim. Acta* **44B**, 155.

12. Wieman, C., and Hollberg, L. (1991). *Rev. Sci. Instrum.* **62**, 1, and the references therein.

13. Tino, G. (1994). *Phys. Scripta.* **T51**, 58–66.

14. Niemax, K., ed. (1993). *Spectrochim. Acta Rev.* **15**(5).

15. Suematsu, Y., and Adams, A. R., eds. (1994). *Handbook of Semiconductor Lasers and Photonic Integrated Circuits*, Chapman and Hall, London.

16. Choi, H. K., Walpole, J. N., Turner, G. W., Eglash, S. J., Missaggia, L. J., and Connors, M. K. (1994). *IEEE Photon. Tech. Lett.* **6**, 7, and the references therein.

17. Franzke, J., Schnell, A., and Niemax, K. (1993). *Spectrochim. Acta Rev.* **15**(5), 379–395; see also general diode laser references [1–7, 14].

18. Bonnell, L. J., and Cassidy, D. T. (1989). *Appl. Opt.* **28**, 4622–4628; Ruprecht, P. A., and Brandenberger, J. R. (1992). *Opt. Comm.* **93**, 82–86.

19. Welch, D. F., Parke, R., Mehuys, D., Hardy, A., Lang, R., O'Brien, S., and Scifres, D. S. (1992). *Electron. Lett.* **28**, 2011–2013.

20. Kasuya, T., Suzuki, T., and Shimoda, K. (1978). *Appl. Phys.* **17**, 131–136.

21. Lang, R., and Kobayashi, K. (1980). *IEEE J. Quantum Electronics* **QE-16**, 347–355.

22. Tkach, R., and Chraplyvy, A. (1986). *J. Lightwave Tech.* **LT-4**, 1655–1661.

23. Tromborg, B., and Mørk, J. (1990). *IEEE J. Quantum Electronics* **26**, 642–654; Mørk, J., Tromborg, B., Mark, J., and Velichansky, V. L. (1992). *Proc. SPIE* **1837**, and the references therein.

24. Zorabedian, P. (1994). *IEEE J. Quantum Electronics* **30**, 1542, and the references therein.

25. Fleming, M. W., and Mooradian, A. (1981). *IEEE J. Quantum Electronics* **QE-17**, 44–59.

26. Fukuda, M. (1991). *Reliability and Degradation of Semiconductor Laser and LEDs*, Artech House, Boston.

27. Belenov, E. M., Velichansky, V. L., Zibrov, A. S., Nikitin, V. V., Sautenkov, V. A., and Uskov, A. V. (1983). *Sov. J. Quantum Electronics* **13**, 792; Akul'shin, A., Bazhenov, V., Velichansky, V., Zverkov, M., Zibrov, A., Nikitin, V., Okhotnikov, O., Sautenkov, V., Senkov, N., and Yurkin, E. (1986). *Sov. J. Quantum Electronics* **16**, 912.

28. Boshier, M. G., Berkeland, D. J., Hinds, E. A., and Sandoghadar, V. (1991). *Opt. Comm.* **85**, 355–359.

29. MacAdam, K. B., Steinbach, A., and Wieman, C. (1992). *Am. J. Phys.* **60**, 1098–1111.

30. Duarte, F. J. (1993). *Laser Focus World*, pp. 103–109, February.

31. Harvey, K., and Myatt, C. (1991). *Opt. Lett.* **16**, 910.

32. Liu, K., and Littman, M. G. (1981). *Opt. Lett.* **6**, 117; McNicholl, P., and Metcalf, H. J. (1985). *Appl. Opt.* **24**, 2757.

33. Day, T., Luecke, F., and Brownell, M. (1993). *Lasers Optronics*, pp. 15–17, June; Day, T., Brownell, M., and Wu, I.-Fan (1995). *Proc. SPIE* **2378**, 37–41.

34. Velichansky, V. L., Zibrov, A. S., Molochev, V. I., Nikitin, V. V., Sautenkov, V. A., Tyurikov, D. A., and Kharisov, G. G., (1981). *Sov. J. Quantum Electronics* **11**, 1165–1171.

35. Bazhenov, V. Yu., Bogatov, A. P., Eliseev, P. G., Okhotnikov, O. G., Pak, G. T., Rakhvalsky, M. P., Soskin, M. S., Taranenko, V. B., and Khairetdinov, K. A. (1982). *IEEE Proc.* **129**(1), 77–82.

36. Bradley, C. C., Chen, J., and Hulet, R. G. (1990). *Rev. Sci. Instrum.* **61**, 2097.

37. Libbrecht, K. G., and Hall, J. L. (1993). *Rev. Sci. Instrum.* **64**, 2133–2135.

38. Van Baak, D. A. (1992). *Am. J. Phys.* **60**, 803–815.

39. Telle, H. (1993). *Spectrochim. Acta Rev.* **15**, 301–327.

40. Simon, U., Waltman, S., Loa, I., Tittel, F. K., and Hollberg, L. (1994). *J. Opt. Soc. Am. B* **12**, 323–327; Petrov, K. P., Waltman, S., Dlugokencky, E. J., Arbore, M., Fejer, M. M., Tittel, F. K., and Hollberg, L. (1997). *Appl. Phys. B*, and the references therein, to be published.

41. Risk, W. P., and Kozlovsky, W. J. (1992). *Opt. Lett.* **17**, 707–709, and the references therein.