REVIEW ARTICLE

Using diode lasers for atomic physics

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We present a review of the use of diode lasers in atomic physics with an extensive list of references. We discuss the relevant characteristics of diode lasers and explain how to purchase and use them. We also review the various techniques that have been used to control and narrow the spectral outputs of diode lasers. Finally we present a number of examples illustrating the use of diode lasers in atomic physics experiments.

I. INTRODUCTION

Much of current atomic physics research involves the interaction of atoms and light in some way. Laser sources that can be tuned to particular atomic transitions are now a standard tool in most atomic physics laboratories. Traditionally this source has been a tunable dye laser. However, semiconductor diode lasers have been steadily improving in reliability, power, and wavelength coverage, while steadily decreasing in cost. It is now possible to have a diode laser system that will produce more than 10 mW of tunable light with a bandwidth of 100 kHz for a cost of less than $1000. Furthermore, the diode laser and power supply will fit in a 1-ℓ box, require very little power or cooling water, and, under the right conditions, will be within a few MHz of the desired wavelength as soon as it is turned on. A further virtue is that the amplitude is very stable compared to most other laser sources so that it is relatively simple to make sensitive absorption or fluorescence measurements. These features make diode lasers increasingly attractive alternatives for a variety of uses.

In this review we present something of a users' guide aimed at atomic physicists who might want to start using diode lasers in their work. In this spirit we present the advantages of diode lasers as well as their negative features (there are several serious ones) and the best ways to deal with them. We begin in Sec. II by discussing relevant basic laser characteristics. Section III addresses some of the most important issues involved in actually setting up and using diode lasers in atomic physics experiments, such as purchasing the correct laser, tuning it to the desired frequency, and how to avoid destroying it. Section IV discusses optical and electronic feedback to control the laser output frequency. In the past, one of the main drawbacks to using diode lasers in atomic physics was the difficulty in obtaining narrowband, easily tunable output. However, the developments covered in Sec. IV have improved this situation considerably. Section V then discusses a selected set of applications of diode lasers in atomic physics, focusing primarily on work that has been made possible by these new wavelength control techniques.

To keep this article to a reasonable length there are necessarily many things we do not discuss. For example, we do not cover progress made on producing special diode lasers that work in marvelous ways, because these developmental lasers are not available to most atomic physicists. We restrict ourselves to lasers that are standard commercial devices. Another notable omission is the extensive work in molecular spectroscopy that has been done using lead salt diode lasers in the middle and far infrared regions of the spectrum.

Camparo[1] completed an extensive review on the use of diode lasers in atomic physics in 1985. That review covered much of the basic physics and characteristics of diode lasers, and the various uses that had been made of them. At that time most devices were simple free-running lasers without feedback, and they had been used principally for optical pumping and low resolution spectroscopy. In the present review, although there will necessarily be some overlap of that discussion, we will emphasize the recent developments including "stabilized lasers" (ones with feedback for frequency control), and new types of applications. There is also an excellent review entitled "Coherence in Semiconductor Lasers" by Ohtsu and Tako[2] that discusses applications in a variety of areas.

II. BASIC LASER CHARACTERISTICS

The basic physics of diode lasers is presented in many references[3] and will not be repeated here. However, we do wish to single out a few features that are relevant to much of the later discussion. The construction of a typical semiconductor diode laser is shown in Fig. 1. The devices are extremely small and yet are capable of reasonable cw output powers with high electrical to optical efficiency. The laser light is generated by sending a current (the "injection current") through the active region of the diode between the n- and p-type cladding layers. This produces electrons and holes, which in turn recombine and emit photons. The laser's emission wavelength is determined by the band gap of the semiconductor material and is very broadband relative to atomic transitions. The spatial mode of the laser is defined by a narrow channel in the active region that confines the light. This confinement of the transverse laser mode is achieved either through the spatial variation of injection current density (gain guided) or by spatial variations in the index of

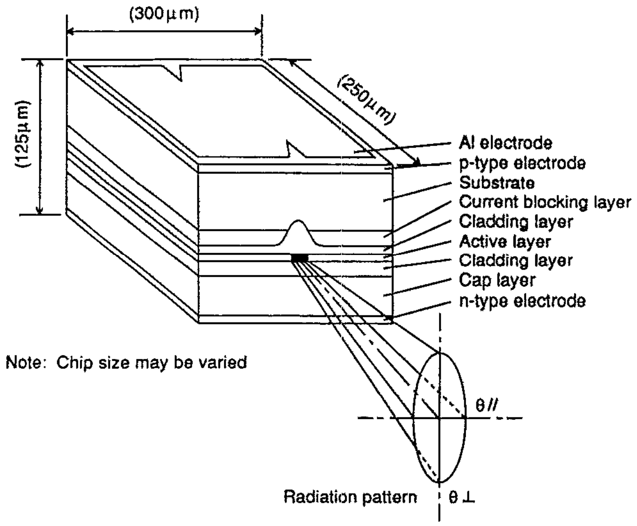

FIG. 1. Illustration of the different layers of semiconductor and the typical dimensions of a diode laser. The rectangular shape of the gain region leads to the oval radiation pattern. (Figure adapted from Ref. 4, with permission.)

refraction due to changes in the materials used in the laser's construction (index guided).

A wide variety of laser designs have been used. Most of the atomic physics done with diode lasers has been carried out using index-guided GaAlAs lasers in the near infrared region of the spectrum. Unless otherwise noted, this type will be assumed in the subsequent discussion. These lasers typically produce single-mode (spatial and longitudinal) output powers of 5–15 mW with just the cleaved facets of the semiconductor serving as the laser's mirrors. Output powers up to ≈50 mW are commercially available from what are essentially the same devices with the addition of a high reflectance coating on the back surface and a reduced reflectance coating on the output facet. Higher power lasers that have special designs such as multistripes or very wide single stripes are also available. These will likely be useful in the future, but at the present time the difficulty and expense in obtaining these special designs at a desired wavelength is a formidable problem.

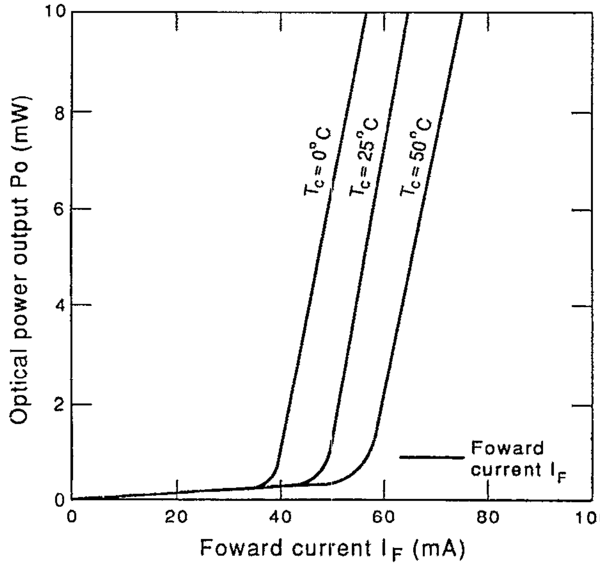

FIG. 2. Output power vs injection current for a typical laser. The sudden change in the slope of each curve marks the onset of laser action, and the current at that point is the threshold current for the laser. The different curves show how the temperature affects the laser output. (Figure adapted from Ref. 4, with permission.)

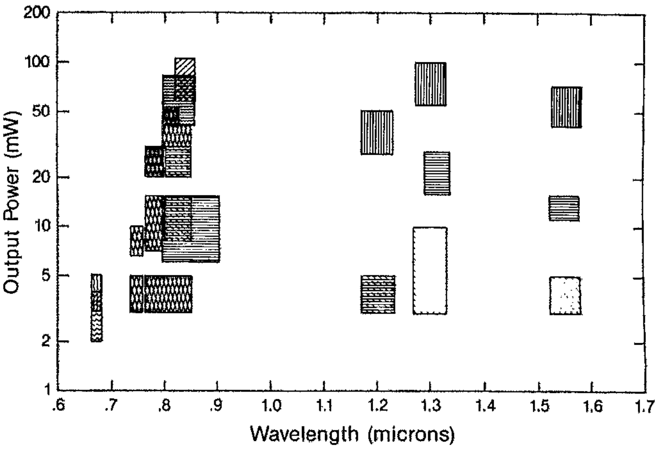

FIG. 3. cw diode laser output powers displayed as a function of wavelength. The various cross hatched boxes are taken from manufacturers catalogs and represent the distributions in wavelength and power that are advertised. In some cases it is possible to obtain lasers outside of these normal distributions. The range shown here is the distribution of lasers from the manufacturers and should not be confused with the tuning range of any specific laser which is much smaller. (The manufacturers shown in this table include; Hitachi, Mitsubishi, Nec, Oki, Sharp, and Spectra Diode and are listed only as being representative, not as an endorsement; other sources should be equally suitable. We have experience with some of these devices but we have not verified all devices nor that the manufactures will deliver all of the devices as advertised.)

The output power of a typical semiconductor diode laser as a function of the injection current and temperature is shown in Fig. 2. This shows the abrupt onset of laser action at the threshold current and the increase in the threshold with temperature. Alternatively, for fixed injection current, the laser's output increases rapidly as the temperature is lowered.

Figure 3 shows the power and wavelength characteristic of cw diode lasers that are readily available from commercial sources. These are divided into five main bands as driven by commercial applications. The two bands in the infrared, at 1300 and 1500 nm, have been developed primarily for fiber optic systems and are based on quartenary InGaAsP semiconductors. The lasers in the 750–890 nm region are based on AlGaAs and have applications in consumer and commercial electronics as well as some fiber-optic applications. The relatively new visible diode lasers near 670 nm are based on InGaAlP semiconductors and have many projected applications in commercial optoelectronic systems. In applying these various lasers to spectroscopy we find that their spectral characteristics vary considerably. Those in the 750–870 nm region have the best overall characteristics.

A. Beam spatial characteristics

Because the light is emitted from a small rectangular region (on the order of 0.1 μm by 0.3 μm) the output of a diode laser has a large divergence (see Fig. 1). A typical output beam will have a divergence angle (full width at 50% intensity) of 30° in the direction perpendicular to the junction, and 10° in the parallel direction. Normally the beam is collimated using a lens with a small f number. If the laser is operating in a single transverse mode, the collimated beam will be elliptical, but it can be made nearly radially symmetric using anamorphic prisms. In addition to the different divergence angles, the output beam of most diode lasers is astigmatic. This astigmatism can also be compensated when necessary.[5] A typical diode laser wavefront collimated in this fashion will often have a significant amount of structure. This is primarily a function of the quality of the first collimating lens and the amount it apertures the beam. However, with relatively inexpensive lenses and spatial filtering, one can obtain wavefronts with good Gaussian profiles. This can be done with relatively little loss in power (10%), but sometimes the optical feedback from the filtering elements can be a problem. If one is forced to work with a laser that is emitting light in a number of transverse modes, a highly structured beam is unavoidable unless one sacrifices a substantial amount of power.

B. Amplitude spectrum

For most applications, the amplitude and spectral characteristics of the light are more important than the spatial characteristics. When compared to other tunable laser sources, the amplitude noise on diode lasers is relatively small, but it can vary considerably depending on the actual laser and its operating conditions. Figure 4 shows the amplitude noise spectrum of a typical single-mode diode laser taken with a fast photodiode and an rf spectrum analyzer. The natural scale for the measurement of laser amplitude noise is the quantum-limited shot-noise level that is indicated on the figure for this detected power. The general structure of the amplitude noise shows peaking at the lowest Fourier frequencies ($f \leqslant 500$ kHz). At intermediate frequencies (500 kHz $< f <$ 3 GHz) there is a broad plateau that rises to a peak at the laser's relaxation frequency (2–3 GHz), and then drops to the shot-noise level for frequencies above the relaxation frequency. The fundamental noise level is a function of both the injection current and the laser's temperature.[6] The amplitude noise decreases as the injection current is increased or the temperature decreased. Both of these changes move the relaxation oscillation to higher frequency. Special laser systems have been built to bring the amplitude noise of diode lasers down to, and even below,[7] the shot-noise level but this performance cannot be expected from standard commercial diode laser systems.

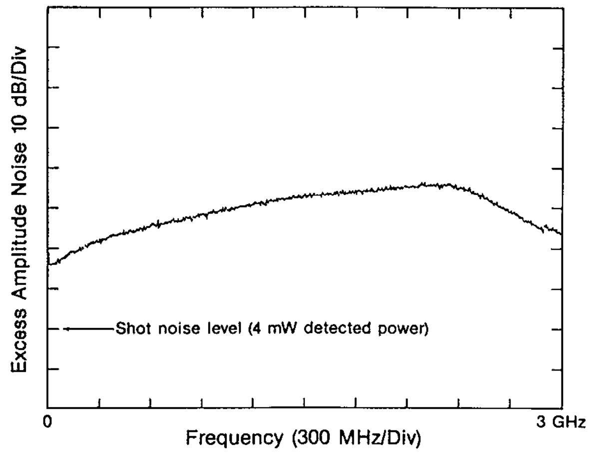

FIG. 4. Spectral distribution of amplitude noise on a typical commercial diode laser operating near 780 nm. The logarithmic vertical scale shows the excess noise on the laser relative to quantum limited shot-noise level for the same detected power level of 4 mW. The laser is operating well above threshold and the peak near 2.4 GHz is due to the lasers relaxation oscillation.

Most atomic physics experiments are done with detection bandwidths centered in the low or intermediate frequency range. In this range, the amplitude noise for a good quality diode laser can be quite low relative to that of a dye laser, typically 10 to 20 dB above the quantum-limited shot-noise level. This translates into power fluctuations for a typical diode laser of one part in 10^5 for a 10-kHz detection bandwidth. The situation can be much worse with some lasers, particularly when the laser runs multimode in only a few modes; the resulting noise is called mode competition noise. External factors such as fluctuations in the injection current, the temperature, and the optical feedback can increase the amplitude noise substantially. Each of these influence the gain of the diode laser and hence its output power.

The suppliers of diode lasers occasionally provide some information about the lasers' intensity noise, but this information is usually specified in a way that is most useful for applications to consumer electronics. For example, the specifications may give a signal-to-noise ratio (S/N) of 80 dB. This is a measure of the laser's amplitude noise taken in a 10 kHz bandwidth centered at 750 kHz. This information is useful but insufficient for many scientific applications.

The peak of the noise at the relaxation oscillation frequency is characteristic of many solid state laser systems[8] and can be a problem for some applications. The fraction of laser power that is contained in the relaxation oscillation peaks varies considerably from one type of laser to another and even varies for a given laser depending on its operating conditions. For example, the power in the relaxation sidebands can vary by as much as a factor of 100 with variations in optical feedback. We find that good single mode AlGaAs lasers operating near 850 nm will have relaxation sidebands that are down from the carrier by a factor of ≈ 1000. In contrast, some of the visible lasers (670 nm) we have tested show relaxation sidebands that are roughly 10% of the carrier. The relaxation oscillation sidebands are not always detrimental. As discussed in Sec. V A, they can provide useful optical pumping.

C. FM spectrum

There are two natural scales to the oscillation spectrum of diode lasers. The first scale is set by the spacing of the cavity modes of the laser which is on the order of 160 GHz (≈ 0.35 nm). The second is the linewidth of a single cavity mode. At the present time, it is quite routine to obtain "single-mode" lasers in the near infrared region (750 to 850 nm, AlGaAs lasers) although the visible (670 nm, InGaAlP la-

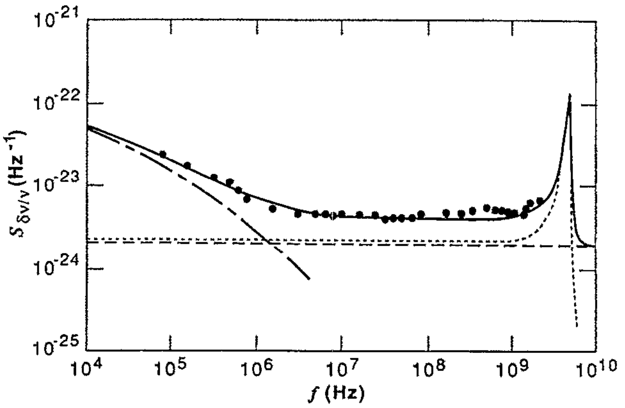

FIG. 5. Spectral density of laser frequency noise for an AlGaAs diode laser. The dots are experimental data which are compared to theory as represented by the lines. The frequency noise peaks at low Fourier frequencies and again at the relaxation oscillation frequency. The theory shows that current induced temperature fluctuations are responsible for the low frequency peak, carrier induced index changes cause the high frequency resonance, and spontaneous emission contributes a flat background noise. (Figure adapted from Ref. 11, with permission.)

sers) and infrared lasers (1300 and 1500 nm, InGaAsP lasers) ordinarily will have their power distributed in many modes. The distributed feedback (DFB) lasers in the infrared will run in a single mode but have a limited tuning range. We might mention a few caveats about nominally single-mode lasers. First, they are not absolutely single mode in that there are small but readily observable amounts of power in numerous other modes that can occasionally be a problem. Second, a laser that has been sold as a single-mode laser will often not run in a single mode for all injection currents. The lasers will always be multimode for very low injection currents, but even at much higher currents there are often ranges of current and temperature where the laser will continue to operate in several modes.

For the remainder of this section we will consider only the linewidth of a single mode. For some applications, including laser spectroscopy, coherent communications, and precision measurements, the diode laser's linewidth can be a serious problem. Many factors contribute to the linewidth of diode lasers; the most fundamental of these is that the laser cavities are so short that the Schawlow-Townes linewidth is significant (typically a few MHz).[9] The linewidths of common single mode diode lasers are larger than the Schawlow-Townes value because of fluctuations in the carriers, the temperature, and in the complex susceptibility of the laser[10] (typically linewidths vary from about 10 to 500 MHz). Linewidths of 20 to 50 MHz are typical for low power index-guided lasers. The spectrum of the frequency noise is similar (and coupled) to the spectrum of the amplitude noise. An example of a frequency noise spectrum of a diode laser[11] is shown in Fig. 5. Unfortunately, we see that the frequency noise is large and extends to very high frequencies. The high frequency FM noise is a problem for two reasons: (1) it is difficult to make electronics that are fast enough to correct the frequency fluctuations and (2) even when the linewidth is narrowed by some optical or electronic means there is usually residual high frequency phase noise that contaminates some types of measurements.

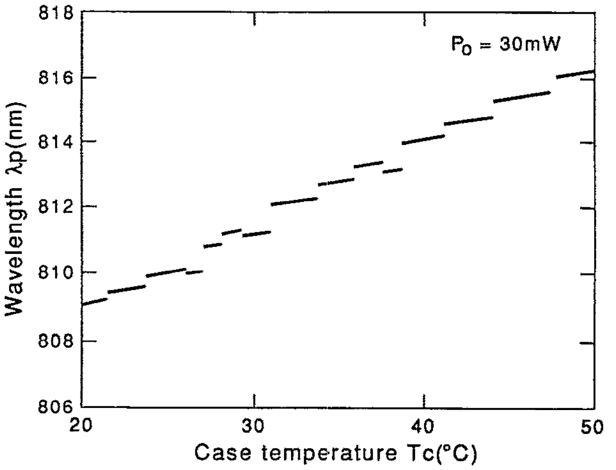

FIG. 6. Laser output wavelength vs the temperature of the laser case. The short continuous segments indicate the tuning of the optical length of the cavity for a given longitudinal mode. When the peak of the gain medium has shifted too far, the laser jumps to another mode. This is indicated by the breaks in the curve. (Figure reproduced from Ref. 4, with permission.)

D. Tuning characteristics

A diode laser's wavelength is determined primarily by the band gap of the semiconductor material and then by the junction's temperature and current density.[12] The band gap that determines the general range of the laser's wavelength is unfortunately not under the control of the laser user. The range of wavelengths that are readily available is shown in Fig. 3, but a given commercial laser will only (and incompletely) tune over a wavelength interval of about 20 nm. Thus the user must buy a laser that is doped to operate within the tuning range of the wavelength of interest.

The laser frequency tunes with temperature because both the optical path length of the cavity and the wavelength dependence of the gain curve depend on temperature. Unfortunately these temperature dependencies are quite different. For example, in the AlGaAs devices the optical length of the cavity changes about + 0.06 nm/K, while the gain curve shifts about + 0.25 nm/K. This results in a temperature tuning curve which, in an ideal device, is a staircase with sloping steps (see Fig. 6).[12] The slope of each step is just the tuning of that cavity mode, while the jump between steps corresponds to hopping from one longitudinal mode to the next ($\approx$0.35 nm) due to the shifting of the gain curve. The spectral "gaps" encountered in the laser tuning as it jumps from one step to the next are the biggest drawback to using diode lasers in atomic physics. We will discuss below some empirical techniques that have been developed for dealing with this behavior in an isolated laser, as well as techniques for using external optical feedback to reduce or eliminate the problem. In practice, although the overall tuning follows the staircase pattern described, often a laser may jump several cavity modes at once, and then perhaps jump back at a slightly higher temperature as shown in Fig. 6. The choice of which mode the laser will hop to next is often extremely sensitive to optical feedback.

"Room temperature" commercial diode lasers are typically rated to operate in a range of ± 30 K about room temperature. This provides a tuning range of about 21 nm for AlGaAs lasers. The elevated temperatures generally cause noticeable degradation in the laser's lifetime. For example, the data sheets indicate that a typical lifetime of about 10^5 h is reduced by a factor of 5 when the temperature is increased by 10 K. Other performance characteristics may also be degraded at higher temperatures. The temperature dependence of the laser characteristics varies substantially for different models and types of lasers; however, detailed information is often provided by the manufacturer. Lasers can actually be cooled far more than 30 K (experience shows that at least some of the commercial lasers can be operated down to liquid He temperatures); the lower temperatures bring some additional complications such as the need to protect the laser from water condensation and mechanical stress due to large temperature changes. For very large temperature changes one must use the Varshni equation[13] to predict the wavelength, rather than the linear approximation given above.

In addition to depending on the temperature, the laser wavelength also depends on the injection current. Changes in the injection current affect both the diode temperature and change the carrier density which also changes the index of refraction, and these in turn affect the wavelength. For time scales longer than about 1 μs the current tuning can simply be thought of as a way to change the temperature rapidly, because the carrier density contribution to the index-of-refraction tuning is relatively small. The current affects the junction temperature because of Joule heating, and the resulting tuning curve for wavelength versus current looks much the same as that versus temperature. Only for times shorter than ~ 1 μs is the temperature rise small enough that the carrier density effect is not overwhelmed.[14] For typical AlGaAs diode lasers the variation in the lasers' frequency is ≈ -3 GHz/mA for frequencies below about 1 MHz, then it drops to ≈ -300 MHz/mA for frequencies from 1 to 3000 MHz. It rises again to ≈ -1 GHz/mA at the frequency of the relaxation oscillation (typically ~ 3 GHz) and then drops off rapidly above this frequency. The crossover behavior between the different regions of FM response can cause considerable complication in high-speed modulation and frequency control systems for diode lasers.

One of the important advantages of diode lasers over other optical sources is that their amplitude and frequency can be modulated very easily and rapidly by changing the injection current. Unfortunately, when the injection current is modulated, one obtains both AM and FM, and these are not independent. The simplest useful picture of the modulation response of diode lasers is that the AM and FM are both present but with different sensitivities.[15] Also modulation can be complicated by the fact that the relative phase between the AM and the FM changes as a function of modulation frequency. To a good approximation, the AM and the FM are linear with the injection current but the FM modulation index can be more than ten times the AM index. This means that the amplitude change can be ignored in many atomic physics applications. Thus the laser can be scanned over spectroscopic features and/or jumped back and forth to specific frequencies just by applying the appropriate modulation to the injection current. Applications of various modulation capabilities are discussed in Sec. V B.

E. Visible lasers

The new visible diode lasers[16] which operate near 670 nm are exciting for spectroscopic and other applications. Because of the newness of these devices we have had only limited experience with them. The primary problem with these lasers is their broad spectral width. Most are gain-guided rather than index-guided, which typically means that they will have very poor spectral characteristics. We find that the visible lasers usually run multimode, with limited regions of single-mode operation. In addition, even in the regions of single-mode operation (and with very limited data) the linewidths of unstabilized devices are 300 MHz or larger. They also have a transverse mode structure that has a very large and asymmetric divergence (7° and 40°). Without compensation, this produces a laser beam with a linear shape rather than a round spot. This structure could be corrected, but it is still difficult to obtain optics designed specifically for these lasers. Finally, the output power of visible diode lasers has a very steep dependence on temperature and injection current which can lead one easily to a light intensity induced laser failure!

III. PRACTICAL GUIDE TO USING DIODE LASERS

Having discussed the basic behavior of diode lasers, we will now present some of the practical issues involved in setting up and using diode lasers for atomic physics. Although we do not discuss lasers with feedback in this section most of the discussion applies to that case as well.

A. Purchasing diode lasers

Probably the single biggest frustration in using diode lasers in atomic physics experiments has nothing to do with scientific or technical issues. Instead it is the difficulty in purchasing diodes that have been doped to emit at the desired wavelength (or close enough to reach it with temperature tuning). Because of this unfortunate fact, it seems worthwhile to provide some discussion to prepare the potential user for some of the problems that must be handled. These arise because the atomic physics market is an utterly insignificant fraction of the total diode laser market, and diode laser production is overwhelmingly Japanese. Therefore, unless you are fortunate enough to have some direct contact, you will probably be dealing with a distributor who is unfamiliar with your special requirements and rather distant from the supplier.

With this background we will now explain what is involved in getting the laser you desire. In the manufacturing process there will normally be a target wavelength which the company is trying to produce, but there will be some scatter in what is actually produced, and they will advertise this as the range over which lasers are available. Thus the first issue is to get the company to screen the lasers and select the desired wavelength. Some manufacturers of lasers will do this and some will not. However, it is quite common for the local distributor for a company that does select to say that it is impossible to get wavelength selected lasers, or simply refuse to handle them. Sometimes extended phone discussions with the national headquarters and/or the distributor will solve this problem. Once you have found a distributor willing to order selected lasers for you, there are still some additional problems. First, if you want a wavelength that is well out on the tail of the distribution of wavelengths produced, you could have a substantial delay. Several years ago there were many anecdotes about 1.5–2 year waits for delivery, but our impression is that in recent years this has happened less frequently, and the quoted delivery times (typically 2–3 months) have been fairly reliable. However, there is still the problem that after waiting several months for lasers, one may receive lasers that have been selected for a wavelength that is not the requested wavelength. Based on our considerable direct and anecdotal experience concerning this phenomenon, the problem usually seems to be with the distributors and their lack of familiarity with handling wavelength selected lasers.

There are two alternatives to going through the time consuming and frustrating purchasing process just described. The first is to buy a wafer doped to your specifications that will then produce a very large number of lasers. The second, and more common, approach is to find a secondary supplier of diode lasers who will provide wavelength selected lasers. There are a number of suppliers who buy large numbers of lasers from various manufacturers and then resell them, often with optional packages including power supplies and/or optics. Frequently such companies will wavelength select lasers from their stock. Of course this is usually more expensive than obtaining them directly from the manufacturer. Electronics distributors are also often willing to select lasers from their stock.

In concluding this discussion we strongly recommend that if you are starting an experiment with diode lasers, buy several lasers at once. Because of the difficulties and delays in purchasing lasers, combined with the possibility that some lasers may never reach the desired transition and others may die abruptly, it is highly advisable to keep a number of spares on hand. Since the typical cost of AlGaAs lasers is $100–$300, this is a worthwhile investment. However, with the special high power and long wavelength lasers that are more expensive, it may not be feasible to afford this luxury.

B. Mounting of diodes and related optical elements

Once the laser has arrived, it must be set up for use. Two important initial considerations about mounting the laser, regardless of application, are optical feedback and temperature control. One needs to consider the best arrangement to minimize unwanted optical feedback and, if desired, provide controlled optical feedback for frequency control. This usually determines the overall physical layout. The details of the mounting are then determined by considerations of how to keep the temperature of the laser as stable as possible. This is discussed below. Normally, the optimum design in terms of temperature and mechanical stability, as with any laser system, is one that is as compact as possible and reasonably rigid. However, because diode lasers and associated optics can be much smaller and lighter than other types of lasers, the scale of the assembly is often quite different.

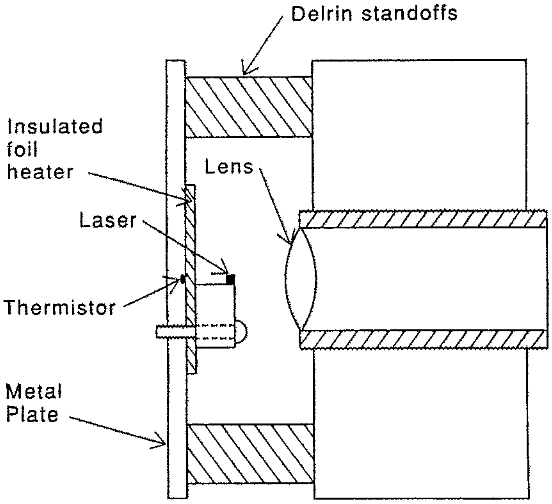

FIG. 7. A simple mount for a diode laser. The heater and thermistor are for stabilizing the temperature. The threaded mount for the collimating lens makes focusing simple.

In Fig. 7 we show a simple laser mount. The laser itself comes attached to a small heat sink. This is mounted with good thermal contact to a small metal plate to which a heater (or thermoelectric cooler) and sensing thermistor are bonded. This plate is then attached to a solid block through a connection that is mechanically rigid, but a poor thermal conductor. The collimating lens is then mounted directly onto this block. A vast variety of types (and prices) of lens are available. Making a rather sweeping generalization, larger lenses that will be mounted farther away from the laser tend to cause less feedback, but it is more difficult to keep the feedback constant than with a small lens close to the laser. The transverse lens position is relatively unimportant; one can simply translate it to the correct position by hand and then tighten down the mounting screw. However, the focusing (longitudinal) adjustment is much more critical, so it is desirable to have some sort of fine screw adjustment on it.

A specific warning to the beginning diode laser user about microscope objectives for collimating lenses: Standard objectives may seem to be a desireable choice because they are so readily available, but they are usually quite lossy for infrared wavelengths, and the optical feedback problems are often quite severe. A superior, low cost alternative is one of the many plastic aspheric lenses made specifically for diode lasers. Another choice when beam quality is not important is the use of inexpensive gradient index (GRIN) lenses.

C. Temperature and current control

As a general rule, the day-to-day repeatability of the laser system performance is determined primarily by the temperature stability. The most direct factor is the temperature dependence of the laser output frequency. However, we have found that the benefits of good temperature stability extend beyond the diode itself. If there is any external feedback, the laser frequency is always somewhat sensitive to the positions of the optical elements and these change with temperature. One almost unavoidable example is back scattering from the collimating lens that feeds back to the laser. If this is not too large and is fairly constant in phase, often it is not even noticeable. However, if variations in the temperature of the apparatus start causing the distance and hence the phase of the feedback light to vary, it can cause quite unwelcome and, at the time, highly mysterious variations in the laser wavelength or linewidth. Thus, poor temperature control can affect the laser performance in a variety of ways. Although it is adequate for some purposes to use only a single stage of temperature control on the laser, we have found that in the long run it is usually worth the small extra effort to add a second stage of temperature control on the base of the mount or on the box enclosing the laser assembly.

A detailed discussion of temperature control servoloops has been given by Williams[17] and we will not dwell on them here. The basic idea is to use a thermistor as one leg in a balanced bridge circuit, and any voltage across the bridge is amplified and used to drive a heater or cooler. As discussed in Ref. 17, one must carefully consider the thermal time delays and the time constants in the electronics to achieve optimum performance. However, we have found that if effort is made to reduce the thermal mass and the thermal delays by mounting the sensing thermistor and the laser in close proximity to the heater, a relatively simple circuit will achieve stabilities on the order of 1 mK. A circuit diagram for such a simple controller is shown in Fig. 8. To achieve this kind of performance, the reference voltage and the bridge resistors must have low temperature coefficients. In addition because of thermal radiation and air currents, it is advisable to enclose the laser mount in some sort of metal container. This has the added benefits of keeping dust out of the system and isolating the laser system from acoustic vibrations.

The last important element in setting up a diode laser is the current control circuit. It is difficult to recommend a generally useful circuit because the requirements of various experiments can be so different. In every case one needs to start with a low-noise current source and some protection against unwanted transients that can destroy the laser. Such a setup can range from a battery and a potentiometer plus a few diodes and capacitors, to quite elaborate circuits. Often the primary consideration in selecting a circuit is its current modulation capabilities. In Fig. 9 we show two sample circuits. See also Bradley and co-workers.[17] As discussed in Sec. III G, it is important to mount the protective diode right on the laser mount.

D. Tuning to an atomic transition

The main difficulty in using diode lasers in most atomic physics experiments is the problem of tuning them to the desired wavelength, usually that of some atomic transition. We have developed some empirical procedures for addressing this problem. To find a transition we set the laser current at the value we would like to operate, and then tune the temperature of the laser to near the correct value by observing the laser's wavelength on a spectrometer. (A note of warning—if one follows the usual procedure of sending a collimated beam into the spectrometer, which no doubt has metal slits, the backscattered light from the slits will often cause the laser wavelength to shift and make the measure-

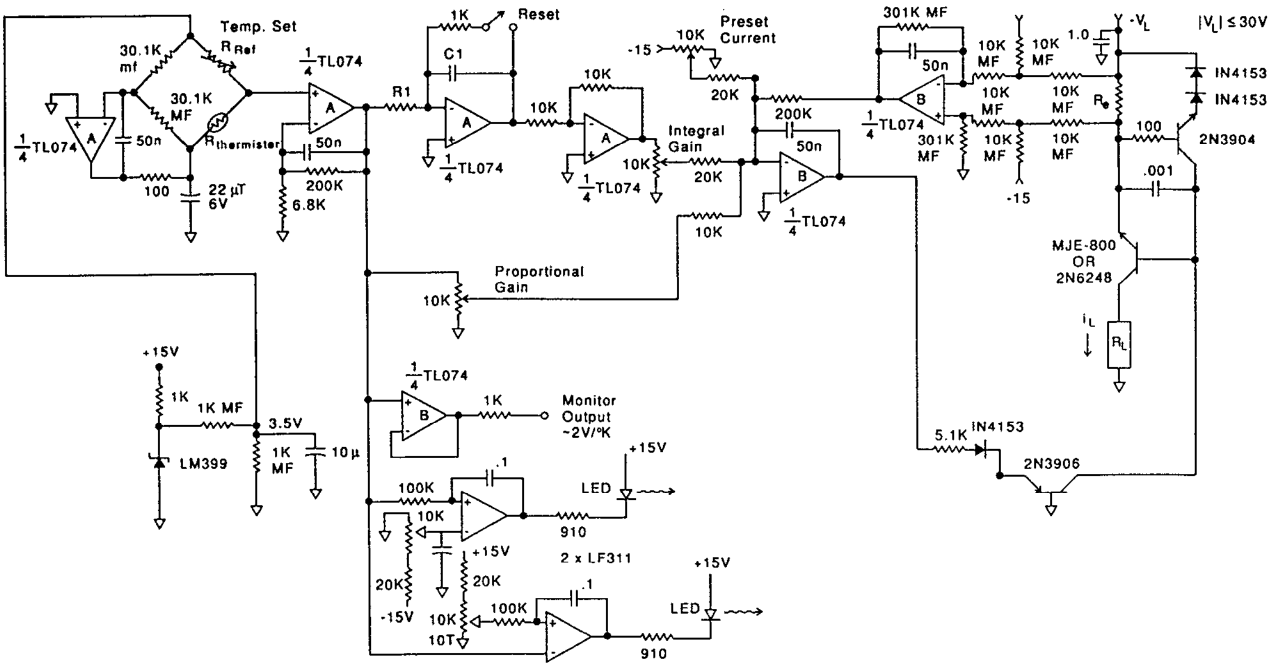

FIG. 8. This simple temperature controller uses a variable combination of proportional and integral feedback and can work as a diode laser controller. The circuit acts to match the resistance of the thermistor with the value of the reference resistor in the bridge. The controller only requires two IC chips (2 - Quad op amps) and a few readily available components. The load R_L can be either resistive or a Peltier element for heating or cooling. R 1 and C 1 determine the integration time constant and are chosen for a given application based on the appropriate system response time. The current is limited to a maximum of 2.4 V/R_e. The LEDs and associated circuitry are optional but useful to indicate whether the temperature is above or below the set point. (This circuit adapted from that of J. Magyar, NIST, Boulder.)

ment meaningless.) Once the laser is near the correct temperature, the current is then rapidly ramped back and forth over a large range, while the mount temperature is adjusted by small increments. The fluorescence or absorption from an atomic absorption cell is used to determine when the desired transition wavelength is reached. Because of the tuning gaps, there may be no combination of current and temperature that produces the desired wavelength. However, there may also be several and one must choose which is most desirable. If maximum laser power is needed, a temperature should be chosen where the laser is on the transition at a high current. On the other hand, if only a small amount of power is needed it is better to pick a low current point so that the diode lifetime will be maximized (although the linewidth and amplitude noise will be somewhat larger). We repeat our previous warning: Never buy a single laser and expect to do an experi-

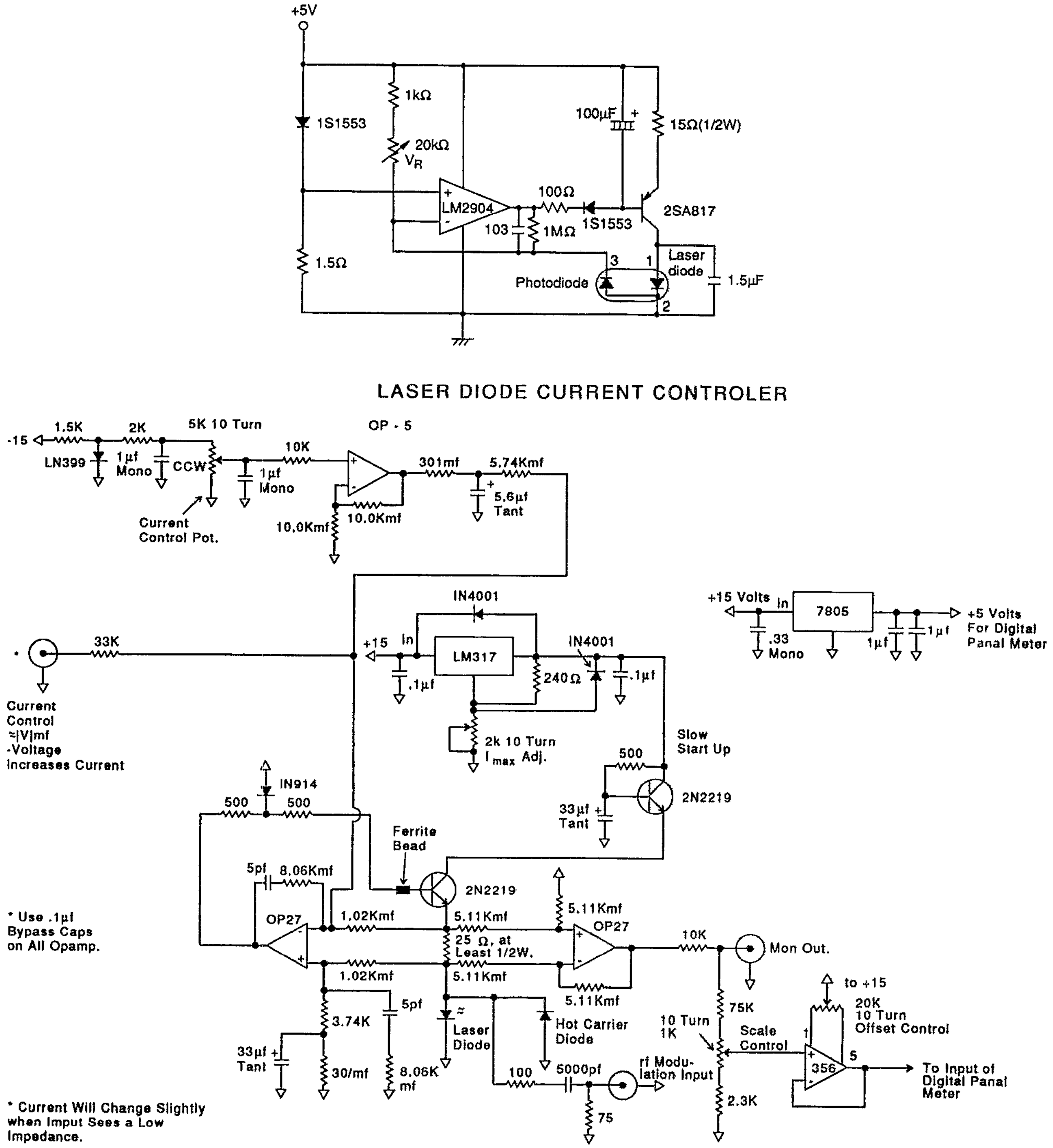

FIG. 9. Two examples of diode laser current sources. (a) A simple diode laser current source that is adapted with permission from the Sharp Corp. (Ref. 4). This circuit has automatic feedback control from a photodiode to maintain constant laser output power. (b) A low-noise diode laser current source that has high speed modulation capabilities. (This circuit with permission from S. Swartz and J. L. Hall.)

ment with it. There is always a significant probability that a given laser will have a tuning gap just at the output wavelength of interest. We have found that, if no external feedback is used, this probability varies between about 30% and 60% for different batches of lasers operating near 852 nm.

As discussed below, additional optical feedback to tune the laser can almost always force it to oscillate at the desired wavelengths, but of course this results in a more complicated device and procedure.

E. Avoiding unwanted optical feedback

We have mentioned several times that the laser performance is affected by optical feedback. One of the unique features of diode lasers relative to most other lasers is their astonishing sensitivity to such feedback. This can be both a blessing and a curse. In Sec. IV we will discuss the blessing aspect; here we will consider the curse.

As discussed in several references,[18] the sensitivity of diode lasers to optical feedback arises from a combination of factors. First, the gain curve is very flat as a function of wavelength; second, the cavity finesse is quite low; and third, the cavity is very short. As a result, the overall gain of the system has an extremely weak dependence on wavelength and there are relatively few photons in the cavity, so that the lasing frequency is very easily perturbed. In addition, when light is returned to the laser it acts as a photodetector, generating more carriers in the junction and affecting the net laser gain. Detailed quantitative discussions are given in the references, but it is probably more useful here to give some general rules for laboratory work using a free-running laser with uncoated output facets. We have already mentioned the problem with scattering from spectrometer slits. In general, we can say that if the laser beam is collimated and hits a surface which scatters strongly, such as burnished metal or a white lab wall, there will be a significant effect on the laser wavelength (frequency shifts on the order of 10 MHz or greater, and easily observable variations in the laser amplitude as the distance changes), but if the surface has a dull black appearance there will probably be little effect. If the beam is going through a focus a larger fraction of the scattered light will be focused back into the laser thus increasing feedback sensitivity. We have found that, as a general rule, one cannot put anything, even good optical glass, at a focus without causing a large perturbation on the laser. These rules must be considered only as very crude guides since there are significant differences in sensitivity among the various types of lasers. How much feedback can be tolerated generally depends on how the laser is being used and the stability of the feedback. If the amplitude and phase of the feedback are constant, it can often be ignored unless one needs to scan the laser's wavelength. Lasers with an output facet coated for reduced reflectance are more sensitive to optical feedback than uncoated lasers. On the other hand, lasers set up to have strong optical feedback to control the wavelength are correspondingly less sensitive to stray feedback.

When using a laser in an experiment where simple positioning of the optical elements does not avoid feedback, one must use some form of optical isolator. The simplest and least expensive isolator is an attenuator in the beam, but this of course is useful only when one can afford to waste most of the laser power. An alternative is a circular polarizer that does not waste light, but only works if the incident and feedback light have the same polarization. This is still fairly inexpensive. When the polarization of the return light is different from the incident light, which happens if there are any birefringent elements in the beam, it is necessary to use a Faraday isolator.[4] Unfortunately these usually cost several times as much as the laser itself.

F. Aging behavior

A key consideration for any experimenter is the reliability of the laser. With diode lasers this has two different aspects. The first is euphemistically referred to as catastrophic failure, which usually means the experimenter did something to destroy the laser. The second is a gradual change in the behavior of the laser, referred to as "aging." Normally one must gain considerable experience with diode lasers before aging becomes relevant compared to catastrophic failure. We will discuss aging first. Although we have not done careful statistical studies of aging behavior we can provide some observations based on our experiences with on the order of 100 lasers. First, while operation at high temperatures and/or high currents can contribute to aging, the original manufacturing process seems to be the dominant factor. We have had some lasers that we used extensively for two or three years before they showed any aging while others changed markedly in just a few weeks. Usually all the lasers in a given manufacturing run will age in a similar fashion.

There are a variety of ways that the characteristics will change with age. One that is hardly noticeable because it is usually slow is that the tuning steps will gradually move. This means that one will occasionally have to adjust the current and/or temperature to keep the laser on the atomic resonance. This becomes serious if eventually the shift causes one to lose the transition entirely, but the opposite can also happen: namely, a laser which formerly could not be tuned to the resonance may age until it can. Aging drift rates can be as large as $+30$ MHz/h and may be due in part to increases in the thermal conductivity of the laser to the heat sink[2,16,19] and changes in the laser due to nonradiative recombination. There are two other symptoms of aging that are more immediately detrimental. The first of these is an increasing tendency for the laser to emit in more than one longitudinal mode, which often means that higher and higher currents must be used to obtain single mode output. The second characteristic is that the spectral width of the single mode output can gradually increase from its initial 20–30 MHz up to several hundred megahertz.

G. Catastrophic failure modes, or 1001 ways to kill a laser

In a lab where diode lasers are applied to a variety of problems and there is a constant flux of students and guest workers, it is a highly unusual laser that can age gracefully and die of the "natural causes" listed above. It is far more common for the lasers to be abruptly destroyed. We have discovered many ways this can be accomplished, and we list these here in the hope it may save others from repeating our experiences. A major weakness of diode lasers is that a very brief transient, which causes too much current to flow or produces too large a back voltage across the junction, can be fatal. A common way this can happen is switching transients when turning the laser on or off. Although one obviously must put in protective circuitry to deal with transients when the laser power supply is switched on and off intentionally, it is also necessary to be concerned with the potential effects of accidental disconnection of the power supply, or intermittent connections in power cables or the ac power line. Other sources of transients are discharges of static electricity and high voltage arcs in other parts of the lab. These last two are minimized by good grounding and shielding procedures. Also the protection diode normally used to prevent excessive back voltage should be as close to the laser as possible. If there is even a fraction of a meter of moderately shielded cable between the laser and the protective diode, a high voltage spark nearby will often destroy the laser. We should point out that a laser which has been electrocuted will often continue to emit laser light, but the wavelength, threshold, and output spectrum will be quite different.

Although electrocution is by far the most common form of death for diode lasers, the lasers that are not mounted in a protective can are also quite delicate and one must be careful not to touch the laser itself, or the tiny current leads, while mounting the laser or associated optics.

Considering all of the possible failure modes for the diode lasers, we find that, on the average, the lasers need to be replaced approximately every six months. This average includes lasers dying for whatever reason or becoming impossible to tune to the appropriate wavelength. Presumably the replacement rate would be much less if the lasers were left alone and not always being tampered with in evolving experiments. This average rate is for moderately experienced users and failure is much more frequent with inexperienced users.

IV. TECHNIQUES FOR CONTROLLING AND NARROWING LASER OUTPUT SPECTRA

Several techniques, both optical and electronic, have been devised to narrow the linewidth and control the center frequency of diode lasers. As mentioned earlier, the effects of optical feedback on semiconductor diode lasers are both profound and complicated, but they have been studied in detail.[18] In particular, the effects of optical feedback on the spectral properties of these lasers can be found in Ref. 20. However, the essence of the optical feedback methods is the simple idea that by increasing the quality factor (Q) of the laser's resonator, the linewidth will be reduced. The simplest implementation of the optical method for spectral narrowing is just to reflect back to the laser a small fraction of its output power. The basic electronic method uses feedback to the laser's injection current to control the laser's frequency. Both the simple optical and simple electronic methods have severe limitations in terms of general applicability.

More elaborate frequency control systems are usually necessary to deal with the variety of diode lasers that are commercially available. No one method has been found to narrow the linewidth and control the frequency of all types of diode lasers. Here we will briefly review some of the more successful methods.

We should mention that there are many errors that one will find in the literature relative to measurements of diode laser linewidths and frequency stability. The most common mistake is that the experimenters will measure the residual noise on an error signal inside a servo loop and use this information to infer a frequency stability. Such measurements do not guarantee that the error signal actually represents laser frequency fluctuations, and they are fraught with systematic errors. Picque and co-workers[21] and Pevtschin and Ezekiel[22] have made more realistic measurements and pointed out some of the possible pitfalls.

A. Simple feedback

Some limited success in narrowing the linewidth of a diode laser has been achieved by using simple optical elements to feed back to the laser some of its output power. Among the optical elements that have been used for feedback are simple mirrors,[23] etalons,[24] gratings,[25] fiber cavities,[26] and phase conjugate mirrors.[27] The resulting systems must be described as lasers with complex resonators where the diodes' facets and the external optical elements all play a role in creating the net resonator structure as seen by the semiconductor gain medium. By providing optical feedback from a small mirror or glass plate placed close to one of the laser facets, sometimes one can force a multimode laser to oscillate on a single mode, or induce a single-mode laser to tune across the forbidden "gaps."[28] The limitations to this method are that it does not work with all lasers, and still requires some sort of frequency reference to stabilize the laser's frequency. Also, as with any complex resonator, it can be difficult to achieve long-term stable performance with such systems.

B. External cavity lasers

The method of the "external cavity laser" uses antireflection (AR) coatings on the diode laser chip, and some external optics to provide the laser resonator. The external optics may contain frequency selective elements such as a grating[29] and/or etalons,[30] with the grating being the least expensive and most common. A variety of geometries are possible and one example of an external cavity laser is shown in Fig. 10. For the nonspecialist these systems can be a challenge because they require having the laser diode facets AR coated, which is usually an expensive and nontrivial procedure. In addition one may need access to both output facets, which is often difficult given the packaging of commercial devices. In principle, this method should work with all types of diode lasers, although only a limited number of systems have been built, and they are not commercially available.

A number of variations on the basic external cavity idea have been demonstrated. These include the use of prisms, birefringent filters, and various other clever optical schemes (of particular interest is the paper by Belenov *et al.*[31]). An example is putting AR coatings on one facet of the laser chip and building pseudo-external cavity lasers as discussed in

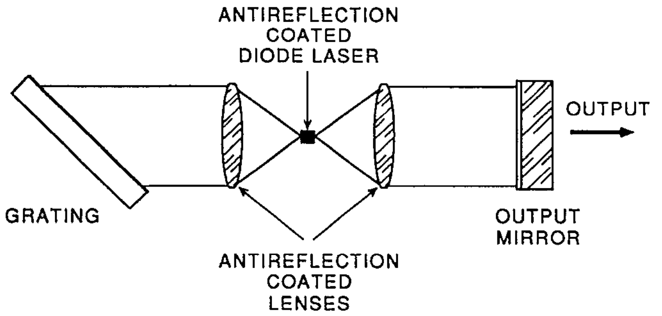

FIG. 10. External-cavity diode laser. This schematic shows an AR coated diode laser chip used in an external cavity with a grating for wavelength selectivity. (Figure from Fleming and Mooradian, Ref. 29, reproduced with permission.)

the next section. This technique has been useful in controlling the spectral properties of 670-nm diode lasers.[32]

C. Pseudo-external cavity lasers

Various laboratories have shown that if only one of the facets of a diode laser is AR coated, the laser's linewidth can be narrowed and its oscillation frequency controlled by providing external frequency selective optical feedback. Fortunately, many of the high power (> 15 mW) commercial lasers already have reduced reflectance coatings on the output facet and high reflectors on the back facet. Gibble and Swann and collaborators have demonstrated that without modification these commercial lasers with coatings can be spectrally narrowed and tuned effectively with grating feedback.[33] An example of such a system is shown in Fig. 11. This method is a combination of the two listed above in that it is not really an external cavity laser, since the laser oscillates without the extra feedback, but the system can operate so that external feedback dominates that from the low reflectance facet. These devices have fundamental linewidths on the order of 100 kHz or less, but the true linewidth is usually dominated by the mechanical and thermal instabilities in the length of the grating-laser cavity. This linewidth can be several hundred kilohertz or larger if the cavity length is not electronically stabilized. We and others have found such lasers to be quite well suited for a variety of applications. Their virtues are that they use standard commercial lasers and inexpensive components, and the grating allows tuning over a range larger than could be easily covered by temperature tuning. Also the tuning can be continuous over much larger spectral ranges, and it is quite easy to set and keep the laser frequency on particular atomic transitions. Minor difficulties in the design are that the grating alignment is moderately sensitive, and to achieve the necessary degree of collimation of the laser light, the distance between the laser and the collimating lens must be adjusted to within a few micrometers or less. In practice it is adequate to have the lens position adjusted with a fine-pitch screw, with the position set so that the beam appears the same diameter to the eye over a path of several meters.

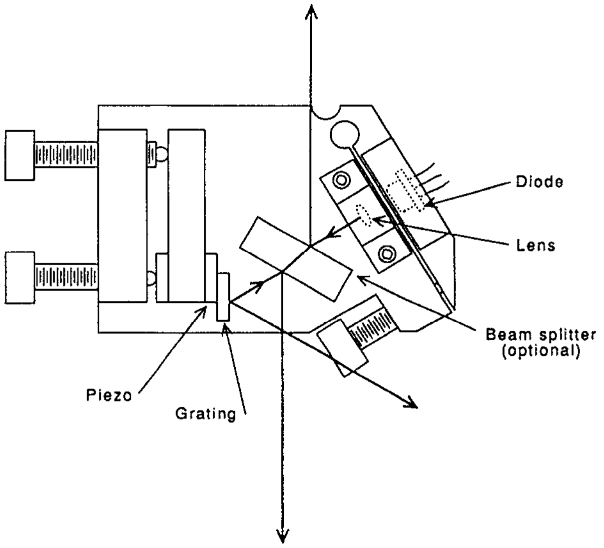

FIG. 11. A pseudo-external cavity laser using a standard commercial laser and a diffraction grating for feedback. The flex pivot is used to obtain the precise focusing of the collimating lens which is necessary. The peizoelectric transducer under the grating is used for fine frequency tuning by changing the length of the cavity. Other tuning options are to have the piezo-electric transducer on the other side of the mount so that it rotates as well as translates the grating, or to do the tuning using an uncoated piece of glass which is mounted on a galvanometer near Brewster's angle and is precisely rotated. Not shown is the temperature control elements (sensors and heaters or coolers) that must be used on the diode and may be used on the baseplate.

There are tradeoffs one can make in the detailed design between greater feedback, and hence more frequency control, versus coupling out more power. The exact performance will depend strongly on the reflectance of the output facet of the laser. For illustrative purposes, we will describe the behavior of such a laser system using a Sharp LT015 laser (mention of this product does not represent a recommendation and we expect other lasers to behave similarly), with $\approx 70\%$ feedback to the laser. As the grating is rotated, the laser will tune continuously over a region of about 80 GHz spanning the peak of the semiconductor laser cavity resonance. To obtain continuous tuning, the grating is mounted so that, as it rotates, the change in the cavity resonant frequency due to the change in the cavity length matches the angle tuning of the grating.[34] A small (2 cm) piezoelectric speaker disk placed between the grating tilt screw and the block on which the grating is mounted is a convenient and inexpensive way to rotate the grating smoothly. There will then be a gap in the tuning of 70–80 GHz until one reaches the next mode of the small semiconductor cavity. This pattern repeats itself as the laser is tuned farther from its gain peak, with the range of continuous tuning gradually decreasing. The maximum range the laser wavelength can be pulled from its gain peak is about ± 10 nm, at which point the tuning range per diode mode is about 10 GHz. With the feedback reduced to 25% to increase the output coupling, the maximum range of continuous tuning is about ± 6 GHz, and the farthest the frequency can be pulled is about 6 nm. Gaps in the tuning are easily filled by adjusting the laser current or temperature to shift the frequency of the laser diode modes. The output power is about 10 mW with this output coupling.

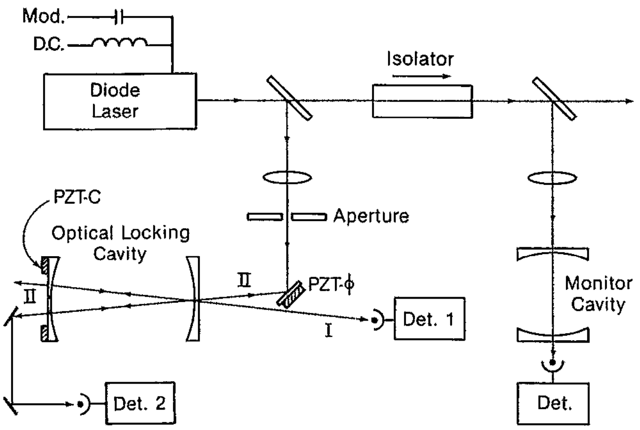

FIG. 12. Schematic diagram of an optical feedback locking system for laser diodes. In the geometry shown optical feedback (type II) occurs when the lasers frequency matches the resonance frequency of the optical locking cavity. This type of feedback locks the laser's frequency to the cavity resonance frequency and narrows the laser's linewidth. The monitor cavity is used as a diagnostic and does not affect the laser's frequency because of the optical isolator. (Figure from Ref. 59, reproduced with permission.)

D. Feedback from high-Q optical cavities

Another optical feedback locking system that we have used quite successfully is diagrammed in Fig. 12. In this system we use weak optical coupling of the laser's output to a high-Q optical resonator.[35] The geometry is such that the laser sees optical feedback from the Fabry–Perot cavity only when the laser's frequency matches a resonance of this cavity. The result is that the coupled (laser plus cavity) system has lower losses at a cavity resonance and the laser's frequency automatically locks up to the cavity resonance. In this way the laser's linewidth can be reduced to a few kilohertz and the laser's center frequency is stabilized to the cavity. One of the limitations of this system is that it requires some additional slow electronics to keep the laser locked to the same cavity mode for long times and to keep the laser synchronized with the cavity for long scans (greater than about 1 GHz). Without the additional electronics, the laser will stay locked to the same cavity mode for times that vary from less than 1 to as much as 30 min, depending on the stability of the cavity and the temperature and current controls for the laser. By reducing the distance between laser and cavity to a few centimeters and mounting the cavity and laser in a pressure-tight temperature-controlled enclosure, we have been able to extend this to several hours without electronic control. We and others use this system with good results with unmodified commercial lasers operating in the diode laser wavelength bands at 780, 850, and 1300 nm. With rather limited experience, we have been disappointed in the results of this method for unaltered gain-guided lasers operating at 670 nm. However, the method appears to work with the new index-guided versions that have some AR coating.[36] The major advantages of this system of frequency control are that the linewidth is very narrow and the stability is determined by the external cavity, which can be made very rigid and insensitive to changes in temperature and atmospheric pressure. Also, the laser retains some high speed modulation capabilities. The disadvantages are the sensitivity to cavity laser separation mentioned above, and the fact that laser tuning range (and gaps) is still essentially the same as that of the basic unstabilized laser.

There are a number of optical configurations that can produce resonant optical feedback from a high Q resonator, but in practice the V configuration shown in Fig. 12 is a very convenient one. The alignment procedure is straightforward and after a little practice can be done fairly quickly when one recognizes the proper signal shapes. During the alignment and afterwards it is best to sweep the laser's frequency over several orders of the Fabry–Perot and to monitor the power transmitted through the cavity. The effects of feedback from the cavity to the laser will be obvious in the shape of the transmitted fringe. By sweeping many cavity modes the effects of the feedback can be observed. The system requires only a small amount of the laser's output power ($\sim 1\%$) for locking but for alignment it is easier to start with higher powers ($\sim 10\%$) so that it is easy to see the beams. After one becomes familiar with aligning the optical feedback lock, the feedback power can be reduced. This 10% of the output is split off and sent through an attenuator and a lens that approximately mode-matches the beam into the high-Q Fabry–Perot cavity. An easy way to determine that the mode matching is correct is to ensure that the return beam reflected from the Fabry–Perot cavity is about the same size as the beam that is incident on the cavity. Next, one looks to see that the input beam is centered on the Fabry–Perot's input mirror and that the reflected beam is at a small angle relative to the input beam. The divergence angle can be quite small but it is necessary that the return beam is a few spot diameters away from the input beam by the time it returns to the laser. One should also observe that there are two output beams transmitted through the cavity on resonance (see Fig. 12). By setting the attenuator for very low powers one will see the usual Fabry–Perot peak structure in the transmitted light; then as the feedback is increased the laser will begin to lock to the cavity resonance and the Fabry–Perot shape will broaden and become squarish. The fringe will typically broaden to a few hundred megahertz, corresponding to the range over which the cavity controls the laser's frequency. The feedback power can be increased to enhance the locking range and to reduce further the laser's linewidth. When the feedback becomes too strong the system will become unstable.[37]

The phase of optical feedback (distance from the laser to the cavity) is optimum when the power transmitted through the cavity is maximum. One can force the lock to the optimum condition by modulating the path length from the laser to the cavity (with a PZT) and detecting the transmitted power. This signal is then demodulated with a lock-in amplifier and fed back electronically to control the position of the PZT. Variations in the optical feedback phase can be minimized by good mechanical stability and by making the distance from the laser to the cavity small. In fact we often operate these optically locked systems without active electronic control.

Although commercial cavities are often adequate it is useful to be able to make simple inexpensive tunable Fabry–

Perot cavities. The simplest method is to glue laser quality mirrors onto a cylindrical Invar or quartz tube, with a PZT disk under one of the mirrors so that the cavity can be scanned. If one of the mirrors can slide inside a tubular mount, the cavity can be aligned and set to the confocal condition by aligning it with a laser before the last mirror is glued in place. For the best stability it is useful to have a hermetically sealed cavity. In these simple cavities this can be accomplished with a glue that does not unnecessarily stress the mirrors (such as Tracon 2143D epoxy, mention of this product does not represent a recommendation). An alternative design uses a fine thread on the Invar spacer to set the cavity to the proper length. For most of our diode laser spectroscopy we use reference cavities with finesses of about 100 and free-spectral ranges of 0.25–8 GHz.

E. Other optical feedback techniques

Other monolithic or semimonolithic extended cavity diode lasers with good spectral qualities have been reported in the literature,[38] but they are usually laboratory test devices that are not commercially available and usually not tunable. There are indications that some of these systems will become commercially available in the near future, but it is not likely there will be broad spectral coverage anytime soon.

F. Electronic feedback

The other competing method for laser frequency stabilization is electronic feedback. It is straightforward to use electronic feedback to lock the center frequency of diode lasers to cavities or atomic absorption lines using standard laser stabilization methods.[39] On the other hand, narrowing the laser's linewidth with electronic servos is a much more difficult task. The problem is that the frequency noise spectrum extends to such high frequencies that most servosystems are not able to act fast enough to correct the laser's frequency fluctuations. A few groups[40–42] have been successful in developing very fast (few ns delay time) electronic servosystems that can be used to narrow the linewidth of diode lasers if the laser's intrinsic linewidth is not too broad to start with. Linewidths on the order of 100 kHz have been achieved with these techniques. Electronic systems have the advantage over most of the optical methods in that they do not degrade the modulation characteristics of the lasers. However, a disadvantage is that they do not extend the laser's tuning range. Unfortunately, considerable expertise in electronics is required to design and build the necessary circuits.

G. Hybrid systems

Hybrid designs are of two basic types. In the first case, electronic feedback is simply used to tune a cavity that controls the laser frequency by optical feedback. In the designs described in Secs. IV B, IV C, and IV D, for example, this would entail moving the end mirror or grating using a piezoelectric transducer. Typically this is done to achieve long-term frequency stability by locking the cavity frequency (and thereby the laser) to an atomic or molecular transition.

Promising results have also been obtained with a second type of hybrid system which uses electronic feedback in addition to optical feedback to reduce the laser's linewidth.[43] In this hybrid optical-electronic system the optical feedback is used to initially narrow the laser to the point that less sophisticated electronics (than that mentioned in Sec. IV F) can further narrow the linewidth and stabilize the laser's frequency. With such systems it should be possible to achieve frequency stabilities that are limited only by one's ability to provide an adequate frequency discriminator. Using this type of servosystem, phase locks between diode lasers have been demonstrated.[43]

H. Injection locking

It is also possible to stabilize the frequency of diode lasers by optical injection locking.[44] The frequency of an unstabilized diode laser can be locked to a spectrally narrow, master laser oscillator by coupling a small amount of power from the master laser into the slave diode laser. This technique may be useful for some applications (e.g., generating higher power) but obviously does not meet many spectroscopic needs, because if a good master laser were available the diode laser would not be needed. The notable exception is that injection locking allows one to use the high powers available from arrays or wide channel lasers and still maintain the precise frequency control which can be obtained with a feedback-stabilized diode.[45]

I. Summary

For some spectroscopic applications the spectral characteristics of commercial diode lasers are good enough as they stand, but for many others that is not the case. Also, unstabilized lasers can be quite difficult to tune in a controlled manner. Unfortunately, none of the existing frequency stabilization methods (perhaps with the exception of the external cavity system) are able to narrow the linewidth and control the frequency of all of the types of semiconductor lasers that are potentially useful for atomic physics. We do not mean to discourage the potential user of high resolution lasers, because at many wavelengths the existing solutions work very well and provide tunable narrow linewidth lasers from commercially available diodes. Such devices have the advantages of very narrow linewidths and excellent amplitude stability, and they are much simpler and more reliable to tune to a particular frequency than are unstabilized lasers.

V. APPLICATIONS

Having discussed how to build and use diode lasers, we will now discuss some of their applications in atomic physics. Of the numerous possibilities, we have chosen to describe a few novel applications that demonstrate some of the new capabilities of diode lasers that have not previously been appreciated. Many of the examples are related to our own work. We do not wish to imply that this is the only work in this field; rather these are simply a number of representative samples that are most familiar to us.

A. Optical pumping

One of the earliest applications of a diode laser to atomic physics was as the light source for optical pumping and probing of a polarized medium. Many applications of this type are reviewed by Camparo.[1] Here we want to mention briefly some interesting new optical-pumping applications using traditional laser approaches.

Diode lasers have been used extensively in frequency standards and atomic clocks. In these applications they optically pump the atoms of interest, and then detect the atoms that have undergone the microwave frequency clock transitions. Fortuitously, the atoms used in some of our best frequency standards (rubidium and cesium) have resonance-line wavelengths that are easily produced by semiconductor lasers. The work in this area started in earnest in the mid-70's[46] and continues with promising results today.[47,48] Significant research and development efforts to incorporate diode lasers into rubidium, cesium, and other atomic frequency standards are under way around the world. These efforts are driven by vast improvements in signal-to-noise ratios, ultimate accuracy, and the relative simplicity obtained by using diode lasers. Figure 13 is a schematic diagram of a diode-laser-pumped cesium atomic clock. The lasers are first used to prepare the atomic beam by putting all the atoms into the appropriate hyperfine level using optical pumping. Then, after the atoms have passed through the microwave region, a laser excites the initially depleted level. Thus the microwave transitions are detected by the increase in the downstream fluorescence.

In an optical-pumping experiment of a different sort, Streater, Mooibroek, and Woerdman[49] used the light from a diode laser to drive very successfully a rubidium "optical piston." The optical piston is an atomically selective drift that is driven by laser light. We list this under optical pumping because a key element in the experiment was the novel scheme of using the relaxation oscillation sidebands of the diode laser to assist in optical pumping of Rb atoms. In this particular case the 3-GHz ground state hyperfine splitting of ^{85}Rb matches the relaxation oscillation frequency of the 780-nm lasers. Thus a single laser allowed them to excite atoms in both hyperfine ground states, which greatly enhanced the operation of the "piston."

B. Applications using fast frequency modulation

One of the unique aspects of semiconductor diode lasers is the ease with which their amplitude and frequency can be modulated. The amount of modulation can be both large and very fast. For common diode lasers the modulation response extends out to a few gigahertz, with a few special lasers capable of modulation rates of more than 10 GHz. This modulation capability has applications in spectroscopy as well as other fields. As mentioned earlier, modulation of the diode laser's injection current produces both AM and FM, but in many cases of atomic transitions the frequency modulation is the dominant effect and we will focus attention on it here. The frequency modulation is dominant simply because the atomic linewidth corresponds to such a small fractional change in frequency.

We can picture the frequency modulation of the laser either in the time domain or in the frequency domain, depending on the particular application. If we first think in the frequency domain, modulation of the injection current at high frequency produces a laser spectrum with modulation sidebands. The application of modulation sidebands to all types of lasers has proven very useful for spectroscopy and other applications.[50] The principal advantage of these optical heterodyne methods is that they increase the signal-to-noise ratio in detecting absorption and dispersion signals. These techniques have been extended to diode lasers by Bjorklund,[51] Lenth,[52] and others.[53] The diode laser case is complicated somewhat by the additional AM that accompanies the desired FM. Lenth in particular has sorted out the effects of having both AM and FM modulation simultaneously.[52]

We have used optical heterodyne methods with frequency modulated diode lasers to detect alkali atoms and optical cavity resonances with high sensitivity. External frequency modulators have been also used with InGaAsP lasers to detect NH_3 using FM spectroscopy.[54] Ohtsu[55] and collaborators have achieved excellent results with optically pumped Rb clocks by using frequency-modulated laser diodes for

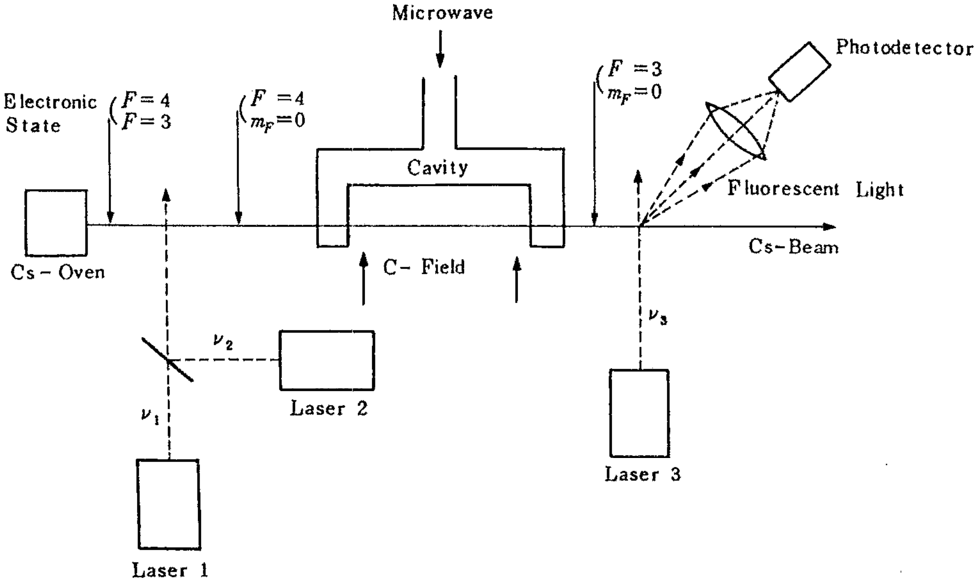

FIG. 13. Diagram of an optically pumped cesium atomic frequency standard. The cesium atomic beam travels in a vacuum through the first laser interaction region where the atoms are optically pumped, it then traverses the microwave cavity region and then on to the second laser interaction region where the atoms are detected. The population in the ground state hyperfine levels is indicated along the path by the F and m_f values. The microwave clock transition is between the $F=4$, $m_f=0$, and the $F=3$, $m_f=0$ states. As shown here the system uses two lasers with different frequencies for optical pumping and a third laser for detection. (Figure from Ref. 2, reproduced with permission.)

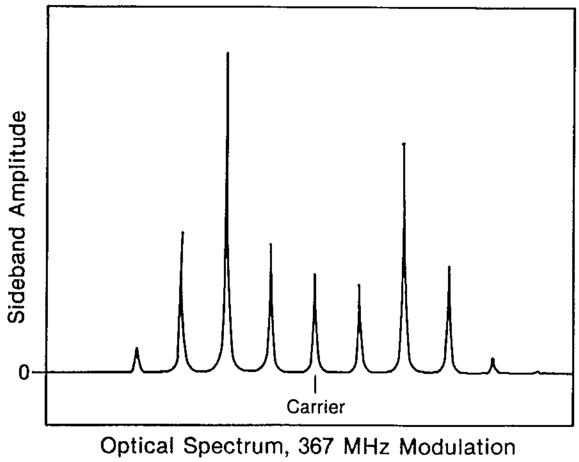

FIG. 14. Modulation response of an optically locked diode laser. The spectrum shown here is taken with the detector (Det.) and monitor cavity system shown in Fig. 12. The laser's injection current is modulated at 367 MHz through the modulation port (Mod.). The modulation frequency is rationally related ($\frac{3}{2}$ times) to the free spectral range of the locking cavity. In this case the optical lock is stable and provides an array of narrow linewidth laser side bands each spaced by the modulation frequency. Lasers without optical locking have similar modulation response but with broad linewidths. (Figure from Ref. 57, reproduced with permission.)

optical pumping and high sensitivity detection. Other applications of frequency-modulated diode lasers include communication systems, length measurements, range finding, and laser radar.

A great deal of spectroscopic work with diode lasers and frequency modulation has been done with the lead salt diode lasers operating in the infrared. Methods have been developed using modulation at two frequencies ("two-tone" modulation) to detect molecular species with high sensitivity.[56] The techniques employed with these lasers are also generally applicable to the GaAs lasers.

If we increase the strength of the modulation of the injection current, it is possible to spread out the diode laser's spectrum into many discrete sidebands. These sidebands can cover spectral windows of many gigahertz. Figure 14 shows a spectrum of a diode laser whose injection current (97 mA dc) is modulated at 367 MHz with an amplitude of 4 mA. This modulation produces eight discrete sidebands spaced by the modulation frequency, in addition to the original carrier, and does not otherwise broaden the spectrally narrow laser ($\approx$10-kHz linewidth). Potential applications of this high modulation index case include laser frequency control, fixed local oscillators for coherent communication systems, and atomic and molecular physics experiments where numerous frequencies are required.

Some applications of diode laser frequency modulation are best viewed in the time domain. For example, rapid chirping or jumping of the output frequency has been used successfully in several experiments. Watts and Wieman[58] demonstrated that the output frequency of a laser can be changed by 10 GHz and become stable to within a few megahertz in a time of 2 μs. This was accomplished by simply changing the injection current through the laser using an appropriately tailored pulse. With this high speed switching it was possible to optically pump all the atoms in a cesium beam into a specific magnetic sublevel (F, M_F) using a single laser. Normally this would be impossible because cesium has two ground state hyperfine levels that are separated by 9.2 GHz. However, in a fraction of the time it took the atomic beam to pass through the laser beam, the laser frequency was switched to excite both levels. Robinson[59] has also used this frequency jump technique to polarize a rubidium cell with a single laser. This capability to rapidly sweep the laser frequency over a large range in a controlled manner is unique. In these experiments it was used to reduce the number of lasers needed for optical pumping, but it may find greater utility in studies of various types of transient phenomena.[1]

A recent application of the frequency chirping capability of diode lasers is the stopping of atomic beams. Ertmer *et al.*[60] showed that by frequency chirping the light from a dye laser it was possible to slow and stop a beam of sodium atoms. To achieve the necessary frequency scan a sophisticated broadband electro-optic modulator was developed. A corresponding frequency chirp is very easy to produce with a diode laser by merely adding a small sawtooth ramp to the injection current. Watts and Wieman used this technique to stop a beam of cesium atoms[61] with a surprisingly simple and inexpensive apparatus. Salomon *et al.*[62] have carried out a similar experiment to study the optimization of the cooling. They showed that by adding 110-MHz sidebands to the laser, they could enhance the number of stopped atoms by 50%. Recently Sheehy *et al.*[63] have used frequency chirped diode lasers to stop rubidium atoms. These various experiments demonstrated that, in addition to slowing atoms, the frequency modulation capability of diode lasers is also well suited to probing atomic velocity distributions rapidly enough to avoid distortion.

The resulting 15-m/s velocity spread of the nearly stopped atoms reported in Ref. 61 was limited by the 30-MHz linewidth of the diode laser. To improve on this, Sesko, Fan, and Wieman[64] stopped atoms in a similar manner using a cavity-stabilized laser of the type discussed in Sec. IV D. In this case, the frequency was ramped by changing both the laser current and the length of the stabilization cavity (using a piezoelectric transducer). The speed of the cavity response was less than that of the laser, but was still adequate for atom stopping. With a cavity-stabilized stopping laser, the number of stopped atoms was found to improve dramatically and the final velocity spread was substantially smaller. We have obtained similar results by stopping atoms with the light from grating cavity lasers of the type discussed in Sec. IV C.

C. High resolution spectroscopy

We mentioned briefly the improvements that cavity locked lasers have made for atom stopping. This is only one of a large number of experiments made possible by optical feedback stabilization. This technique provides a very narrow bandwidth source which is valuable for high resolution spectroscopy and other experiments where narrow linewidth is important. Although often neglected in the English literature, a great deal of forefront work on diode laser stabilization and applications to high resolution spectroscopy has been done by Velichanski and co-workers.[65] Other examples of high resolution and high sensitivity spectrosco-

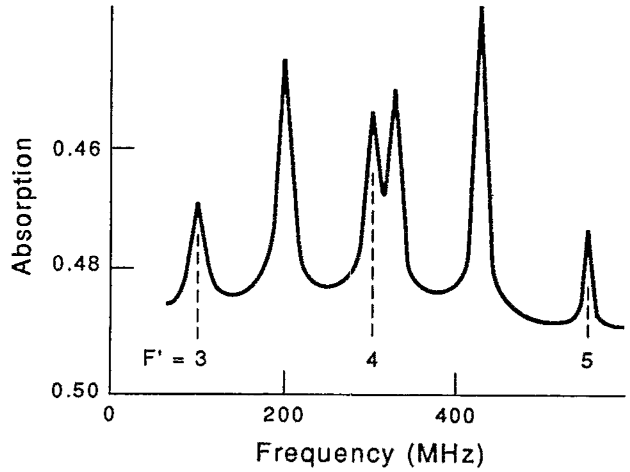

FIG. 15. A saturated absorption spectrum of the $6S$ to $6P_{3}/2$ transition in cesium obtained using a stabilized diode laser. This spectrum was a single oscilloscope trace with no signal processing except the subtraction of the Doppler broadened absorption line. This demonstrates the signal-to-noise ratios that can be obtained with diode lasers. The diode linewidth gave a negligible contribution to the resolution (10 MHz for the narrowest line).

py are described in Refs. 66–69. Figure 15 illustrates the capabilities of cavity stabilized lasers for high resolution spectroscopy. This figure shows a fluorescence spectrum of the $6S$-$6P_{3/2}$ transition in cesium observed in a single 100-ms oscilloscope trace. The spectral linewidths were limited entirely by the 6-MHz natural linewidth of the transition, and had no contribution from the laser linewidth. Figure 15 also illustrates how the amplitude stability of the laser leads to very good signal-to-noise ratios. This laser was used to make precise measurements of the Stark shifts and the hyperfine structure of the $6P_{3/2}$ state of cesium. These measurements had an uncertainty of only 20 kHz.

Good examples of applications that use the unique modulation capabilities of diode lasers for precision spectroscopy are the work of Martin and co-workers.[68] They have demonstrated time-resolved spectroscopy of BaCl and velocity-modulation spectroscopy of N_2^+.

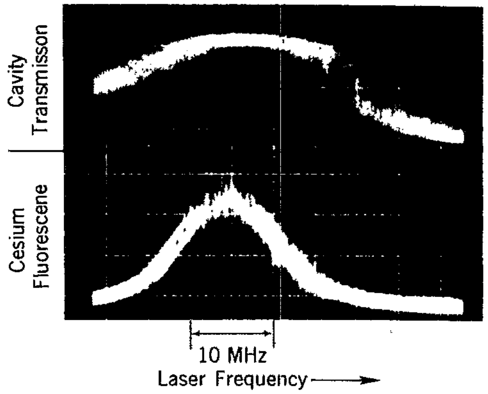

FIG. 16. Fluorescence measurements of the $6S$ $F=4$ to $6P_{3/2}$ $F=5$ resonance line in a cesium atomic beam. The laser's frequency noise causes excess amplitude noise on the cesium fluorescence signal. This noise is surprisingly irregular as can be seen by comparing it to the noise observed on the Fabry–Perot cavity transmission signal that was taken simultaneously. We see the frequency noise shows up on the sides of the cavity transmission fringe whereas it is enhanced on the peak and one side of the fluorescence signal. This noise disappears when the lasers linewidth is narrowed.

Avila *et al.*[69] have used diode lasers to make a high precision measurement of the absolute energy of the $6P_{3/2}$ state in cesium. The laser frequency was locked to the cesium resonance line by observing fluorescence from a collimated cesium beam. A wavemeter was then used to measure the absolute frequency to 12 MHz (3 parts in 10^8).

In the work of Gibble and Gallagher,[67] a pseudo-external cavity laser with grating feedback was used to study velocity changing collisions in rubidium. Using a saturated absorption technique and this continuously tunable narrowband laser, they were able to measure collisional distortions of the saturated absorption line shapes which were a small fraction of the 10-MHz natural linewidth.

Feedback-stabilized diode lasers are uniquely simple and inexpensive sources of very narrowband tunable light. For this reason, they will undoubtedly be widely used for high resolution spectroscopy in the future.

D. High sensitivity spectroscopy

Another developing area of application of diode lasers is to high sensitivity spectroscopy. This includes the application to optical pumping, optical heterodyne or FM spectroscopy,[51–53] ultrasensitive detection,[70] optogalvanic spectroscopy,[71] and other areas.[68] Also, significant work in sensitive spectroscopy has been done using the lead salt diode lasers[72] which we have not addressed in detail in this article. Often these applications are just extensions (to diode lasers) of well-established techniques of spectroscopy. On the other hand, there are a few applications that utilize the unique capabilities of the diode lasers.

Diode lasers stabilized by optical feedback have been found to be much better than unstabilized lasers for high precision measurements of fluorescence or absorption where the signal-to-noise ratio is important. In some cases the feedback not only reduces amplitude noise on the laser, but also reduces some previously unexpected noise on atomic spectra associated with the laser FM spectrum. In using diode lasers for precision spectroscopy some workers have reported that the measured signal-to-noise ratios are much lower than expected.[73] For example, we observe large amounts of excess noise in diode laser-induced fluorescence and direct absorption measurements of the $F=4$ to $F=5$ resonance line in cesium (see Fig. 16). This noise results from the frequency fluctuations in the diode laser and is eliminated when the diode laser's linewidth is reduced by using the high-Q cavity feedback lock. Two surprising features are observed in this excess noise relative to what one would expect from simple rate equation analysis of the laser induced transition: first, it is much too large; and second, the noise can also be asymmetric with respect to laser detuning from the resonance. By properly treating coherence and atomic saturation with a noisy laser source, Zoller and co-workers[74] have provided an explanation of these observations.

Two significant instances in which the elimination of this noise has been a major concern are the new optically pumped cesium clocks being constructed at NIST and other national standards labs[48] and the precise measurement of parity nonconservation in cesium using an optically pumped beam.[75] In these experiments the use of feedback-stabilized lasers has been essential because of the reduced noise in the atomic fluorescence.

E. Self-locking power buildup cavities

Another application of feedback from high-Q cavities is the self-locking power-buildup cavity, which can provide large enhancements in laser power. One obvious shortcoming of diode lasers is the small output power, but buildup cavities allow one to overcome this limitation in some experiments where there is little optical absorption. The basic idea of such a cavity is the same as discussed in Sec. IV D, but the optics are arranged so that a large fraction of the laser power is coupled into the locking cavity. This results in the intracavity power becoming much higher than the output power of the laser. Buildup cavities have been used with lasers for many years; however these always required some electronic feedback system to keep the cavity and laser frequencies the same. With a diode laser, the need for electronic feedback can be eliminated because the optical feedback locks the laser to the cavity resonance. Enhancements as high as 1500 in the one-way power buildup[76] have been obtained with such "self-locking buildup cavities." These have provided a circulating power of 45 W.

Tanner, Masterson, and Wieman[76] used a self-locking buildup cavity to study how a strong blue-detuned standing wave can collimate a cesium atomic beam. Using this technique they were able to reduce the divergence of the beam from 15 to 4 mrad using only a 10-mW laser source.

In another application, over 1 mW of tunable light at 432 nm was produced by placing a potassium niobate crystal inside such a self-locking buildup cavity to produce the second harmonic of the diode laser light.[77] With the proper lasers and crystals, it may be possible to use this approach to achieve several milliwatts of narrowband tunable light over much of the blue region of the spectrum. When this technology is combined with injection-locked diode arrays or arrays that are themselves optically locked to buildup cavities,[78] many tens of milliwatts will be available. On the other hand, for applications not requiring a large amount of second-harmonic light, Ohtsu[79] has shown that it is possible to do spectroscopy with the small amount of second-harmonic light that is emitted from ordinary diode lasers.

F. Trapping and cooling atoms using diode lasers

Another area in which stabilized diode lasers have been used very successfully is in cooling and trapping neutral atoms. Such experiments often require several different laser frequencies with linewidths of less than 1 MHz, and thus they are quite expensive to set up using dye lasers. This expense precludes the use of dye laser-cooled and/or trapped atoms in a wide range of atomic physics experiments for which they would otherwise be well suited. The use of cavity- and grating-stabilized diode lasers overcomes this problem. Sesko and co-workers[64] have recently cooled cesium atoms using a three-dimensional standing wave tuned to the red side of the cesium resonance line (so called "optical molasses"). This has produced atomic samples containing 5×10^7 atoms with a temperature of $100\,\mu$K. In a related experiment he and co-workers then observed the cesium "clock" transition between the two ground hyperfine states in this cold sample.[80] The low temperature allowed an interaction time of 20 ms and hence a linewidth of only 44 Hz, in an interaction volume of less than 1 cm^3.

In other experiments Sesko *et al.*[81] have succeeded in trapping atoms using a Zeeman shift spontaneous force trap created with diode lasers. Using four stabilized lasers, samples of up to 4×10^8 atoms were trapped, and trapping times of greater than 100 s were obtained.[81] A variety of interactions between the trapped atoms were studied. In both the optical molasses experiments and these trapped atom experiments, features of the diode lasers other than their cost have been important. There were a number of probe studies where very low amplitude noise and ease of rapid frequency changes were invaluable.

Inexpensive diode lasers are proving to be valuable tools for atomic spectroscopy. They offer continuously tunable sources of radiation with linewidths under 100 kHz and powers of 30 mW or more. They can cover much of the near infrared region of the spectrum and are moving into the visible. These devices can (though they may not) be simple and highly reliable. Their low cost and ease of use make multilaser experiments quite feasible, and more importantly, diode lasers allow laboratories with limited resources to still be involved in "state-of-the-art" laser-atomic physics experiments. These include the areas of laser cooling and trapping, nonlinear optics, and high precision spectroscopy.

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