Frequency stabilization of diode lasers

Santa Chawla

National Physical Laboratory, Dr K. S. Krishnan Road, New Delhi 110 012, India

Diode lasers are compact and low cost alternatives to huge and expensive dye lasers for many atomic physics experiments such as laser cooling and trapping of atoms, high resolution spectroscopy, etc. Tremendous improvements in the diode laser fabrication technology in the recent past have made it possible to obtain single mode output with hundreds of mW output power in cw lasers. Linewidth of diode lasers can be reduced to kHz level by optical feedback from a frequency selective element in an external cavity configuration. Wavelength tunability of approximately 10 nm or more by variations of temperature, injection current and external cavity parameters make diode lasers a very desirable laser source for frequency stabilization against saturated absorption of alkali atoms and locking the laser frequency to a desired atomic transition with electronic servocontrol. Such frequency stabilized diode laser systems have been successfully used for various novel experiments in many research laboratories all over the world.

SEMICONDUCTOR diode lasers are the smallest lasers in existence. Diode lasers started lasing in 1962 almost simultaneously at three different laboratories, namely R & D Centre of General Electrics, IBM's T. J. Watson Research Centre and MIT's Lincoln Laboratory – all in USA. First laser diodes were made from GaAs *p–n* homojunctions, required very high current and could be operated only in the pulsed mode with cryogenic cooling and heatsinking. Room temperature continuous wave (cw) operation was achieved in 1970 in a double heterostructure junction diode laser. Subsequent rapid developments in the technology, e.g. Metal Organic Chemical Vapour Deposition (MOCVD) technique for semiconductor fabrication, double heterostructure, stripe geometry, quantum well structure have revolutionized the field of diode lasers in terms of low cost, small size, low power consumption, sufficient laser output power, wide wavelength range and tunability to such an extent that diode lasers have become indispensable tools in research laboratories as well as in commercial instruments like laser printer, CD player, bar code scanner, optical fibre communication systems, etc. The emission wavelength of commercially available diode lasers[1] broadly range from 630–680 nm (InGaAlP), to 750–900 nm (GaAlAs) to 1–1.9 μ (InGaAsP). The blue diode laser[2] (InGaN) has already been produced and the possibility of extending the wavelength range to far IR by using different semiconductor material exists. Output power ranges from a few milliWatts to tens of Watts for cw system and to a few kW for pulsed peak power. The available wavelength range of diode lasers covers atomic transitions of many inorganic atoms such as Li, Na, Rb, Cs, Ca and provide very attractive alternatives to huge and costly dye laser for laser cooling of such atoms and their high resolution spectroscopy. Actual use of diode lasers for such sophisticated experiments has a few impediments. They are large frequency noise, mode hops and tuning discontinuity depending upon parameters such as fluctuations in temperature, injection current and optical feedback. The aim of frequency stabilization is to minimize/overcome the above drawbacks and obtain a narrow linewidth, single mode operation with the frequency locked against a reference frequency – preferably an absolute reference in terms of atomic absorption. Such a laser system whose output frequency corresponds, over a period of time, to the desired atomic transition is an essential requirement for atomic physics experiments.

Technology of diode lasers

Lasing mechanism

For lasing action, the two primary requirements are population inversion in the gain medium and optical feedback in the resonator cavity. Diode lasers have evolved from Light Emitting Diodes (LED) which are simple forward biased *p–n* junctions of direct band gap semiconductors, e.g. GaAs. It may be mentioned that the most widely-used silicon photodiode detectors are reverse biased *p–n* junctions of indirect band gap silicon which is not used for making diode lasers due to the dominance of nor-radiative recombination processes. The first requirement, i.e. population inversion is achieved in LED by heavily doping the *p* and *n* type materials and by applying a strong forward bias so that a large density of electrons and holes are injected into the junction region. The injection of carriers produces an electric current through the junction and a traffic jam of electrons and holes at the junction. The recombination of electrons and holes produces light, wavelength of which depends upon the band gap of the semiconductor material (Figure 1 *a*). In contrast to gas lasers where

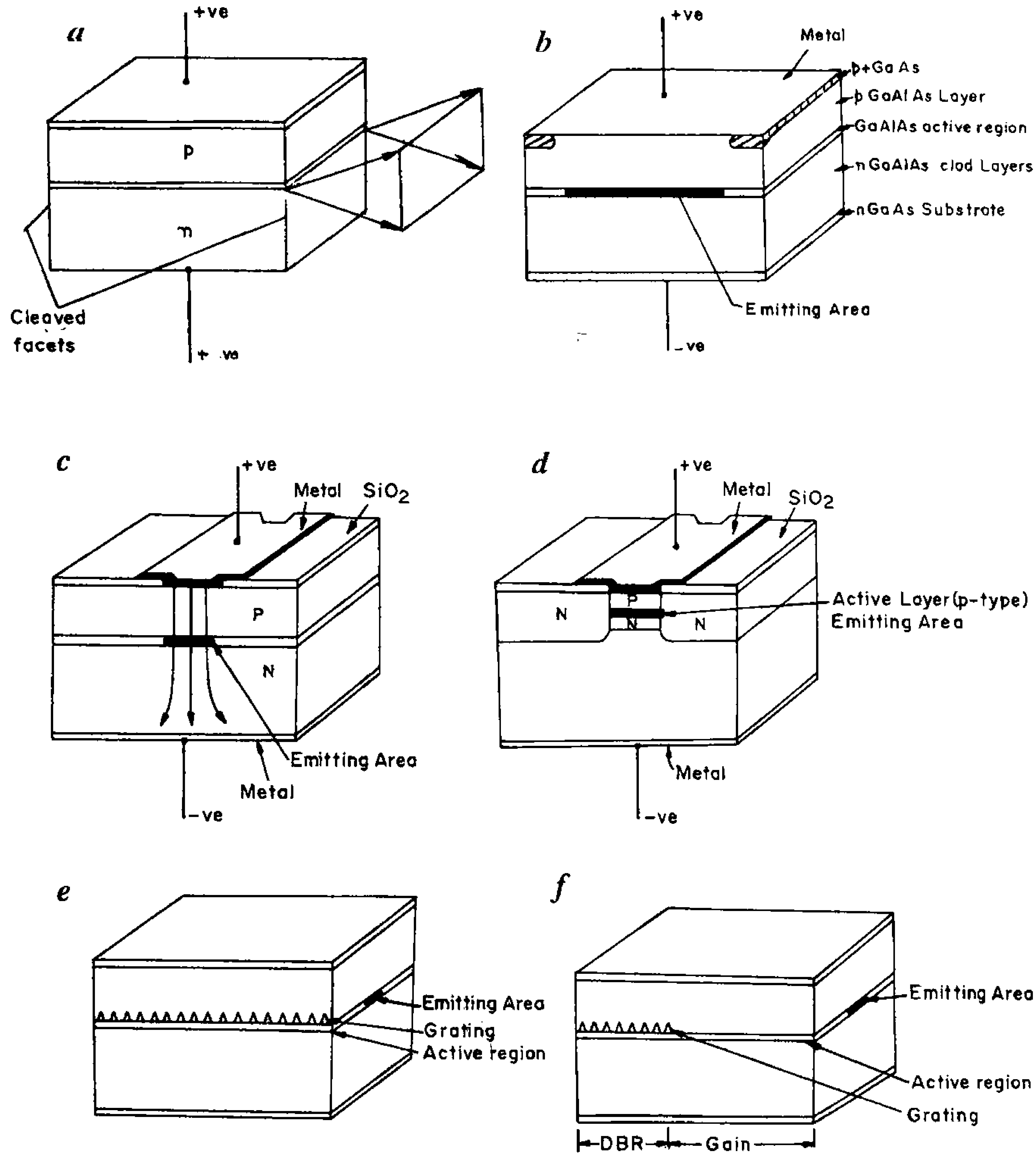

Figure 1. Device structure of diode lasers. ***a***, *p–n* homojunction, the light emission and beam shape are shown; ***b***, double heterostructure, broad area; ***c***, gain guided, arrows indicate the narrow region of current flow, wide band gap surrounding layers of *p*- and *n*-type semiconductors are indicated as P and N respectively; ***c***, index guided; ***e***, DFB; ***f***, DBR.

lasing transitions are between discrete atomic energy levels, in semiconductor lasers the lasing transition is between the continuous energy bands, i.e. valence and conduction bands of the semiconductor.

Once the light is generated, optical feedback is achieved in a Fabry–Perot resonator cavity formed by two cleaved end faces, which are mirrors. The laser cavity sustains such oscillations which have an integral number of wavelengths contained in a round trip so as to form standing wavefield, which are called modes. When light amplification is more than the losses in the cavity, the mode receiving the highest gain from the active medium will start to oscillate (lase). At a low bias level, diode laser emits weak, incoherent and spatially broad light (mostly spontaneous emission) similar to LED. Lasing action begins at a characteristic level of injection current called threshold current and above threshold, light output increases rapidly with current. Threshold current is determined from the measurement of optical power output with drive current (Figure 2). The ratio of light output to electrical power consumed defined as the device efficiency[3] of diode lasers, is about 10% which is comparable to that of a CO_2 laser. The differential quantum efficiency which is increase in photon number per unit increase in injection current is as high as 40–60% for diode lasers, and can be estimated from the slope of the output power vs current curve.

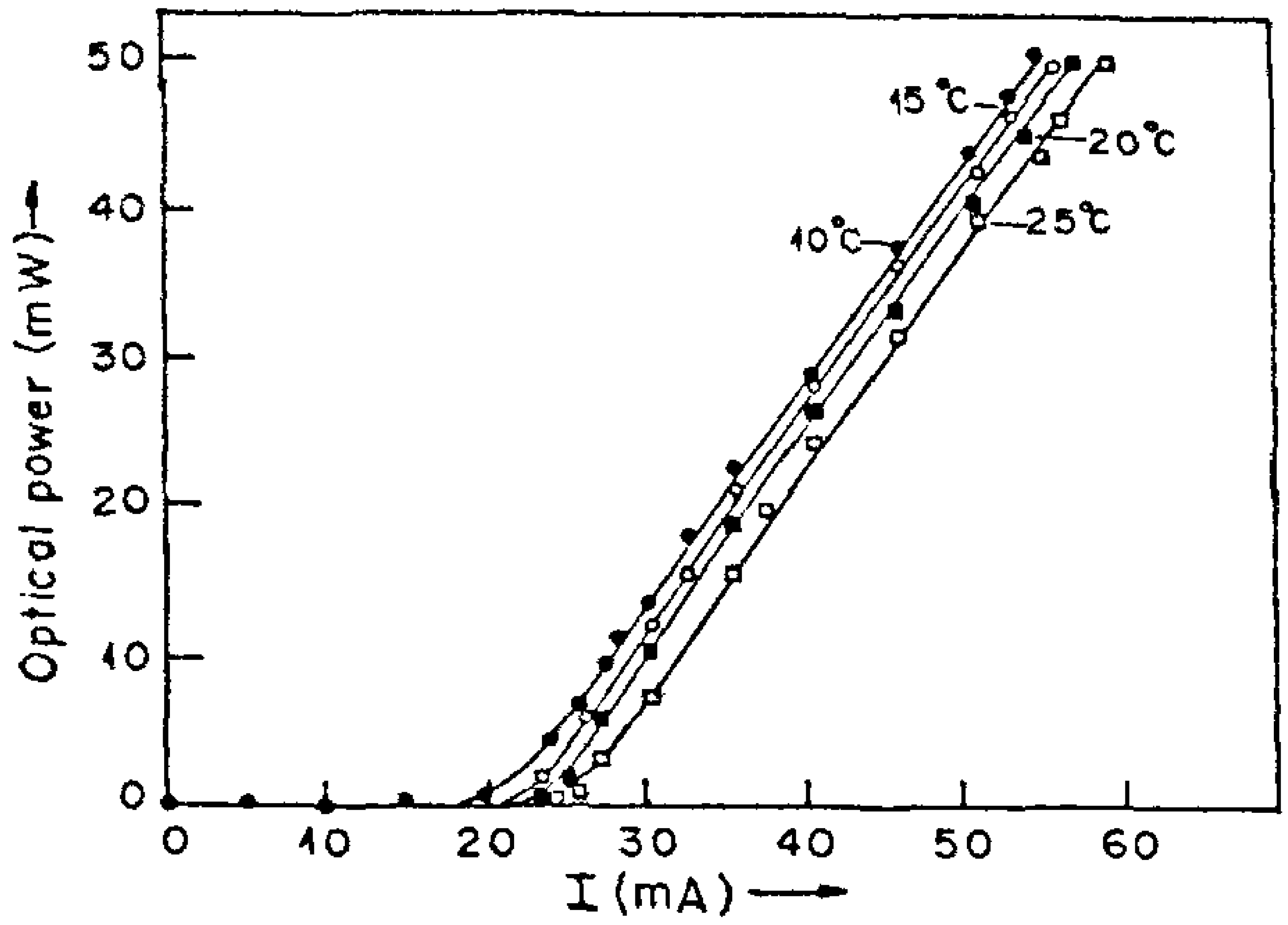

Figure 2. Diode laser output power vs. drive current for GaAlAs (846 nm) diode laser. The sudden increase of laser power indicates the threshold current. It may be noticed that threshold current increases with increase in diode temperature.

Evolution of diode laser technology

Simple homojunction diode lasers are quite inefficient in terms of carrier confinement, power consumption, etc. Tremendous improvements in the performance have been achieved in double heterostructure laser diodes in which thin (~0.2 μ) *p*-type active layer is surrounded by thick *p*- and *n*-type layers (clad layers) of slightly larger bandgap than the active layer (Figure 1 *b*). Under forward bias, electrons and holes injected into the active layer remain confined because of the energy barrier between the active and clad layers. This efficient carrier confinement in the small volume of the active layer gives rise to a lower threshold current, cw operation, higher efficiency and higher output power. The emission of such diode lasers is broadband relative to atomic transition. Further improvement was dictated by the need to confine the electrons in a narrow two-dimensional area for lowest transverse mode oscillation. Such stripe geometry diode lasers are of two types – gain guided and index guided. In gain-guided lasers, the current flows through a limited gain region of the active layer, which acts like a narrow waveguide for the light (Figure 1 *c*). The transverse mode confinement is not very effective and multilongitudinal mode operation is possible. In index-guided lasers, a true optical waveguide to confine the laser light to a narrow region of the smaller bandgap, higher refractive index active layer is accomplished due to total internal reflection of light by higher bandgap, lower refractive index surrounding layers (Figure 1 *d*). The transverse mode-controlled index-guided lasers usually give a single longitudinal mode operation. The laser diode cavity structure is further improved by the equipment of longitudinal mode control and single longitudinal mode operation. Such lasers include Distributed Feed Back (DFB) laser and Distributed Bragg Reflector (DBR) laser. In DFB laser (Figure 1 *e*), a diffraction grating structure is fabricated from higher band gap semiconductor alongside the active layer which provides feedback only for a specific wavelength, while all other wavelengths suffer larger cavity losses. In DBR laser (Figure 1 *f*), the grating structure is in the passive layer and index guiding layer is required to optically link it to the cavity gain region. Whereas the linewidth of gain-guided and index-guided lasers range from few hundreds to few MHz, tens of kHz linewidth have been reported from DBR lasers.

Characteristics of diode lasers

Beam characteristics

The diode laser light is generated in a small rectangular active region of typical thickness of 0.1 μ, width 3 μ, and length 300 μ. Broad area laser diodes have near-Gaussian intensity profile in the plane perpendicular to the junction and a more complex pattern in the plane parallel to the junction. Index-guided lasers of low to moderate power have nearly Gaussian beam profile in both the planes. The active region is not only small but asymmetric which leads to large diffraction effects, thus producing a highly diverging beam of asymmetric dimensions. Typical half angle beam divergence is 30° in the direction perpendicular to the junction and 10° in the direction parallel to the junction. Moreover, the light output is also astigmatic. Diode laser output beam is usually collimated with a compound lens of high numerical aperture and short focal length. The collimated beam is elliptical due to difference in divergence in planes parallel and perpendicular to the junction. A circular beam can be obtained by passing the beam through an anamorphic prism pair, which changes the beam dimension in only one direction. Astigmatism may be corrected by using a weak cylindrical positive lens. It may be mentioned that index-guided single mode devices have very little astigmatism and radiate as nearly diffraction limited sources. The coherence length of broad area diode lasers[4] are about 0.5 mm and index-guided lasers about 1 to 10 metres. Due to shorter coherence length than the gas lasers, speckle noise of diode lasers is less. Diode lasers produce linearly polarized light with electric vector parallel to the junction. The polarization ratio (parallel component/perpendicular component) is typically 30:1 for broad area diode lasers and about 100:1 for index guided diode lasers.

Wavelength tunability

The emission frequency/wavelength of a diode laser of Fabry–Perot type depends upon the gain curve maximum in the coarse scale and the longitudinal mode frequency in a fine scale[5]. Typical emission linewidth of broad area diode laser is about 1000 GHz (2 nm), within which 10 longitudinal modes operate. Linewidth of individual longitudinal mode may range from a few MHz to a few GHz depending upon the power in the mode. The gain maximum determined by the bandgap of the semiconductor, temperature and injection current. The frequency position of a longitudinal mode depends upon the optical round trip length of the cavity which is dependent on the geometrical length of the cavity and the refractive index which in turn is controlled by temperature and carrier density, i.e. injection current. The longitudinal mode closest to the gain maximum, at a particular temperature, lases. The temperature coefficient of the gain curve and the longitudinal mode frequency differ by a factor of 3. Due to temperature change the mode closest to gain maximum shifts causing the laser oscillation to jump from one longitudinal mode to another. Mode hopping in diode lasers is very common because the gain difference between adjacent longitudinal modes is very small as the gain curve is quite flat as a function of wavelength. Therefore there are two main parameters for tuning the wavelength of diode lasers – temperature and injection current.

Temperature. It provides a coarse handle for tuning the wavelength of diode lasers since temperature changes the bandgap and the cavity length. Due to mode hopping, as explained above, the temperature tuning curve is a staircase of sloping steps. The slope corresponds to tuning in a particular longitudinal mode within the temperature range, whereas the different steps signify hopping from one longitudinal mode to another. The temperature-tuning coefficient of the index-guided GaAlAs diode laser (Figure 3) is 0.19 nm/°C. Due to temperature increase, the gain maximum and the longitudinal cavity modes shift toward lower frequencies, i.e. higher wavelengths. For atomic physics experiments, it is possible to pull the laser frequency to the desired value by choice of proper operating temperature. However, operating the diode laser at elevated temperature decreases the lifetime approximately by a factor of 5 for a decade increase in temperature[6]. The normal lifetime of a diode laser is about 10^5 h, provided the diode is not killed by any of the catastrophic failures such as electrical transients, etc.

Injection current. It provides a handle for fine tuning of the diode laser wavelength. Variation of injection current changes the *p–n* junction temperature (Joule heating) and the carrier density which in turn changes the refractive index. For time scales longer than 1 μs, temperature effect is predominant. The tuning curve for an index-guided InGaAlP diode laser is shown in Figure 4, which indicates a tuning coefficient of 0.049 nm/mA[7].

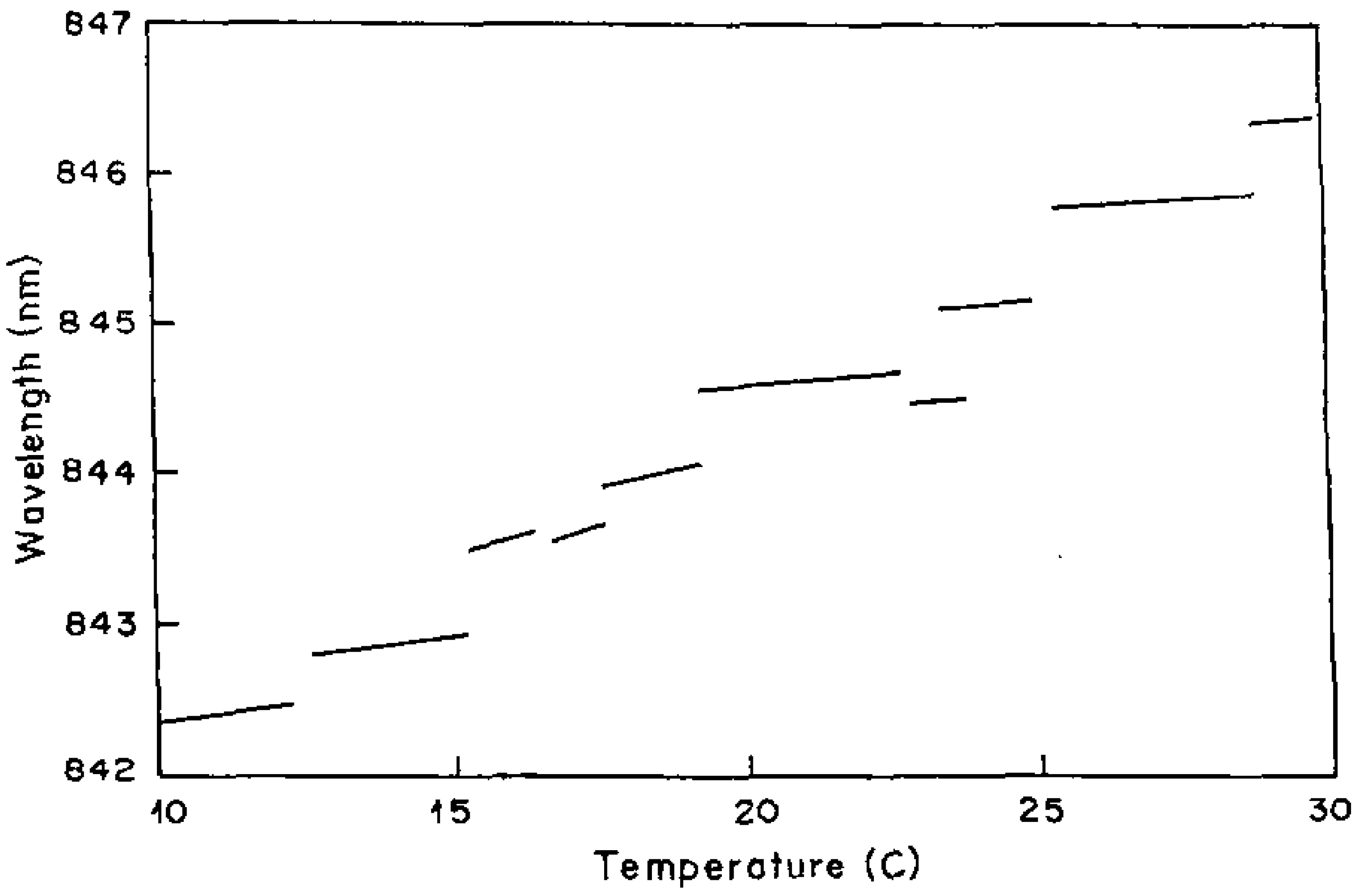

Figure 3. Wavelength tuning curve of GaAlAs index-guided diode laser.

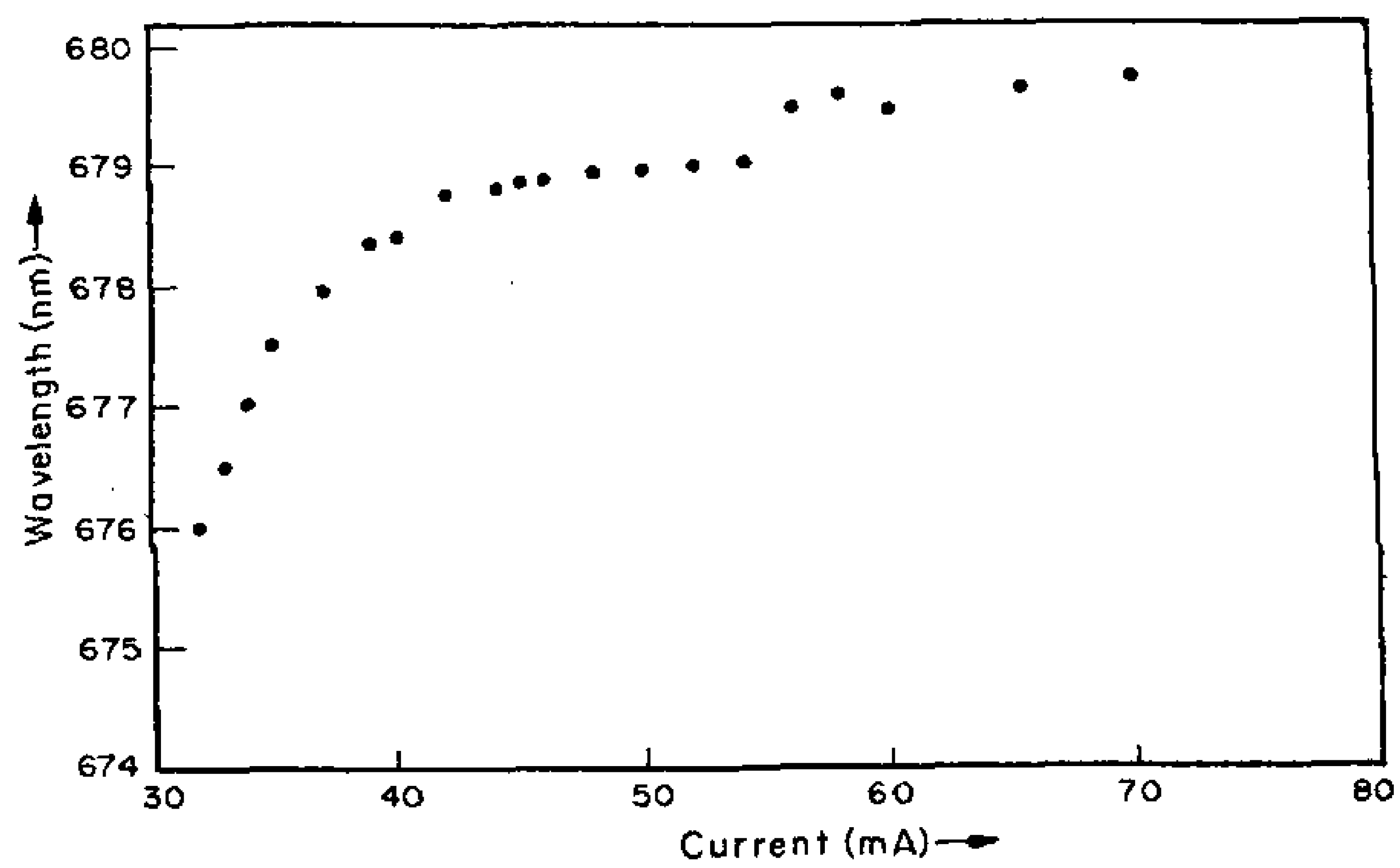

Figure 4. Wavelength tuning with injection current of InGaAlP index-guided diode laser.

Combination of all effects shows that slow increase in injection current redshifts the emission frequency.

The discontinuity in the wavelength tuning curve of diode lasers may pose a little problem for atomic physics experiments. Subsequent sections will discuss how this problem can be overcome by using diode lasers in external cavity configurations and a judicious combination of temperature, injection current and cavity parameters can produce a desired frequency output.

AM–FM noise

Properties of amplitude (intensity) modulated (AM) noise and frequency modulated (FM) noise in diode lasers give the idea about the fluctuations in the output intensity and frequency of the diode laser arising due to intrinsic quantum noise as well as external noise, e.g. fluctuations in the current source, environmental temperature, acoustic vibrations, unwanted optical feedback, etc. If we consider a single longitudinal mode laser driven by a low noise current source and minimize other external causes, then amplitude noise of good quality diode lasers is much less compared to other tunable lasers, e.g. dye lasers.

For frequency stabilization of diode lasers, it is very important to know the FM noise characteristics.. The fundamental noise source for frequency fluctuations of semiconductor lasers is fluctuations arising from spontaneous emission and carrier density[3]. Power spectral density of a diode laser frequency noise is shown in Figure 5. The low frequency peak arises due to current-induced temperature fluctuations, additionally flicker noise – $1/f$ noise can also be present. The flat background noise is caused by spontaneous emission and the high frequency resonance called the relaxation oscillations is caused by carrier density fluctuations. The resonance phenomenon occurs due to a second order time lag system between injected carriers and emitted photons. The relaxation oscillation frequency ranges from 1 GHz to tens of GHz and corresponds to high frequency cut-off. If it is approximated that below the relaxation oscillation frequency, the FM noise can be taken as white noise then the Full Width at Half Maximum (FWHM) of the optical field spectrum, i.e. the linewidth can be taken as a measure of the magnitude of the FM noise. The typical linewidth of commercially available diode lasers is in the range of 1 to 100 MHz and depends on the device and operating conditions. For atomic physics experiments with diode lasers, it is essential that linewidth is reduced by special methods, e.g. by optical feedback and/or negative electrical feedback and the fluctuations in the centre frequency is reduced. The improvements in the stability of the centre frequency depends upon the reduction of FM noise in the Fourier frequency range less than 1 MHz. Fluctuations

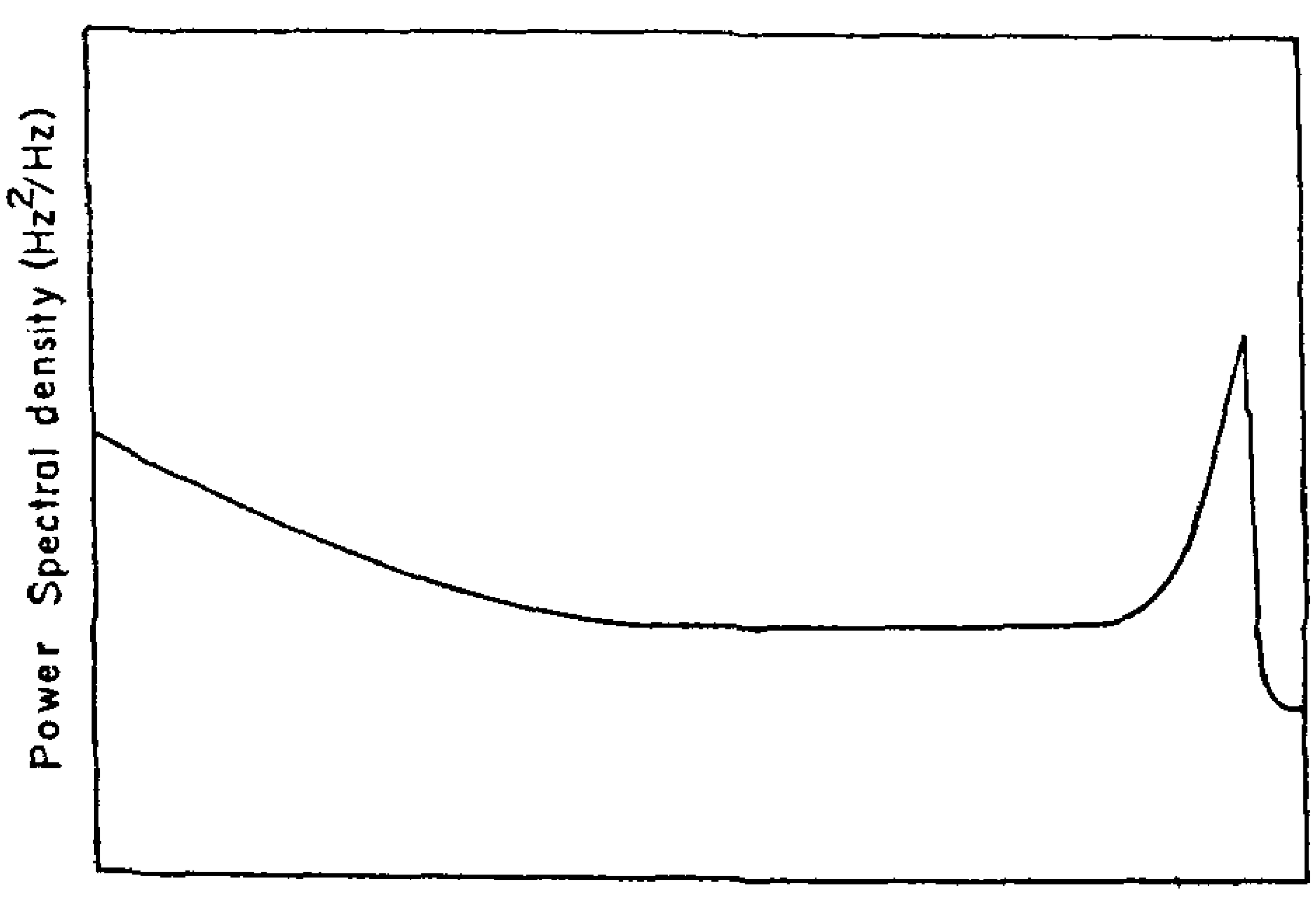

Figure 5. FM noise characteristics of diode laser (schematically adapted from ref. 3).

in diode laser temperature has a major contribution to such FM noise and frequency drift. Temperature control of the diode laser and frequency locking against a stable reference frequency is the best solution to overcome such effects.

Mode structure

The mode structure of a diode laser can be analysed with an optical spectrum analyser employing a scanning Fabry–Perot interferometer with mirrors coated for the suitable wavelength range.

Linewidth

The FWHM of the optical field spectrum gives a measure of the linewidth. The modified Shawlov–Townes formula for linewidth indicates that the diode laser linewidth is inversely proportional to the laser power at low power but the minimum linewidth is limited by linewidth rebroadening[8] effect where linewidth increases at high output power and has non-zero value (linewidth floor) at extrapolated infinite power (Figure 6). Such effects have been attributed to spatial hole burning effect, mode partition noise, $1/f$-type frequency noise induced by carrier mobility fluctuations and other factors.

Linewidth measurement

Linewidth of diode lasers is measured mostly by two methods.

Confocal Fabry–Perot (CFP)

By using a CFP of low Free Spectral Range (FSR) the mode structure is studied on the oscilloscope screen which is calibrated so that two consecutive modes are separated by e.g., 10 divisions which is equal to the FSR of the CFP. Resolution of linewidth measurement by this method is of the order of 1 MHz.

Heterodyne method

In heterodyne method, the test laser beam is mixed with a reference laser beam whose frequency is close to the test laser and the linewidth is estimated from the HWHM of the Lorentzian-shaped intermediate frequency spectrum. Many times, a narrow linewidth reference laser of suitable wavelength is not available and a delayed self-heterodyne method is employed for linewidth measurement. In this method[9], the test laser light is split into two parts. One part is frequency shifted by an acousto-optic modulator and to the other part a

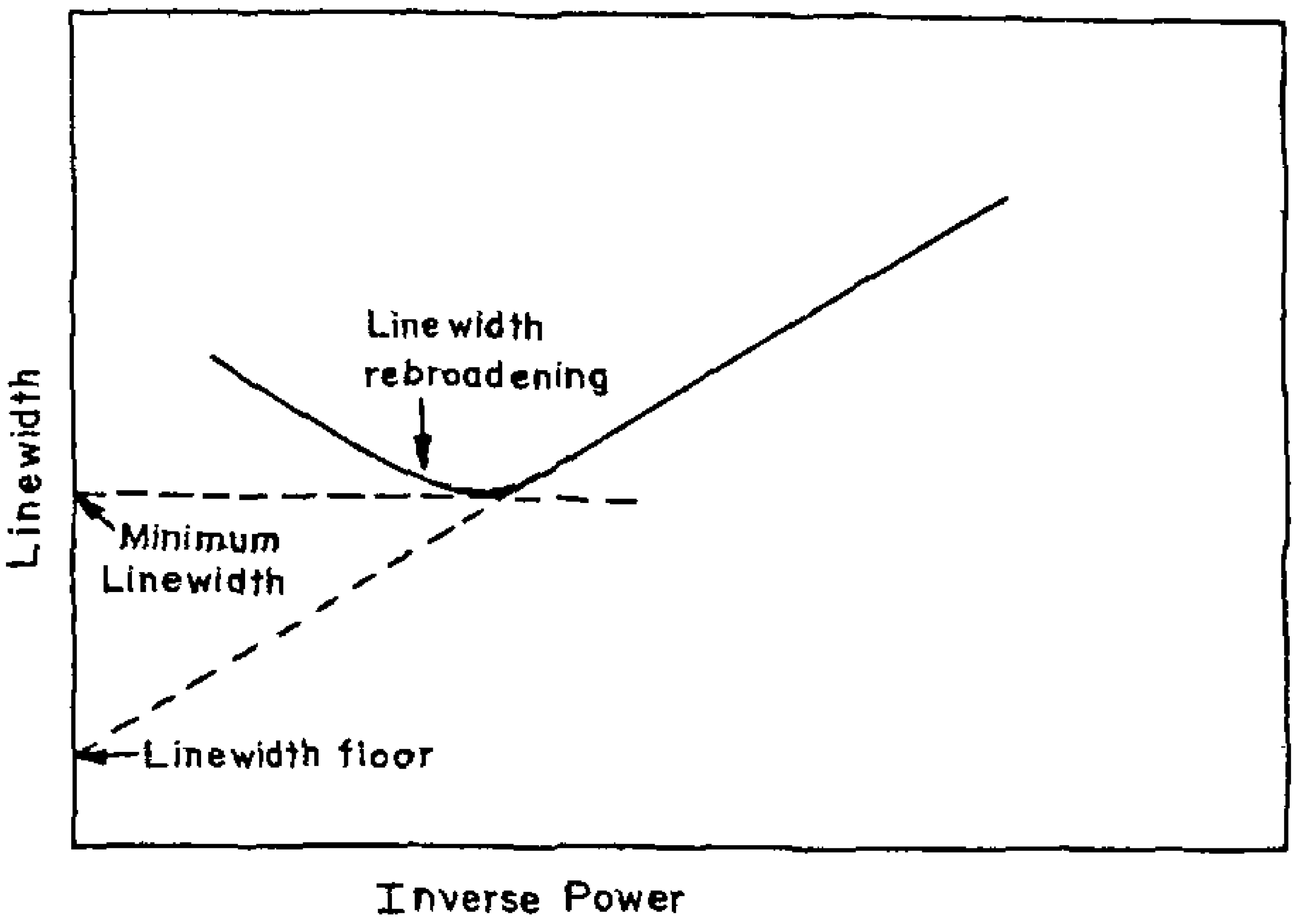

Figure 6. The relationship of spectral linewidth of diode lasers with inverse power. Linewidth floor indicates the residual linewidth at infinite power (schematically adapted from ref. 8).

delay is introduced by sending the light through a long single mode optical fibre. If the delay time is much longer than the coherence time, the two split beams become uncorrelated and the heterodyne signal is measured in RF spectrum analyser. The resolution of the delayed self-heterodyne method depends upon the length of the delay fibre and resolution of the order of 1 kHz may be achieved.

Linewidth narrowing

Optical feedback

One of the most effective methods of spectral narrowing of diode lasers is optical feedback, i.e. coupling a part of the laser's output power back to the diode cavity. In such stable optical feedback, phase of the reflected light is same as the light emitted from the laser cavity. This means that the separation between the diode cavity and the reflector should be an integral multiple of half wavelength. The coating of the diode laser output facet should be such that sufficient reflected power can be fed back to the diode because in case of very low optical feedback, the competition between the external cavity (formed by the diode laser and the reflector) and the diode cavity modes may give rise to optical chaos and coherence collapse. It is therefore desirable that the diode laser output facet be antireflection coated.

The FM noise of a diode laser depends upon three factors: photon lifetime (inverse relationship), fluctuations in spontaneous emission and external noise[3]. Optical feedback reduces the linewidth because feedback increases the photon lifetime of the external cavity which in turn reduces the cavity loss. Increasing the photon lifetime in the cavity decreases fluctuations due to randomly generated photons due to spontaneous emission. Moreover, the quality factor Q (centre frequency/half linewidth) of diode lasers is low due to short cavity length, etc. Optical feedback in the external cavity configuration increases the quality factor and decreases the linewidth[3,5,6].

It may be mentioned that diode lasers are extremely sensitive to optical feedback[10]. Optical feedback has been used extensively in diode lasers to improve the coherence properties and controlling the emission wavelength. However, unwanted and random optical feedback can introduce instabilities and chaotic behaviour in the diode laser output leading to coherence collapse. The signature of such effect is huge broadening of the laser linewidth and increase in optical power. A representative example is shown in Figure 7, which was observed with a InGaAlP index guided laser. The best way to avoid such random feedback is to use an optical isolator in the path of the diode laser output beam. Faraday rotator type optical isolator with 60 dB extinction is much costlier than the diode laser itself. An inexpensive alternative could be using a combination of $\lambda/4$ plate and polarizer which works only for reflected light of same polarization as the incident light, with a compromise on the extinction (~15 dB).

Negative electrical feedback

In this method, the FM noise of diode laser is reduced by detecting its magnitude and then negatively feeding back the detected signal to the operating parameter of the laser to countermodulate the laser frequency. Since the thermal response through temperature variations is slower than the response by injection current, the parameter chosen is usually the injection current for a wide bandwidth negative electrical feedback loop. Few groups have achieved linewidth narrowing and frequency stabilization by this method. However, the FM noise spectrum of diode laser extends to very high frequencies which makes it difficult to design a servosystem acting fast enough to correct diode laser frequency fluctuations. Sufficient expertise in electronics is essential for development of such feedback system. Moreover, the tuning range of diode lasers is not further extended by negative electrical feedback unlike optical feedback methods.

Frequency stabilization

External cavity

An external cavity can be formed between the diode laser rear facet and an external reflector which may be a frequency selective element, e.g. grating, to achieve

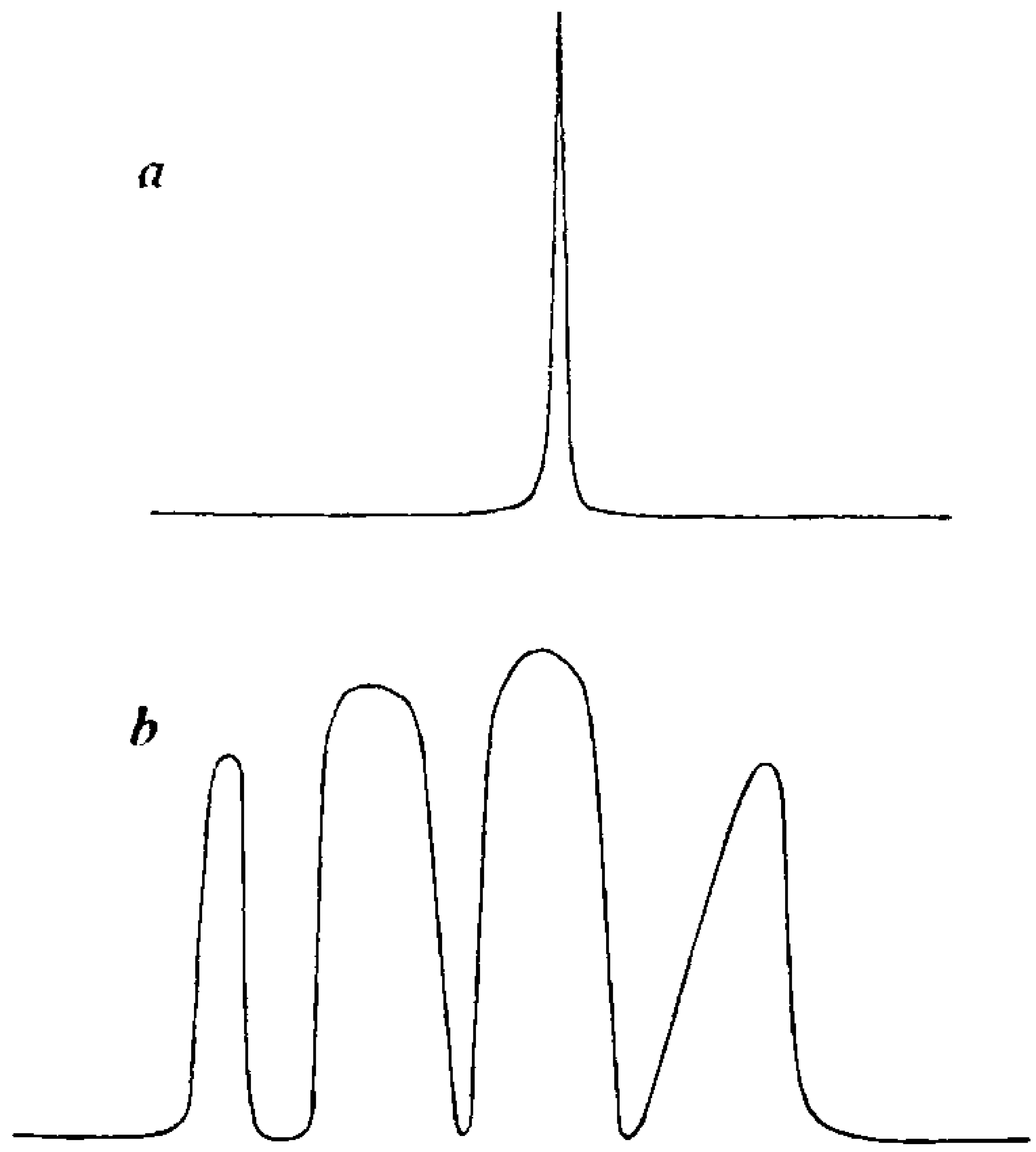

Figure 7. Optical instability, chaos and coherence collapse observed in index guided diode lasers with random feedback. *a*, normal single mode operation; *b*, instability when reflected light from the scanning CFP, as shown in Figure 8, goes back to the diode cavity. Single mode structure is destroyed accompanied by increase in power.

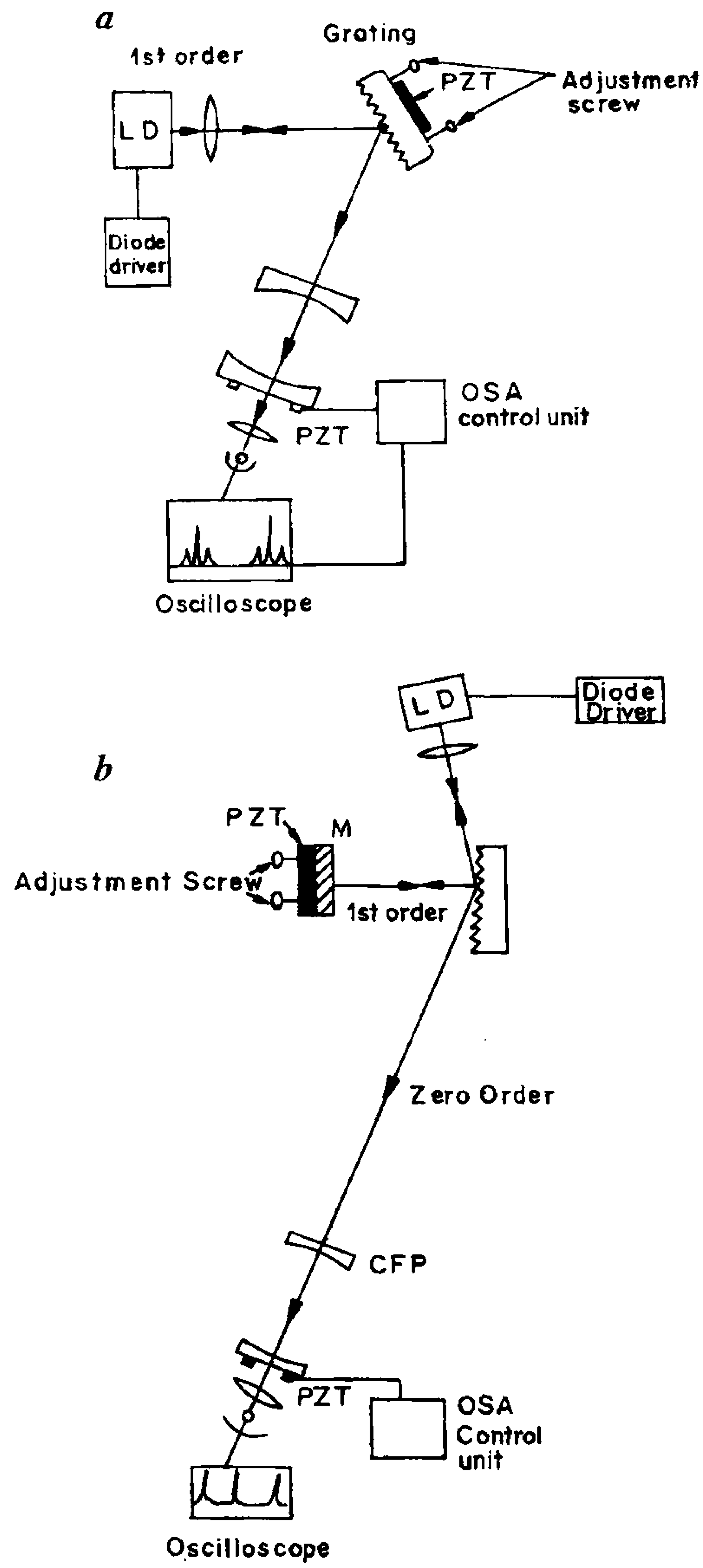

Figure 8. External cavity configuration for linewidth narrowing by optical feedback method. *a*, Littrow cavity; *b*, Littman cavity. The experimental arrangement for observing mode structure with optical spectrum analyser is also shown.

linewidth narrowing by optical feedback. The external cavity has the added advantage that by changing the position of the frequency selective element of the cavity, the wavelength can be tuned. Two external cavity configurations have been tried successfully for narrowing linewidth of diode lasers.

Littrow cavity

The experimental arrangement of this cavity configuration and observation of mode structure are shown in Figure 8 *a*. The cavity is formed between the rear facet of the diode laser and the reflection type grating in such a way that the zero order beam goes out as output beam and 1st order diffracted beam is coupled back to the diode. In the Littrow configuration the angle of incidence and the angle of diffraction are the same. The Littrow angle for a grating of 1200 lines/mm and for 852 nm diode laser is 30.75°, i.e. the grating surface is to be positioned at 59.25° to the laser beam, whereas for a 670 nm diode laser, the Littrow angle is 23.71° and the grating surface has to make an angle of 66.29° to the laser beam. It is better to use a blazed grating to get maximum efficiency in the first order. The tuning of the cavity can be achieved by changing the position of the grating by the adjustment of screws on a coarse scale and by PZT displacement on a fine scale. The mode structure of an index-guided diode laser in the free running and in Littrow configuration is shown in Figure 9. For certain cavity lengths, more than one mode can be observed. It may be mentioned that external cavity modes are closely spaced compared to the diode laser cavity modes since mode separation is equal to $C/2L$, where C is the velocity of light and L is the cavity length.

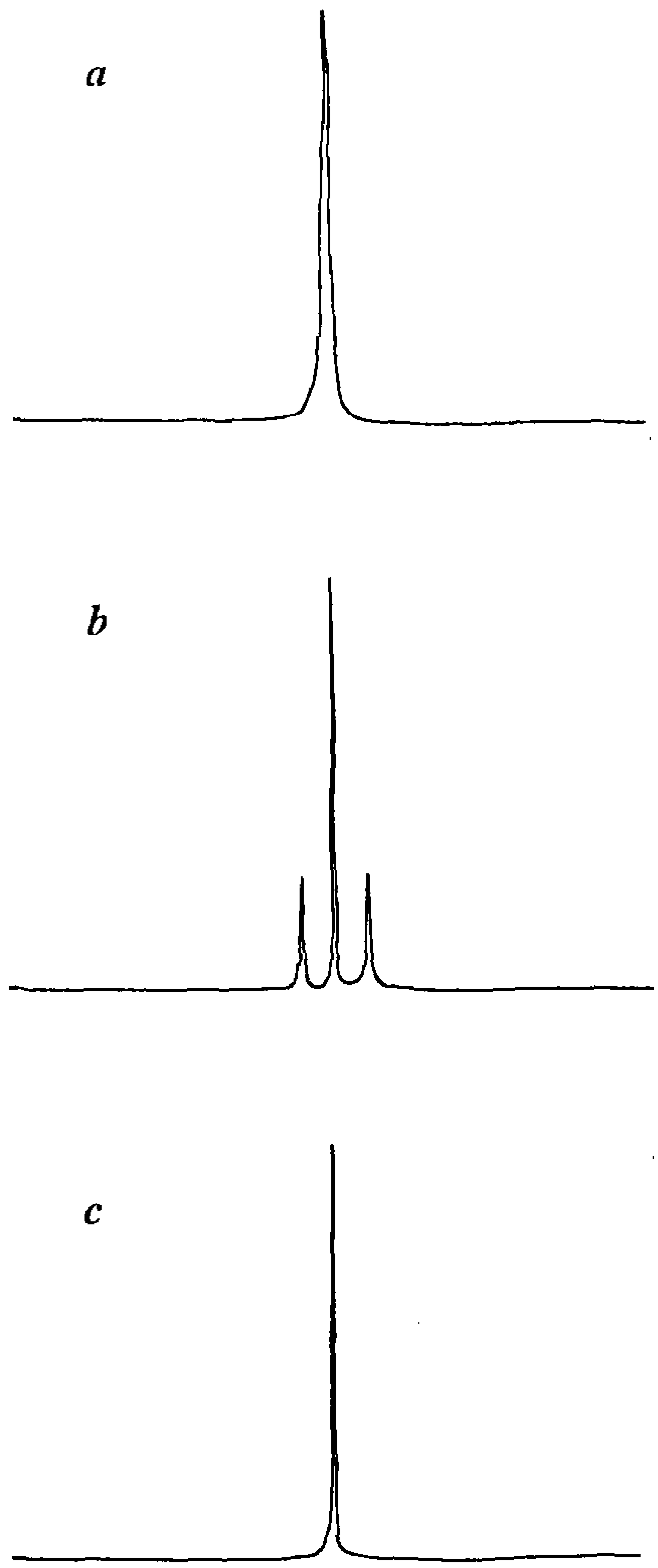

Figure 9. Mode structure of index-guided diode laser. ***a***, free running, linewidth (FWHM) ~ 30 MHz; ***b***, Littrow cavity; ***c***, Littman cavity. Linewidth narrowing has been observed but exact value could not be estimated due to limited resolution of the CFP used.

Littman cavity

In the Littman configuration, the diode laser beam falls at a grazing incidence on the grating. The zero order beam goes as the output beam and the 1st order beam is reflected by a tuning mirror back to the diode (Figure 8*b*). The external cavity is formed between the rear facet of the diode and the mirror. The narrow single mode operation in the Littman configuration is shown in Figure 9*c*. In Littman configuration, since the wavelength tuning is done by rotating the mirror and not the grating, the output beam position remains unchanged unlike the Littrow cavity where there is horizontal deflection of the output beam with wavelength scanning (~0.08 degree/nm)[11].

Temperature control

The external cavity diode lasers using optical feedback have fundamental linewidth of a few hundreds of kHz or less depending upon the device. But actual linewidth is influenced by temperature fluctuations. Thermal changes affect the diode laser emission wavelength as well as introduce instabilities in the external cavity length. The temperature control has to be done in two stages. First, the diode laser temperature is controlled by a thermoelectric cooler (TEC). In the second stage, the temperature of the base plate containing the diode laser and the external cavity elements, e.g. grating, mirror, etc. should be controlled with TEC or heater and employing a servoloop. It is advisable to keep the diode laser temperature 1–2°C above the base plate temperature so that condensation does not take place on the diode laser. For long term reliable operation of the diode laser, precise control of temperature is essential.

Vibration isolation

Mechanical and acoustical vibrations disturb the positions of the optical elements, causing fluctuations in the laser output. Diode laser itself is a very good vibration indicator; any vibration shows up as a sudden jerk of the mode seen in the oscilloscope screen. The external cavity should be covered to avoid air draughts. The experimental setup should be on a vibration isolation table and preferably in a room away from sources of frequent vibration, e.g. lifts, etc. The base plate in turn should be isolated from the working table with the help of rubber pads, etc. Vibrations in very low frequency range (1–100 Hz) should be taken care of by the electronic servosystem.

Saturated absorption spectroscopy

Narrow reference frequencies for frequency stabilization can be obtained by Doppler free saturated absorption spectroscopy of alkali vapour, e.g. cesium. The experimental arrangement is included in the block diagram of Figure 10. Two counter-propagating overlapping beams derived from the same laser pass through a vapour cell containing alkali atoms at a low pressure (~ mTorr). If the laser frequency is different from the atomic transition frequency, then due to Doppler effect, one beam interacts with a group of atoms with velocity v and the other beam interacts with another group of atoms with velocity $-v$. When the laser frequency is tuned to the

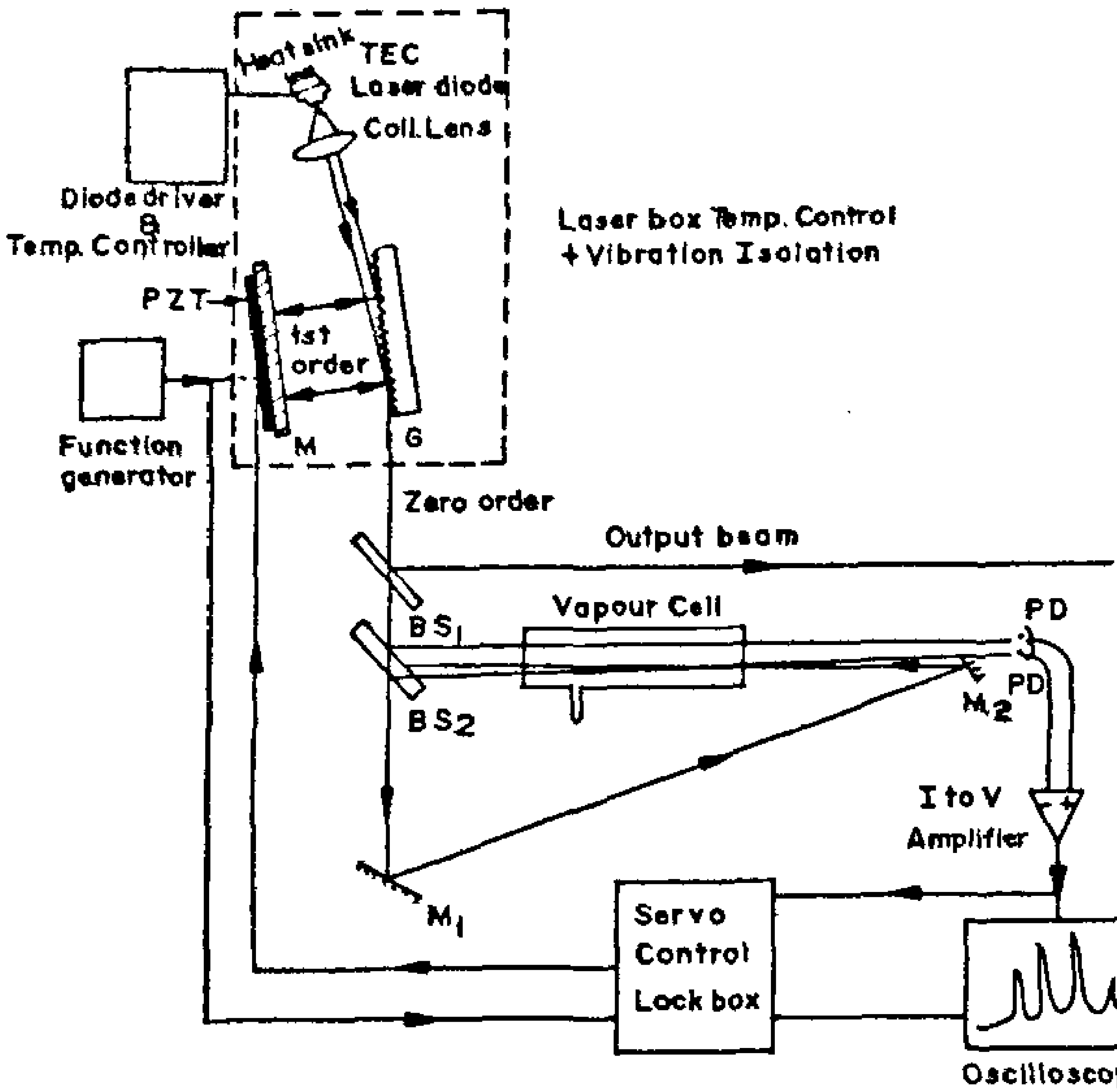

Figure 10. Schematic of the experimental setup for frequency stabilization against saturated absorption. Alkali vapour is contained in the vapour cell. The two probe beams for saturated absorption are derived from two surfaces of the beam splitter BS_2. The stronger pump beam is reflected by the mirrors M_1 and M_2.

atomic transition frequency, both the beams interact with only one group of atoms with velocity $v = 0$ along the laser beam. In this case, if one of the laser beams (pump beam) is strong enough to saturate the transition, then over a narrow range of frequencies the absorption decreases and a narrow dip can be observed in the Doppler broadened absorption line. To eliminate the Doppler profile, a third probe beam is passed through the vapour cell and is detected by a photodiode and the two signals detected by the pair of photodiodes are subtracted to obtain only saturated absorption dips on a nearly flat background. These dips arise from the transitions between different hyperfine levels of the alkali atoms. Bandwidth of the saturated absorption dips is the atomic linewidth due to homogeneous broadening. Since the vapour pressure in the cell is low, narrow linewidth can be obtained. For example[11] in Cs (natural linewidth 5.2 MHz), saturated absorption linewidth of 20 MHz has been obtained which is much narrower than the room temperature Doppler linewidth of approximately 500 MHz. Resolution of the features can be better than 20 kHz.

Stabilization against saturated absorption

The schematic diagram of the experimental arrangement for locking the diode laser frequency against saturated absorption of alkali vapour is shown in Figure 10. To the PZT attached to the mirror of the Littman cavity, a ramp is applied for scanning the frequency of the diode laser by modulation of the external cavity length. The maximum output power is taken away with the help of a beam splitter for experiments, e.g. laser cooling of alkali atom. A part of the laser beam is utilized for the saturated absorption spectroscopy. The difference signal between probe beam and the reference beam is displayed in the oscilloscope screen as the saturated absorption peaks. The frequency of the diode laser can be locked to the saturated absorption component with the help of electronic servo control[11], where any deviation from the locked frequency is taken as the error signal which is applied to the external cavity component (e.g. PZT attached to the mirror) for controlling the cavity length so as to pull the laser frequency to locked position. Frequency stability of the order of 1 MHz (1 part in 10^8) can be achieved by this method. Further improvements are possible by a combination of two parallel servoloops. The bandwidth of PZT is usually a few kHz. For higher bandwidth requirement, the error signal after filtering and amplification, can be fed back to laser current through the second servoloop.

Another way of locking the laser frequency is through lock-in amplifier. In this technique, the PZT is modulated sinusoidally at a reference frequency (~ 1 kHz) and the resulting modulated saturated absorption signal is phase sensitively detected at the reference frequency and the laser frequency is locked at the peak. Any deviation from the locked position again generates an error signal which after smoothening and amplification is applied to PZT.

Applications of frequency stabilized diode lasers

In various research laboratories world-wide, frequency stabilized diode lasers have become an essential tool for a variety of experiments in atomic physics such as laser cooling and trapping of atoms, atomic fountain of laser cooled atoms, Bose–Einstein condensation, high resolution spectroscopy, optical pumping of cesium and rubidium atomic clocks and others. Particularly in laser cooling and related experiments, use of frequency stabilized diode lasers has made the experimental setup compact and cost effective. It may be mentioned that for laser cooling of a particular atom, offset locking of the frequency against saturated absorption dip of that particular transition has to be done. The most effective laser cooling[12] has been achieved with the laser frequency redshifted with respect to the atomic transition frequency. In addition to the above applications, frequency stabilized diode lasers can be very effectively used in optical interferometry, metrology, optical fibre communication, etc.

Conclusions

With a proper choice of diode laser device and a judicious combination of operating parameters, it is possible to obtain a desired wavelength output. Narrow linewidth, single mode operation can be achieved by optical feedback in an external cavity configuration. With output frequency stabilized against atomic transition frequency through saturated absorption, diode laser can be a very effective laser source for many high precision atomic physics experiments.

1. Higgins, T. V., *Laser Focus World*, April 1995, 65–76.
2. Nakamura, S., *Photonics Spectra*, May 1998, 130–135.
3. Ohtsu, M., in *Highly Coherent Semiconductor Lasers*, Artech House, Boston, 1992.
4. *SDL Laser Diode Operator's Manual and Technical Notes*, SDL Inc., 1994.
5. Telle, H., *Spectrochem. Acta Rev.*, 1993, **15**, 301–327.
6. Wiemann, C. E. and Hollberg, L., *Rev. Sci. Instrum.*, 1991, **62**, 1–20.
7. Chawla, S., Kanjilal, A. K., Roy, B. K. and Narain, R., *J. Instrum. Soc. India*, 1998.
8. Okai, M., in *Frequency Control of Semiconductor Lasers* (ed. Ohtsu, M.), John Wiley and Sons, New York, 1996, p. 9.
9. Okoshi, T., Kikuchi, K., and Nakayama, A., *Electronics Lett.*, 1980, **16**, 630–631.
10. Mork, J., Tromborg, B., Mark, J. and Velichansky, V., *SPIE*, 1992, **1837**, 90–104.
11. MacAdam, K. B., Steinbach, A. and Wieman, C., *Am. J. Phys.*, 1992, **60**, 1098–1111.
12. Wieman, C., Flowers, G. and Gilbert, S., *Am. J. Phys.*, 1995, **63**, 317.