UNLOCKING DYNAMICAL DIVERSITY

OPTICAL FEEDBACK EFFECTS ON SEMICONDUCTOR LASERS

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We would like to dedicate this book to our families. DMK to her husband Robert Carman and children, Sarah and Geoffrey; KAS to his wife Lis Shore and children, Angharad and Rhodri.

Contents

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Preface

Semiconductor lasers represent 99.8% of the world market for lasers, in terms of the number of units sold in a year (∼600 million units 2003/2004).[1] In monetary terms they represent 63% of the world market (∼US$3.4 billion) reflecting their low unit cost compared to other lasers and laser systems commercially available. The high volume arises due to their use in optical storage systems; telecommunications; solid state laser pumping; medical therapeutics; and inspection, measurement and control. These are the five biggest application areas.[2] Examples of high volume devices include the single wavelength distributed feedback (DFB) semiconductor lasers, with narrow linewidth, which are the standard sources used in the optical communications networks that now span and criss-cross the globe. The tens to hundreds of nanometre wavelength-gain-bandwidth of semiconductor lasers, combined with frequency filtered, strong optical feedback, lead to the tunable laser systems that are used in telecommunications, medical therapeutics, environmental sensing, and basic science investigations. The diversity of device structures and the diverse characteristics of the output of semiconductor lasers represent impressive achievements from the study of the basic science of semiconductor lasers carried out in parallel with developments in materials, fabrication and packaging technologies. This book illustrates this diversity in the context of telling the scientific story of the semiconductor laser with optical feedback. The book has been planned to provide the reader with a logically developed and reasonably complete coverage of the topic to date.

The applications of these semiconductor lasers with optical feedback systems are driving rapid developments in both theoretical and experimental research. This book represents a timely synthesis of the background laser physics and dynamics in a broad context. The reader can expect a future book on this subject to be needed in the not too distant future, to explore further this rapidly developing area.

Notes

1 *Laser Focus World* (2004) **40**, Jan., p. 75.
2 *Laser Focus World* (2004) **41**, Feb., p. 71.

Acknowledgements

The editors (DMK & KAS) extend their appreciation to all the other contributors to this book. The book was formulated to develop the topic of semiconductor lasers subject to optical feedback in a manner which embraces theory, experiment, new developments and applications. As such, the contributors were invited to write a chapter to a preliminary brief which fitted into the overall plan for the book. The contributors, as leaders of research in the various areas covered, bring to the chapters their specialist knowledge and ability to give an overview of the various sub-fields in a manner that we, the editors, could not have done as well or as expertly, and certainly not to the deadline that was required. We are also grateful to the contributors for engaging in the discussion of their chapters, as they have been evolving, which we believe has resulted in valuable cross-fertilization on the basis of how theory will be read by experimentally oriented readers and vice versa. The contributors include Dr Peter Davis, Professor Silvano Donati, Dr Tom Gavrielides, Dr Guido Giuliani, Dr Esa Jaatinen, Professor Bernd Krauskopf, Professor Daan Lenstra, Dr Cristina Masoller, Professor Junji Ohtsubo, Dr Iestyn Pierce, Dr Paul Pees, Dr Siva Sivaprakasam, Dr Paul Spencer, Professor David Sukow, Professor Gautam Vemuri and Dr Mirvais Yousefi. As these contributors are resident in Australia, India, Italy, Japan, the Netherlands, the United Kingdom, the United States of America, and Uruguay, the book is very much an international collaboration by all involved and has been an enriching experience for the editors.

We would also like to extend our warm thanks to all those at John Wiley & Sons, Ltd who have been involved with the publication of the book, at its various stages: Sophie Evans, Daniel Gill, Kathryn Sharples, Laura Kempster, and Sarah Hinton, and also to Susan Dunsmore, the copy editor, Sowmya Balaraman from Integra and all others who we have not known by name.

1

Introduction

Deborah M. Kane and K. Alan Shore

The laser as a directed, high brightness, coherent source of light was a dream come true at its first demonstration in 1960. A jump of several orders of magnitude improvement towards the ideal of a single frequency, 'zero' linewidth, spatially coherent, plane wave source of light had been made. A major new research field in physics and engineering – the development of different types of lasers, aiming to cover that part of the electromagnetic radiation spectrum that can be called 'light', grew rapidly. The 'solution without a problem', as the laser was unsupportively described, soon became the light source of choice in so many applications, that as we write, the research field of laser applications is a far larger one than lasers. Indeed, much of laser development has been motivated by the significant markets for their end use.

As laser physics and engineering grew, so did the knowledge that real lasers have outputs that are dynamically and spectrally diverse. The dynamics refer to output power variations in time and the spectrum means the time-averaged, optical-frequency-spectrum. The single-frequency, frequency-stabilised dye laser or titanium sapphire laser, generating output with a sub-MHz linewidth [1] is quite different from a Kerr-lens-mode-locked titanium sapphire laser propagated through an optical fibre, generating femtosecond pulses with an optical frequency spectrum made up of a comb of mode-locked modes covering hundreds of nanometres, spaced by the pulse repetition frequency [2]. Almost any laser can be made to generate an output that is unstable in time by optical feedback of part of the output light back into the laser cavity. In some cases the resulting output can be shown to follow a well-defined route to deterministically chaotic output. Thus, the diversity of dynamic and spectral outputs available from lasers is high. Semiconductor lasers, as a subset of all lasers, represent a category in which a very broad range of the possible dynamic and spectral outputs obtainable from lasers can be achieved – from the chaotic to the narrow-linewidth, single-frequency, for example.

The semiconductor laser has a history essentially as long as that of the laser itself, being first demonstrated in 1962. However, to a large extent, the development of the semiconductor laser has been quite separate from laser development more generally. This is primarily due to the knowledge, skills and infrastructure in semiconductor device fabrication being more

Unlocking Dynamical Diversity Edited by Deborah M. Kane and K. Alan Shore

closely aligned to semiconductor physics and electronics than to the atomic and solid state physics, and optics that underpin most other laser systems. A large part of the semiconductor laser research community knows little about other types of lasers and laser systems and vice versa. However, the areas of overlap are growing. Incoherent diode laser arrays have become the pump source of choice for solid state lasers [3] and tunable diode laser systems based on the same design principles as other tunable, single frequency lasers have become common in spectroscopic, interferometric, sensing and telecommunications applications. Also, the range of wavelengths achievable with semiconductor lasers continues to grow with efficient and reliable blue and violet gallium nitride lasers now being commercially available [4] and 4–12 micron quantum cascade lasers have been used for high resolution spectroscopy. The future for semiconductor lasers and their application is bright, and it is strengthened by the diversity of possible modes of operation of the devices and systems, in addition to the broad range of device structures and material systems.

The diversity of possible dynamic and spectral outputs from a semiconductor laser is well illustrated by the semiconductor laser subject to optical feedback. The feedback of part of the output light can be achieved using a mirror, a phase conjugate reflector or a diffraction grating. The latter will also frequency filter the optical feedback field. The coupled rate equations, or delay differential equations (DDEs), which describe these systems are among the classic examples of nonlinear science. Within the practically achievable parameter space (varying the strength of the optical feedback field, for example), sequences of bifurcations and transitions to chaos are seen. The nonlinear characteristics of these semiconductor laser systems are of interest both in their own right and in contrast to other biological, mechanical, hydrodynamical and electronic nonlinear systems. They also contrast with the nonlinear dynamics of other laser systems because of the high frequencies and small timescales (picoseconds) involved. The potential applicability, of chaotic semiconductor lasers, when synchronised in pairs and cascades of similar systems and devices, in secure optical communications has given a strong applications-based motivation for fully exploring the nature of chaotic outputs from semiconductor lasers with optical feedback. Optoelectronic feedback and optical injection (injection of light from a separate source) are also of interest.

In the chapters which follow, the semiconductor laser, including all the device structures in a highly developed stage, are introduced and discussed in the context of their behaviour when subject to optical feedback. The key theory and theoretical results are presented so that the nonlinear science of these systems can be fully understood and appreciated. The full range of dynamic and spectral outputs from the systems that have been demonstrated experimentally are covered, as are the key applications in commercial systems, and systems with commercial potential. The subject of the book, semiconductor lasers with optical feedback, has been synthesized for audiences in laser physics, semiconductor lasers, and nonlinear science. As such, the commonality and complementarity of the usual language and perspectives of these three sub-disciplines have been presented for the reader.

1.1 SEMICONDUCTOR LASER BASICS

1.1.1 Semiconductor Laser Materials and Output Wavelengths

Semiconductor lasers or laser diodes are the most widely used laser ever devised. They are normally pumped directly with an injection current. They are small, easily used devices which can be produced at low cost. Laser diodes are used in such everyday items as CD players and laser printers and are finding a host of new applications ranging from medical imaging to environmental sensing. The semiconductor laser is also the source which drives optical fibre communications. Indeed, it was this latter application which provided the motivation for progressing the development of semiconductor lasers. This started with simple structure prototype devices, made of relatively poor quality material, first operated pulsed, at liquid nitrogen temperatures [7–10]. It has progressed to the present sophisticated, versatile devices, made from high quality semiconductors, which are capable of reliable, long-lived, continuous wave (cw) operation in a range of environments.

A specific aspect of the progress made in semiconductor lasers is the wide wavelength range covered by the sources using different semiconductor materials. Laser diode sources from the ultra-violet through to the mid and far infrared are available. The III–V semiconductor materials used for the devices are summarized in Table 1.1, along with some of their key physical properties. The materials are grouped as nitrides, arsenides, phosphides and antimonides which sequentially lead to longer wavelength devices when combined as ternaries (see Figure 1.1). Quaternaries combining the arsenides and phosphides are used

Table 1.1 Key III–V Semiconductor materials used in semiconductor lasers which operate at room temperature and their key physical properties

III–V Compounds	Lattice Constant (Angstroms)	Electron (Conduction band) Effective Mass^{+}	Heavy Hole (Valence band) Effective Mass^{+}	Relative Dielectric Constant	Refractive Index (Near E_G)	Band Gap (E_G) at ~300 K(eV)
AlN	3.112$^{\#}$ 4.982	0.40	3.53	8.5	2.15	6.28
GaN	3.190 5.185	0.20	0.80	8.9	2.5	3.425
InN	3.545 5.703	0.11	1.63	15.3	2.9	1.20–1.9$^{\$}$
AlAs*	5.6611	0.146	0.76	10.1	3.2	2.168
GaAs	5.6533	0.067	0.45	13.1	3.4	1.42
InAs	6.0584	0.022	0.40	15.1	3.5	0.354
AlP*	5.4635	0.83	0.70	9.8	3.0	2.45
GaP*	5.4512	0.82	0.60	11.1	3.37	2.26
InP	5.8686	0.08	0.56	12.4	3.4	1.35
AlSb*	6.1355	0.33	0.47	12.0	3.5	1.63
GaSb	6.0959	0.041	0.27	15.7	3.9	0.70
InSb	6.4794	0.014	0.34	16.8	3.5	0.175

Notes:
* Indirect Band Gap Compound, all others Direct Gap
# Nitrides have a hexagonal (Wurtzite) crystal structure, hence two lattice constants, a_o and c_o, c/a~1.633 from theory for closest packed arrangement
+ Relative to the rest mass of an electron
$ Earlier value of 0.70 is now regarded as incorrect, actual value measured varies in different materials

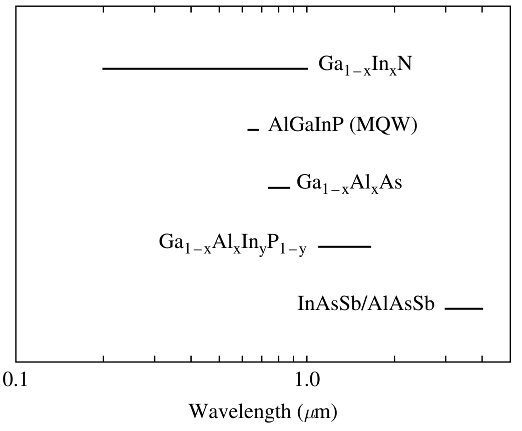

Figure 1.1 Range of emission wavelengths possible with different III–V semiconductor material compositions.

for devices at the key telecommunications wavelengths of 1.3 and 1.55 μm. In all the materials, lasers of shorter wavelength than that associated with the energy band gap of the bulk semiconductor material, a binary, ternary, or quaternary, can be obtained using quantum wells. The visible semiconductor lasers based on AlGaInP are quantum well (QW) devices, usually multiple QWs. Longer wavelength lasers (4–12 μm) have been produced using intersub-band transitions in quantum cascade lasers [5]. Strain can also be used to vary the energy band gap of the active layer material in a semiconductor laser [11].

The II–VI semiconductor materials, such as ZnSe, ZnS and $Zn_xCd_{1-x}S$, have been used to develop short wavelength devices, and the lead salts such as PbS_xSe_{1-x}, $Pb_xCd_{1-x}Se$, $Pb_xGe_{1-x}Te$, $Pb_xGe_{1-x}Te$, $Pb_xSn_{1-x}Se$, and $Pb_xSn_{1-x}Te$ have been developed as tunable systems emitting in the 2–30 μm range. These lasers operate at cryogenic temperatures. The study of optical feedback effects in semiconductor lasers has been primarily confined to room temperature systems and thus, these devices that operate at cryogenic temperatures will not be described further.

1.1.2 Semiconductor Laser Structures

In the 40 years since their first demonstration the design of semiconductor lasers has undergone an almost continuous evolution. Laser action arises in laser diodes due to a recombination of charge carriers injected into semiconductor material using an electrical contact. In the first homojunction (p-n) lasers, optical gain was achieved in a volume essentially defined by the area of the electrical contact and a thickness determined by the charge diffusion and recombination processes. The major advance, which achieved laser diode operation at room temperature, was to utilise layers of dissimilar semiconductor materials – so-called heterostructures – to effect control over the thickness of the active volume. The double heterostructure semiconductor laser [12] is now regarded as the basic, standard semiconductor laser structure. This is shown in Figure 1.2. It achieves confinement of the injected carriers in the active layer region via potential barriers as indicated in the band structure for a forward biased ppn double heterostructure laser diode shown in Figure 1.3 [12, 13].

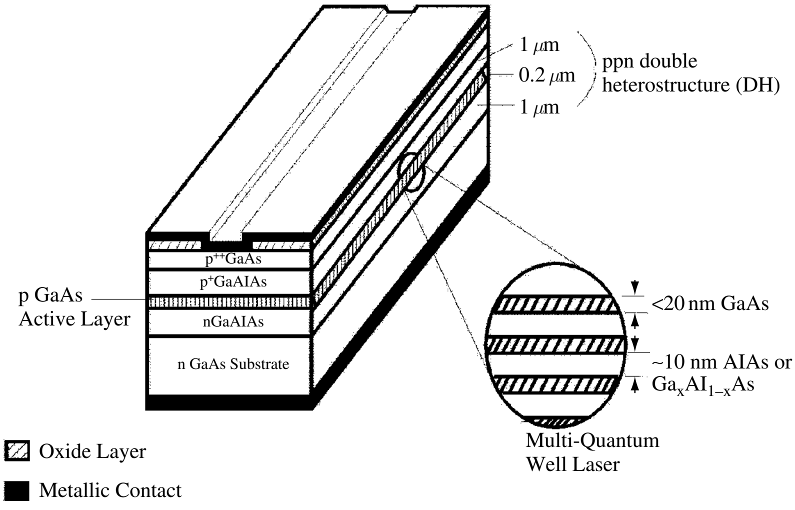

Figure 1.2 Standard GaAs/$Ga_{1-x}Al_xAs$ stripe double heterostructure laser diode (DH LD). In the case of a QW stripe DH LD the active layer is made up of one or more quantum wells as indicated by the inset expansion.

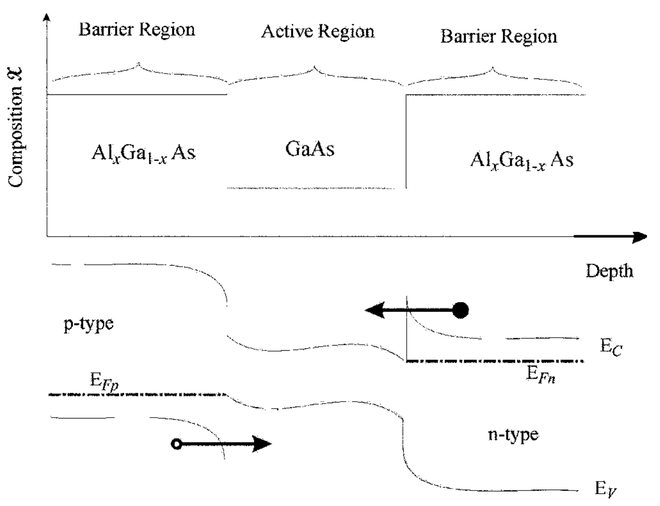

Figure 1.3 Energy band diagram of a ppn double heterostructure showing the potential confinement for the conduction band electrons injected from the n-type $Ga_{1-x}Al_xAs$ into the GaAs (active) layer and for the holes in the valence band injected from the p-type $Ga_{1-x}Al_xAs$ into the GaAs layer.

A typical semiconductor laser chip has a volume of 100 μm × 200 μm × 500 μm. This small size also brings with it a simple physical limitation on the output power which can be extracted from such lasers. Typically, single-stripe laser diode output powers are cited in milliwatts (mW). This limitation has been addressed with some considerable success so that laser diode arrays delivering many watts of output power are now commercially available. Broad area and tapered waveguide devices are also of interest for output power scaling, but in common with coherently coupled laser arrays, they introduce spatial beam quality issues which need to be addressed. One approach to obtaining high power and high brightness is to use high-power laser diode arrays as a pump laser for solid-state lasers [3].

The narrowness of the active laser stripe (0.2 μm as shown in Figure 1.2, and the limited width of the material excited laterally (~2–10 microns, determined by the width of the electroded stripe into which current is injected (Figure 1.2) or by the use of other carrier and light confinement techniques) means the beam emitted by the semiconductor laser is highly divergent, more so perpendicular to the stripe than parallel to it. Typical values of 20–25 degrees and 5–10 degrees, respectively, are seen in real devices (Figure 1.4(a)). This necessitates the use of short focal length lenses of high numerical aperture to collimate the output beam so that it may be utilized in applications. Direct butt coupling of the output into optical fibre is also common (Figure 1.4(b)).

Further innovations in device structures have been enabled by advances in material growth and material processing which have allowed practical implementation of advanced device concepts. The vigorous development of laser diodes has involved the development of a rather large range of structures which have been advanced in order to enhance one or more aspect of laser performance, e.g. output power, output beam quality, emission spectrum, and laser dynamical response. From this rich variety of designs it is possible to identify two general classes of structures whose distinction has some considerable significance in relation to their dynamical behaviour. We use the terms *horizontal cavity* and *vertical cavity* to denote these two classes of device. In the former, the laser cavity is defined by mirrors which are perpendicular to the plane of the heterostructure layers, as in Figure 1.2; in the latter, the cavity mirrors are parallel to the heterostructure layers as shown in Figure 1.5. It is generally the case that the orientation of the cavity determines the manner in which light is emitted from the lasers. With the configuration illustrated in Figure 1.2, the laser emission occurs through the cavity mirrors giving rise to the term *edge-emitting lasers*. In contrast,

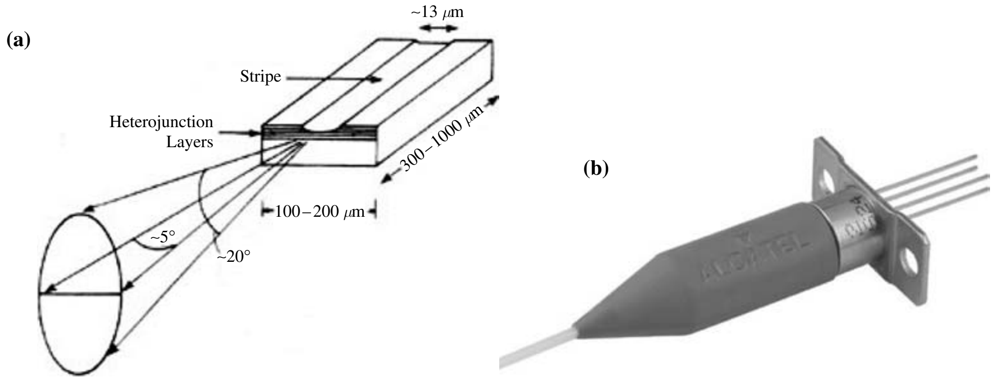

Figure 1.4 (a) shows the elliptical, divergent beam emitted by a standard semiconductor laser. This output gets collimated using a short focal length lens or the output is coupled directly to an optical fibre in a fibre pig-tailed device (b).

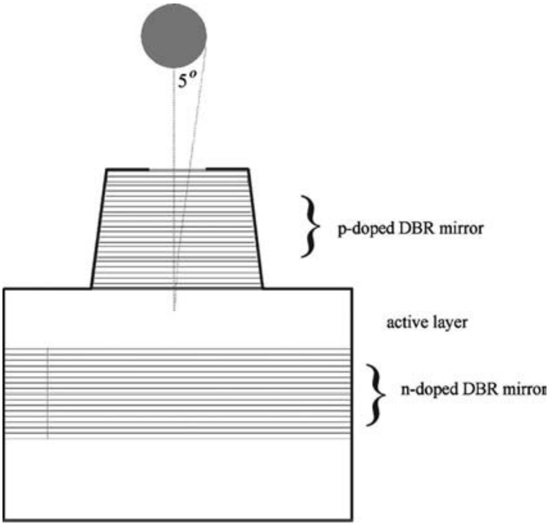

Figure 1.5 VCSEL semiconductor laser structure showing the two distributed Bragg reflector (DBR) high reflectance mirrors and the active layer of order of micron thickness.

the device in Figure 1.5 is said to be a vertical cavity *surface emitting* laser (VCSEL). It is noted that surface emission can be achieved in horizontal cavity laser diodes and conversely that edge-emission can be derived from vertical cavity structures.

The horizontal cavity laser has been the mainstay of most laser diode designs and consequently much effort has been productively employed to optimize device designs. Specific attention has been given to the use of waveguide structures which offer high beam quality by ensuring that the laser can operate stably in the lowest order spatial mode of defined polarisation. In its simplest form, with the cleaved surfaces of the semiconductor forming the mirrors, it is a moderate finesse Fabry–Perot cavity. Such Fabry–Perot cavity semiconductor lasers tend to support lasing action on a number of longitudinal cavity modes. This has profound implications for both the spectral and dynamical properties of the lasers. Robust single longitudinal mode output can be obtained using distributed feedback (DFB), distributed Bragg reflector and external or extended cavity laser structure and systems as shown in Figure 1.6.

The motivation for developing VCSELs was to utilise very short optical cavities – typically of the order of the emission wavelength – in order to ensure that only one longitudinal cavity mode would lie within the gain spectrum of the laser material. One consequence of the geometry of such devices is that they are generally found to support multiple transverse modes whose emission polarization cannot be determined *a priori*.

From the above it is clear that laser diodes are a rich source of dynamics in their own right. The opportunities for accessing interesting dynamics are immeasurably increased when the laser is subject to optical feedback. This is the subject of this book. However, we would indicate that further varieties of dynamical behaviour can be generated in laser diodes, e.g. by subjecting them to external optical injection and opto-electronic feedback. Semiconductor lasers are thus seen as an ideal test-bed for exploring concepts in nonlinear dynamics.

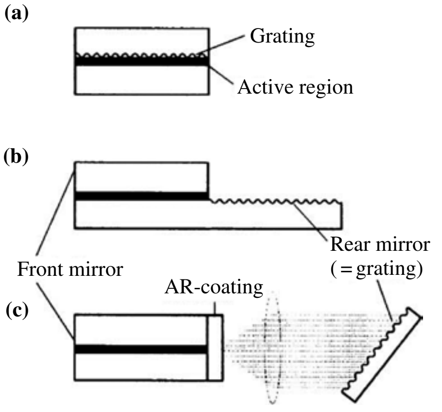

Figure 1.6 Laser structures ((a) DFB, (b) DBR, (c) external cavity semiconductor laser) for achieving robust single longitudinal mode output from semiconductor lasers, and which also allow some wavelength tunability.

1.1.3 Semiconductor Laser Gain and Output Power versus Injection Current

The gain coefficient, g(ν) in a laser based on an atomic transition is commonly derived as given in Equation (1.1) [14, Eq. 8-4-4]. This is the coefficient of exponential growth of the irradiance of the resonant light field as it propagates through the gain medium (Eq. 1.2) if the pumping (usually optical) and atomic level population densities (N_1 and N_2, with degeneracies ρ_1 and ρ_2) are spatially uniform. The variation of the gain with frequency is given by the lineshape function $l(\nu)$, λ is the centre wavelength in vacuum, n is the refractive index and τ_{sp} is the spontaneous lifetime of the laser transition. The lineshape is typically a Doppler profile for a gaseous discharge.

$$g(\nu) = \frac{\left(N_2 - N_1\dfrac{\rho_2}{\rho_1}\right)\lambda^2}{8\pi n^2 \tau_{sp}} l(\nu) \tag{1.1}$$

$$I_\nu(z) = I_\nu(0)e^{g(\nu)z} \tag{1.2}$$

Growth in the irradiance requires a population inversion, i.e. a positive value for $(N_2 - N_1/(\rho_2/\rho_1))$ This is simply interpreted as requiring population density for the upper laser level to be greater than that (weighted) for the lower laser level, for lasing on an atomic transition. This simple interpretation does not apply to semiconductor lasers as here the laser 'levels' are bands (the upper level is the conduction band and the lower level is the valence band), with energy widths of several eV, made up of a quasi-continuum of energy levels described statistically by a density of states. Nearly all the energy levels in the valence band are occupied by electrons and it is not probable that more electrons can be elevated to the conduction band than are left behind in the nearly filled valence band. However, statistically, there are many electrons in the conduction band and many ‘holes’ (vacancies) in the upper levels of the valence band to allow efficient direct radiative recombination of electrons and holes. The band theory of semiconductors for non-thermal equilibrium systems, utilizing Fermi Dirac statistics and quasi-Fermi levels, is required to describe the inverted semiconductor [11, 15]. The resulting gain per unit length can be written in the form [11, Eq. 4.37]:

$$g_{21} = g_{\max}(E_{21})(f_2 - f_1) \tag{1.3}$$

where

$$g_{\max}(E_{21}) = \frac{\pi q^2 \hbar^2}{n\varepsilon_o c m_o^2 h\nu_{21}} \left|M_T(E_{21})\right|^2 \rho_r(E_{21})$$

$$f_1 = \frac{1}{\exp(E_1 - E_{Fv}) + 1}$$

and

$$f_2 = \frac{1}{\exp(E_2 - E_{Fc}) + 1}\,.$$

E_{Fv} and E_{Fc} are the nonequilibrium quasi-Fermi levels for the valence band and conduction band, respectively. E_{21}(k) is the energy between the conduction band and valence band, $\rho_r(E_{21})$ is the reduced density of states which has a different functional form for bulk semiconductor and reduced dimension structures such as quantum wells. $|M_T(E_{21})|^2$ is the transition matrix element, ν_{21} is the transition frequency, q is the magnitude of the electron charge, $\hbar$ is Planck’s constant divided by 2π, n is the refractive index of the semiconductor material, m_o is the rest mass of the electron, c is the speed of light in vacuum and ε_o is the permittivity of free space. The full derivation of Equation (1.3) can be found in Chapter 4 and appendices of [11]. Another excellent discussion is found in Chapter 11 of [15]. Values of g_{21} of 10^3–10^4 cm^{-1} are achieved for different semiconductor laser structures using high quality materials.

Describing the semiconductor laser phenomenologically, when the laser is operating in a steady state the gain per unit length must equal the loss per unit length. The loss includes the light transmitted out of the cavity through the partially reflecting laser mirrors and a second component describing the distributed loss per unit length, α due to scattering, free carrier absorption etc., in the cavity. Also, only a factor $\Gamma(0 < \Gamma < 1)$ of the light is confined to the volume which is subject to gain via the injection of carriers. Γ is called the confinement factor. For one round trip in the cavity under steady state conditions this gives:

$$\text{Gain} = 1 + \exp[(\Gamma \mathrm{g} - \alpha)L]R_1 \exp[(\Gamma \mathrm{g} - \alpha)L]R_2 \tag{1.4}$$

where L is the length of the laser cavity and, R_1 and R_2 are the reflectances of the semiconductor laser facets. Solving this yields:

$$\Gamma \mathrm{g}_{\mathrm{th}} = \alpha - (1/2L)\ln(R_1 R_2) \tag{1.5}$$

Making the link between Equation (1.1) and Equation (1.5) [13], the threshold current density is

$$J_{th}(0) = \frac{qd\,8\pi\,\Delta\nu}{\eta_i \lambda^2}\left(\alpha - \frac{1}{2L\Gamma}\ln(R_1 R_2)\right) + J(T) \tag{1.6}$$

where $\Delta\nu$ is the full width at half maximum of the gain profile, d is the stripe thickness for a DH semiconductor laser and η_i is the internal quantum efficiency, (the number of photons produced per injected carrier) and $J(T)$ is a term to take account of the effective non-zero $N_1(\rho_2/\rho_1)$ value at temperatures above 0 K. The threshold current I_{th}, which is easily measured in practice, can be calculated from the threshold current density if the effective area over which the carriers are injected can be determined. The temperature dependence of I_{th}, or J_{th}, is of the form:

$$J_{th}(T) = J_{th}(0)\,e^{T/T_0} \tag{1.7}$$

where T_0 is called the characteristic temperature. It has values >120 K for near infrared GaAs/GaAlAs DH lasers and ~150–180 K is determined for QW GaAs/GaAlAs lasers. The stimulated optical power inside the laser cavity increases linearly with the injection current according to:

$$P_{in} = \frac{(I - I_{th})}{q}\eta_i h\nu \tag{1.8}$$

The external power, P_{ex} is:

$$P_{ex} = \frac{\ln\left(\frac{1}{R_1 R_2}\right)}{2\alpha L + \ln\left(\frac{1}{R_1 R_2}\right)}\frac{(I - I_{th})}{q}\eta_i h\nu \tag{1.9}$$

The external differential quantum efficiency, η_{ex} is:

$$\eta_{ex} = \frac{\ln\left(\frac{1}{R_1 R_2}\right)}{2\alpha L + \ln\left(\frac{1}{R_1 R_2}\right)}\eta_i \tag{1.10}$$

The slope efficiency listed in the specification sheets of commercial semiconductor lasers is given in W/A and can be calculated from η_{ex} as:

$$\eta = \eta_{ex}\left(\frac{h\nu}{e}\right) \tag{1.11}$$

Often it is the slope efficiency pertaining to the output from one of the output facets of the device that is of interest. For a laser with a large output coupling, the values associated with facets of R_1 and R_2 are given by [16]:

$$\begin{aligned} \eta_1 &= \eta\frac{(1 - R_1)\sqrt{R_2}}{\left(\sqrt{R_1} + \sqrt{R_2}\right)\left(1 - \sqrt{R_1 R_2}\right)} \\ \eta_2 &= \eta\frac{(1 - R_2)\sqrt{R_1}}{\left(\sqrt{R_1} + \sqrt{R_2}\right)\left(1 - \sqrt{R_1 R_2}\right)} \end{aligned} \tag{1.12}$$

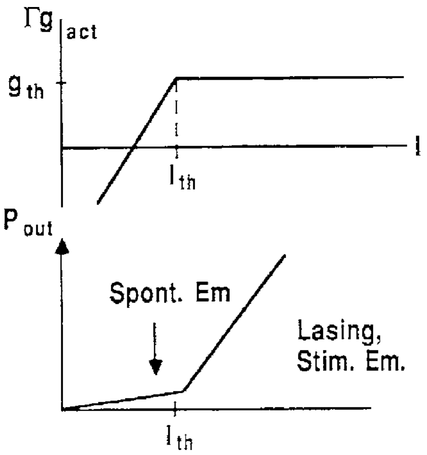

Figure 1.7 Gain per unit length and output power as a function of the injection current. *Source*: Reproduced with permission from [17].

A typical output power versus injection current graph for a semiconductor laser is shown in Figure 1.7. Semiconductor lasers operate as LEDs (spontaneous emission predominantly) below the injection current threshold for lasing. Figure 1.7 indicates that this contribution due to spontaneous emission is large. It also contributes to noise in the laser output making semiconductor laser noisy compared to other lasers.

1.1.4 Semiconductor Laser Relaxation Oscillations, Noise, Modulation and Linewidth Enhancement Factor

Other distinguishing features of semiconductor lasers, relative to most other lasers, that contribute to their dynamic timescales and diversity, and the extreme sensitivity to optical feedback include enhanced spontaneous emission; enhanced linewidth (due to spontaneous emission, and the strong coupling between variations in intracavity optical power and frequency, through the irradiance and carrier density dependent refractive index); high relaxation oscillation frequency, which scales as the square root of the injection current above threshold; a modulation bandwidth up to the relaxation oscillation frequency, and mixed FM and AM arising when the injection current is modulated, again, due to the coupling between power variation and frequency variation. All these topics are interrelated but they are dealt with separately, mostly, in standard texts on semiconductor lasers. Some key results and references are summarized here.

Relaxation oscillation of the output power has been observed in most lasers and occurs with a time characteristically long compared to the laser cavity decay time, or the cavity round trip time. Typical periods of the relaxation oscillations in, for example, solid state lasers such as Nd:YAG are ~ 0.1–$1\ \mu s$ [14]. The basic mechanism is an interplay between the oscillation field in the resonator and the atomic/molecular/solid state inversion. An increase in the intracavity power leads to a reduction in the inversion due to the increased rate of stimulated emission. This in turn leads to a reduction in the power, and so on cyclically.

In semiconductor lasers the competing timecales are very much shorter. The inversion can change dynamically on nanosecond timescales τ_c and the photon lifetime τ_p in the short, relatively low finesse semiconductor laser cavities is 1–3 picoseconds, typically. The relaxation oscillations in this case occur at GHz frequencies, f_r. The relaxation oscillation frequency scales as the square root of the injection current for DH semiconductor lasers. The relaxation oscillations are damped with a rate f_d which scales as $f_r^{\,2}$.

$$f_r = \frac{1}{2}\left(\frac{1}{\tau_c\tau_p}\right)^{\frac{1}{2}}\left(\frac{I}{I_{th}} - 1\right)^{\frac{1}{2}} \tag{1.13}$$

Small signal modulation of a semiconductor laser is achieved by adding a small sinusoidal current of frequency f, to a dc injection current that operates the laser well above threshold. In this case the rate equations which describe the carrier density and photon density, with the modulation, can be linearised and solved. The general power modulation response, as the modulation frequency is varied, is given by the modulation transfer function (Eq. 1.14), the magnitude squared of which is shown in Figure 1.8. The power modulation follows the current modulation up to frequencies near the relaxation oscillation frequency, with a resonant response at a frequency close to, but slightly lower than the f_R (Eq. 1.13). The modulation transfer function also depends on the damping constant, $f_d(\omega_x = 2\pi f_x)$.

$$H(\omega_m) = \frac{1}{1 + \frac{i\omega_m\omega_d}{\omega_r^2} + \left(\frac{i\omega_m}{\omega_r}\right)^2} \tag{1.14}$$

The modulation of the carrier density modulates both the power and the refractive index. This gives rise to frequency modulation which in semiconductor lasers dominates the power modulation. The ratio of the frequency modulation index to the power or irradiance modulation index is proportional to the linewidth enhancement factor, α, which is given by

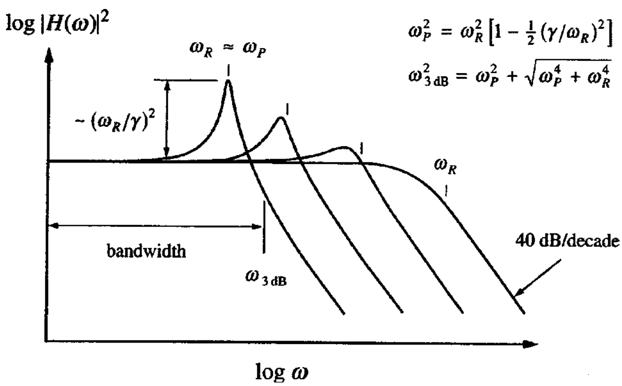

Figure 1.8 Log of the magnitude squared modulation transfer function for power/irradiance modulation as a function of (log circular) modulation frequency. The function broadens and flattens as f_r and f_d increase.
Source: After [11].