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LASER DIODE-TO-SINGLEMODE FIBER BUTT-COUPLING AND
EXTREMELY-SHORT-EXTERNAL-CAVITY LASER DIODES:
ANALYSIS, REALIZATION AND APPLICATIONS

by

Yakov Sergeevich Sidorin

A Dissertation Submitted to the Faculty of the
COMMITTEE ON OPTICAL SCIENCES (GRADUATE)
In Partial Fulfillment of the Requirements
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THE UNIVERSITY OF ARIZONA

1998
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Yakov S. Sidorin entitled Laser diode-to-singlemode fiber butt-coupling and extremely-short-external-cavity laser diodes: analysis, realization and applications and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

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Dedicated to my mother, Clara, my uncle, Emmanuel,

and the memory of my grandparents, Ester and Dmitry.
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The butt-coupling of a Fabry-Perot semiconductor laser diode and a singlemode optical fiber was realized and characterized in the near field. A novel butt-coupling model was developed and found very effective in describing all physical phenomena that occur when the butt-coupling parameters are varied over a wide range. The strong external optical feedback to the laser diode cavity that is present at extremely-short separations between the laser diode and the fiber is advantageously used to realize an extremely-short external cavity laser diode. By varying the length of the external cavity, the operational characteristics of this external cavity laser diode are controlled in a predictable and repeatable manner; a wavelength tunable laser diode source based on this effect was developed and analyzed. Another realization of an extremely short external cavity tunable laser diode, based on a closely spaced external filter with variable characteristics, was demonstrated. A potential application of the butt-coupling technique for light collection in an optical recording head is discussed. The work presented here is a research tool that can be used to facilitate the design of extremely-short external cavity laser diodes, which in many ways are technologically novel.
CHAPTER 1.

1.1 MOTIVATION AND RELEVANCE

The efficient coupling of light sources to fibers or waveguides is a complex engineering problem. Technical and cost considerations become challenging when the coupling unit has to be miniaturized and packaged. The coupling problem has been studied extensively from both theoretical and technical points of view in recent years (Karioja and Howe 1996 and references therein). It was determined that a "direct end-coupling" ("butt-coupling") configuration, i.e. when the laser diode (LD) and a singlemode fiber or waveguide are positioned end to end, is the most tractable from an integrated optics point of view. To analyze butt-coupling, a simple coupling model, based on the modal overlap integral (Kogelnik 1964), was created. This was improved as ways to simulate the LD’s parameters were introduced and equations to predict system tolerances were developed (Hall et al. 1979, Joyce and DeLoach 1984, Karioja and Howe 1996). To overcome the mismatch in modal sizes of components to be butt-coupled (this is the major factor that reduces the coupling efficiency) various modal size conversion methods - that work equally well with passive and active components - were demonstrated (Buus et al. 1993, Yanagawa et al. 1994, Rahman et al. 1996, and references therein). Various means for mutual positioning of the coupled LD and waveguide/singlemode fiber were developed (Foley et al. 1990, Ladany et al. 1991).

Laser-to-waveguide/fiber coupling, however, is traditionally characterized from the point of view of its efficiency only. A very important effect, which is usually ignored
by this characterization, is the perturbation of the LD's operational characteristics caused by feedback into the solitary LD cavity from the effective Fabry-Perot etalon that is formed by the facets of the LD and the singlemode fiber to be butt-coupled. Such feedback is usually viewed as a parasitic effect, destabilizing the LD output (Hall et al. 1980, Hammer et al. 1981, Karioja and Howe 1996); accordingly care is taken to get rid of unwanted external cavity reflections.

The entrance facet of the fiber/waveguide, which is responsible for the excessive feedback, together with the LD used in the butt-coupling configuration, can be viewed as forming a short-external-cavity-LD (SEC LD). SEC LDs can be constructed using most multimode, gain-guided, or index-guided lasers and offer a simple and inexpensive alternative to other tunable near IR lasers. Indeed, intrinsically single-mode distributed feedback (DFB) lasers, for instance, are constructed mostly to operate in the 1.3-\textmu m or 1.5-\textmu m regions used in optical communication systems. Custom DFB lasers have a restricted frequency tuning range and high cost of manufacturing. Long external cavity lasers, on the other hand, exhibit a wide tuning range and narrow linewidth, but they require careful alignment of the external reflector and special antireflection coating of the laser facet that faces the external cavity (Favre et al. 1986, Schremer 1990). SEC lasers therefore, have a technological niche of their own: we shall show that they provide a tunable, low-noise single-mode laser source that does not require serious investment in design and construction. Because of their potential technological applications, the most
promising of which is various sensors - chemical, acoustic, magnetic, displacement (Miles et al. 1983, Zhu and Cassidy 1997 and references therein) - increased attention is being paid to SEC LDs.

The above introduction makes it clear that there might be an interest in a butt-coupling configuration that exhibits reasonable efficiency and also takes advantage of otherwise unwanted optical feedback. The work presented here focuses on such a configuration. We analyze and experimentally characterize an extremely-short-external-cavity LD (ESEC LD) that is intrinsically formed when efficiently butt-coupling a LD and a singlemode fiber (SMF). We also report a hybrid (multi-module) ESEC LD formed by close positioning of a micro-machined, electrostatically tuned, thin-film Fabry-Perot interferometer to the output facet of a LD.

Although several attempts have been made to build an ESEC LD (Ukita et al. 1994, Uenishi et al. 1995, 1996), the idea of simultaneously controlling both the coupling efficiency and the LD’s operational characteristics via adjustment of the butt-coupling parameters has not, to the best of our knowledge, been considered. Nor has the behavior of such an ESEC LD been thoroughly examined and understood. The analysis described herein is a research tool that allows investigation of the ESEC LD’s performance and forms a platform for the design and technological development of new wavelength tunable devices in integrated optics.

The ability to realize a tunable laser source on an integrated optics scale using a commercially available laser diode and waveguide could have a significant impact in an
area such as frequency doubling in quasi-phasematched waveguides. Here the laser diode source and the waveguide can be phase-matched to increase the conversion efficiency simply by changing the separation between the butt-coupled components, with (relatively) minor sacrifice in coupled power. Other potential applications of this type of tunable source are various sensors and optical communications systems.

1.2 SCOPE OF RESEARCH

The objective of this research is two-fold:

(1) to characterize and implement butt-coupling techniques that exhibit high efficiency, compact optical coupling of LD sources to singlemode optical fibers (SMF),

(2) to analyze and realize novel configurations of an ESEC wavelength tunable LD, based on butt-coupling, that are potentially useful as write/read sources in frequency conversion and sensor applications. Special attention is given to realizing high-power, single temporal frequency, single spatial mode tunable diodes that may be efficiently coupled to SMFs and/or waveguides.

The factors that must be addressed when analyzing the performance of a device that incorporates direct end-coupling include: (1) the radiation field of the laser diode and its dependence on the laser diode structure; (2) the mode profile of the optical waveguide upon which this radiation is incident; (3) the longitudinal displacement (separation) between the laser diode and the waveguide; (4) their transverse misalignment; (5) their angular alignment; and (6) the feedback coupling into the laser diode from the reflective
surfaces of the waveguide. In the work presented here we relied upon commercially available LDs and SMFs; this limited our control of the factors (1) and (2) listed above.

In the following Chapters we address the key points in the development of an ESEC LD formed by butt-coupling (hybrid or integrated) between a LD and a SMF/waveguide.

In Chapter 2 we analyze methods of coupling and support our choice of the direct end-coupling technique. We introduce the idea of an extremely-short-external-cavity LD. Then we develop a "butt-coupling" formalism that is used to compute coupling efficiency and analyze the operation of butt-coupled LDs. This is greatly simplified by the assumption of Gaussian profiles for the LD and SMF eigenmodes (Appendix A). Our model treats the gap between the LD and SMF as a compound laser (output) mirror and thus views the butt-coupled LD and SMF as an ESEC LD. The theoretical rigor of our discussion is somewhat sacrificed in order to achieve an intuitive understanding of the feedback process and to realize a physically realistic butt-coupling model. Appendix B presents some aspects of overlap integral calculation used in the model. The description of our experimental set-up and the components we used is presented in the final Section of Chapter 2.

Experimental verification of our butt-coupling formalism is discussed in Chapter 3. The ESEC LD is characterized (theoretically and experimentally) in terms of threshold current, differential quantum efficiency, output power hysteresis and coupled output power (which subsumes the coupling efficiency).
Chapter 4 presents experimental observations of the optical feedback effects that are encountered in near-field LD-to-SMF coupling: multimode and singlemode wavelength tuning regimes, wavelength tuning range, and relative intensity noise. The singlemode output linewidth is discussed as well. Wavelength tuning data are compared with the predictions of the "butt-coupling" model. The variation of the LD active gain spectrum versus feedback was incorporated into the model in order to obtain good agreement with experiment (Appendix C).

Chapter 5 presents a tolerance analysis. The effects of positioning misalignments and variation in the reflectances of the facets on coupling efficiency and wavelength tuning are discussed.

In Chapter 6 we discuss two potential applications of our research. First, we discuss a novel hybrid tunable LD based on butt-coupling an electrostatically tunable external reflector to a high-power LD. This device was demonstrated as a part of a collaborative effort between the Optical Data Storage Center and VTT Electronics (Oulu, Finland). Next, it is shown that the use of fibers butt-coupled to laser diodes can improve the efficiency of power delivery to the write/read objective used in certain optical recording systems.

Chapter 7 provides a summary of the work and addresses points to be investigated in the future. A list of relevant references is also included.
CHAPTER 2.

DIRECT END-COUPLING OF A LASER DIODE AND OPTICAL FIBER;
THE "BUTT-COUPLING" MODEL

2.1 EXCITATION OF A GUIDED WAVE: WHY DIRECT END-COUPLING?

An alternative to the monolithic integration of optical components, such as in optical integrated circuits (OIC) where all elements are fabricated in a single substrate, is a hybrid optical integration in which the various elements (sources, waveguides, etc) are fabricated in different substrate materials and then appropriately joined together. This approach offers a major advantage in that various substrates can be chosen to optimize the performance of each element. The ultimate utility of hybrid guided-wave optical devices depends then, to a great extent, on how well the modes of the separate elements can be intercoupled and coupled to the modes of optical fibers. When a plane optical wave that is characterized by a propagation vector \( k \) (i.e. a wave that has a space dependence of \( \exp(-i\mathbf{k} \cdot \mathbf{r}) \)) is incident upon a guiding structure, it can be coupled to a mode of that structure, as long as the appropriate component of the propagation vector matches the propagation constant of the field in the structure. This means that a phase-matching condition

\[
\mathbf{k}_i = \beta,
\]

where \( \beta \) is the propagation constant of a guided mode, and \( \mathbf{k}_i \) is the appropriate component of \( \mathbf{k} \), has to be satisfied. An effective method to realize such matching is then needed. Below I shall describe some fundamental techniques for excitation of a guided
wave in planar waveguides, as well as in optical fibers. A detailed discussion on this subject was presented by Nishihara et al. (1989).

2.1.1 Prism Coupling.

A wave impinging onto a surface of a planar waveguide from an incident medium with smaller permittivity is the conjugate of a radiation mode of the structure, and thus cannot become a guided mode. The prism-coupling method utilizes a high-index prism to phase-match the incident wave and guided mode (Fig. 2.1), i.e. to introduce into a waveguide a wave with propagation constant $k_f$ that satisfies a guiding condition

$$k_c \leq \beta < k_f,$$  \hspace{1cm} (2.2)

where $\beta$ is the mode propagation constant, $k_c$ and $k_f$ are the magnitudes of wavevectors of lane waves in the waveguide superstrate (cover) medium and waveguide (film) medium, respectively, along the waveguide plane ($z$ or $\rho$-direction).

To satisfy the guiding condition, one needs to use a prism with an appropriate index $n_p \geq n_f$ and apex angle, $\alpha_p$, and adjust the incident angle, $\theta$, to produce a propagation angle $\theta_p$ beyond the critical angle inside the prism. Then, by placing the prism in close proximity to the waveguide, the total reflection at the prism bottom is frustrated and a guided wave is excited when (Fig. 2.1b)

$$\beta = k_p \sin \theta_p = n_p k \sin \theta_p, \quad k = 2\pi/\lambda$$  \hspace{1cm} (2.3)
Prism-coupling offers the following advantages for input coupling: (1) High efficiency (~80%) is feasible under optimum conditions; (2) Any of the guided modes can be selectively excited; (3) It can be applied to channel waveguides as well as planar ones; (4) The prism is detachable and coupling can be adjusted during the experiment. There are, however, some disadvantages: (1) The adjustment of separation and beam position is very critical and, therefore, the stability is rather poor; (2) An expensive high-index prism and high-precision adjustment mechanism are required.
2.1.2 Grating Coupling

Various grating structures may serve the same purpose - to realize the phase-matching condition. Indeed, the grating's periodic structure along the waveguide plane can be expressed as a Fourier expansion of relative dielectric permittivity

\[ \Delta \varepsilon(x, y, z) = \sum_q \Delta \varepsilon_q(K) \exp(-iqK \cdot r), \]

\[ K = K_x e_x + K_y e_y + K_z e_z \]

within the grating layer, and \( \Delta \varepsilon = 0 \) outside the grating layer. In Eq. (2.4) \( K \) is the grating vector that is normal to the grating grooves; it is correlated with the fundamental grating period \( \Lambda \) by \( |K| = K = 2\pi/\Lambda \). Then, for coupling between an incident wave \( k \) and the waveguide mode \( \beta \), propagating in \( z \)-direction, the phase matching condition \( \beta = (k + qK) \cdot \hat{z} \) must be satisfied (Fig. 2.2). Here \( q = 0, \pm 1, \text{ etc.} \) is the order of coupling.

The advantages of the grating-coupling method are: (1) Possible high efficiency (with optimum design); (2) Any chosen one of the guided modes can be selectively excited; (3) Gratings are compact, stable, and inexpensive integrated components; (4) Input-beam adjustment position is not very critical; (5) Excitation of a guided wave with a large width is easy because coupling is uniform in the lateral direction.
There are some drawbacks, however: (1) The design of the grating involves complex theoretical calculations, and its fabrication requires advanced techniques; (2) Parameters of the device cannot be adjusted after fabrication; (3) Beam-profile matching is difficult for channel waveguides.

2.1.3 Hybrid Methods.

There exists a variety of hybrid coupling methods that include, but are not limited to:

- **prism-grating coupling**: this uses a grating structure fabricated in the prism-waveguide gap region. The stringent requirements imposed by high-index waveguides on prism-coupling (expensive high-index prism) and grating-coupling (short grating period, that is difficult to fabricate) are reduced in this case;
- modulation of the period and/or changing the periodic permittivity pattern of a grating coupler: this results in coupling of a diverging wave from a laser diode or fiber into the waveguide (Heitman and Ortiz 1981);

- holographic coupler: this combination of a grating coupler on the waveguide and an external hologram enables guided wave excitation by a diffused input beam (Ash et al. 1974);

- tapered coupler: a gradual decrease of the waveguide thickness (Tien and Martin 1971), causes the guided mode to reach the cut-off condition and radiate into the substrate. By introducing a wave conjugate to this leaking waveguide mode, it is possible to couple light into the waveguide as well (wavefront matching, however, is difficult due to the non-planar wavefront of the leaking beam).

2.1.4 End-Coupling.

General end-coupling (end-fire coupling) is the simplest way to excite a guided wave (Shubert 1968): here a light wave with a profile similar to that of the guided-mode is incident onto a waveguide facet parallel to the guided-wave propagation direction, thereby localizing coupling at the waveguide facet. Guided mode excitation efficiency is given by the relative magnitude of the guided-mode component in the modal expansion of the field of the incident wave at the waveguide end. In order to obtain high efficiency of coupling, the profile of the incident wave must resemble the profile of the mode to be excited as closely as possible (Fig. 2.3a). The required high-quality waveguide facet is
prepared by the polishing or cleaving the waveguide. An external Gaussian beam of width $2W$ is focused into a width $2w = \lambda f / (\pi 2W)$ by a sufficiently high numerical aperture lens with a focal length $f$. Thus, via the proper choice of $W$ and $f$, relatively high efficiency can be obtained. When realizing end-coupling between an edge-emitting LD and a circularly symmetric SMF, the use of anamorphic corrective optics (Karstensen and Drögemüller 1990) may somewhat increase the coupling efficiency via a reduction of the LD beam ellipticity and astigmatism. A limitation of the end-coupling is that it is difficult to selectively excite a non-fundamental guided mode in a multimode waveguide. Also, for singlemode waveguides (with guiding layer thickness on the order of $1 \text{ \mu m}$), some practical problems in implementing direct end-coupling may be caused by the restrictive requirements on the waveguide flatness and alignment accuracy.

*Fig. 2.3: a) End-coupling with a lens; b) Direct end-coupling (butt-coupling) configuration.*
End-coupling is applied in optical-fiber-to-waveguide coupling as well as to guided wave excitation by a semiconductor laser, as shown in Fig. 2.3(b). Such coupling is called direct end-coupling (butt-coupling, butt-joining - in this work we use all these terms interchangeably), since no optical components are used to realize coupling. Fiber coupling is sometimes referred to as pig-tailing. To achieve high efficiency, the distance $z$ between the components should be minimized and profile matching should be satisfied for the input and guided waves. The front facet of the waveguide and the output facet of the laser diode form an external (with respect to the laser) cavity, that will affect the coupling efficiency as well as create feedback into the laser cavity, unless the Fresnel reflection from the waveguide is eliminated by antireflection coating.

Previous experimental demonstrations proved direct end-coupling to be an efficient, straightforward and competent means to achieve coupling between the laser diode and thin film waveguides (Hunsperger et al. 1977, Burns 1979, Mueller et al. 1980, Hall et al. 1980). Indeed, efficient coupling of these is difficult to obtain by means of prisms, gratings, or tapered edgers couplers that are used with gas lasers. The reason for this is that the highly diverging laser diode beam is not compatible with any coupler that is strongly sensitive to the angle of incidence of the input light beam. Reported experimental results include -2 dB efficiency in butt-coupling a single-mode fiber to LiNbO$_3$-waveguide (Alferness 1982).

A hybrid of the butt-coupling and lens-coupling methods is sometime used for coupling light to a SMF: here a microlens formed on the facet of the SMF produces the
LD beam phase front conversion. Early reports on the use of cylindrical (Weidel 1974) and hemispherical (Kuwahara et al. 1980) microlenses on the SMF facet cited an improvement in coupling efficiency, compared to butt-coupling. I see the major advantage of this method, however, to be an extended working distance, i.e., a longer acceptable LD-to-SMF separation. Presby and Edwards (1992) reported achieving 90% efficiency in coupling a LD to a SMF with a hyperbolic microlens on its end. Technological difficulties, associated with the fabrication of various microlenses (by tapering and melting of SMF facet, development of photoresists coated on the SMF facet, or laser-micromachining), have prevented them from being used widely.

Direct end-coupling (butt-coupling) is probably considered to be the most effective method for realization of practical optical integrated circuits (Nishihara et al 1989). This is due to its potentially high efficiency and simple structure. Also, keeping in mind that lens- or microlens- coupling is not preferred in integrated optics structures, we restrict our interest to the butt-coupling technique. However, this method does involve problems concerning end-face preparation, component alignment, and fixing.
2.2 EXTREMELY-SHORT-EXTERNAL-CAVITY LASER DIODE REALIZED BY DIRECT END-COUPLING INTO AN OPTICAL FIBER

The term external-cavity laser diode is often used generically to describe any configuration in which the path of feedback extends beyond one or both of the facets of the gain medium.

The simplest short-external-cavity (SEC) laser diode is comprised by a multimode semiconductor laser directly end-coupled to an external planar mirror (Fig. 2.4). Usually the laser facet that is coupled to the external mirror is antireflection coated. The opposite facet is either uncoated, or coated as a high reflector; it serves as the end mirror and, sometimes, as the output coupler. Compared to conventional external-cavity configurations, such as the extended-cavity, double-ended external-cavity and ring-external cavity (Zorabedian 1995), the arrangement shown in Fig. 2.4 is extremely simple since the number of optical elements is minimized. Although several experimental demonstrations of laser diodes that are butt-coupled to external planar mirrors, and which beneficially utilize optical feedback, have been made (Bonell and Cassidy 1989, Bruce and Cassidy 1990, Cassidy et al. 1991, Ventrudo and Cassidy 1993, Ruprecht and Brandenberger 1992, Ukita et al. 1994, Uenishi et al. 1995 and 1996), only a few of these (Ukita et al. 1994, Uenishi et al. 1995 and 1996) employed an extremely-short external cavity (ESEC). To distinguish between the SEC and ESEC devices, we use the ratio of the optical length of the external cavity of the laser to the Rayleigh range of
Fig. 2.4: General scheme of a simple short-external cavity (SEC) laser diode. SEC \((n_z z \gg Z_g)\) is comprised by the external mirror and the output laser facet. \(d\) - laser diode cavity length; \(z\) - external cavity length; \(\theta\) - general angular misalignment; \(P_{\text{out}}\) - traditionally utilized power output (external mirror has zero transmission).

Fig. 2.5: a) Two-dimensional schematic of an extremely-short external cavity laser diode (LD) formed via butt-coupling into a singlemode fiber (SMF). ESEC - extremely-short external cavity; \(n_d, n_z\) - refractive indices of the LD active layer and ESEC medium, respectively; \(\delta, \Theta\) : general transverse and angular misalignments between the axes of propagation of eigenmodes of LD and those of the outcoupled medium. 1,2,3 - mirrors with reflection coefficients \(r_1, r_2\) and \(r_3\), respectively. \(P_{1,2}\) - values of LD output power through facets 1,2 respectively ; \(P_3\) - power, coupled to SMF.

b) Device, equivalent to that in Fig. 2.5a: the ESEC LD can be viewed as a single-cavity LD with a compound (effective) mirror that has effective reflectance \((r_{\text{eff}})\) and transmittance \((t_{\text{eff}})\).
its lowest transverse mode output beam

\[ \rho_I = \frac{n_z z}{z_R} \]  

Here \( n_z \) is the effective refractive index of the external cavity medium and \( z_R \) denotes the Rayleigh range. Then the SEC laser will be characterized by \( \rho_I \gg 1 \), while for the ESEC laser \( \rho_I \sim 1 \). ESEC LDs can be clearly realized by butt-coupling a LD to a waveguide or a SMF (Figs. 2.3b and 2.5). Such a device would be characterized not only by its output \( P_3 \) (power coupled into the SMF, Fig. 2.5), but also by the variation of its operational characteristics due to feedback effects - in this case of laser-to-fiber coupling the origins of the feedback into the laser cavity are the Fresnel reflections from the front and rear end fiber facets as well as the backscattering within the fiber (Dandridge and Miles 1981). In the following Chapters we will examine the effects of variable feedback in this type of ESEC LD (that we realized by butt-coupling a LD to a SMF). Such optical feedback is controlled simply by varying the LD-to-SMF separation \( z \).

2.3 TRADITIONAL DESCRIPTIONS OF AN EFFECTIVE MIRROR

Passive external cavity devices can be rigorously analyzed by appropriately combining the effects of all external optical paths and cavities coupled to the end of the laser into a single complex effective Fresnel amplitude reflection coefficient, \( r_{\text{eff}}(z,\lambda) \), for that end of the laser: such mathematical condensation allows many of the basic formulae that describe the Fabry-Perot etalon to be used, Fig. 2.5b. This substitution is
valid for steady-state analysis, but might not be a basis for a model that can be used for the dynamic characterization of the compound cavity, since matching the boundary conditions requires well-established fields.

Butt-coupling of a LD with an antireflection-coated output facet ($|r_2|^2 \approx 4\%$; this is the case for a high-power laser diode) via a very short external cavity to a waveguide that is formed in a high-index material (e.g., KTP), is an example of a case in which optical feedback becomes important. In this case the ESEC LD compound mirror reflectance $r_{df}$ may differ significantly from $r_2$ (Fig. 2.5) for certain values of ESEC length $z$. Consequently, the effective modal coupling coefficient at the LD facet (mirror 2 in Fig. 2.5a) becomes a very important parameter that determines the device’s operational characteristics. Some authors have included the effect of multiple reflections in their analysis by assuming that the same amount of light power is coupled into the active region of the laser diode for each reflection from the external cavity (Seo et al. 1989), while others considered the power fed back to the LD cavity to be reduced monotonically as the number of reflections increases (Hui and Tao 1989). The effective modal coupling coefficient in the external mirror plane (mirror 3 in Fig. 2.5a) is not considered in the literature - probably for the reason that, in all practical cases that utilize the feedback from the external mirror, that mirror was intended to work in reflection only, such that the useful LD power output was collected through the opposite mirror of the LD (Fig 2.4).
One practical way that has been exploited to simplify the effective mirror description is a linear wave scattering formalism (Haus 1984). This approach considers optical beams with diameters large compared to the wavelength and thus approximates field distributions by plane waves. Also, diffraction effects are not accounted for over propagation distances less than $\pi w^2/\lambda$. If these approximations are not valid, one must consider the efficiency of intermodal coupling. That is, a modal overlap integral approach should be applied. The basic assumption made in both the scattering matrix and overlap integral approaches is that the guided modes of the laser cavity are smoothly matched to the eigenmodes of the external cavity.

The scattering formalism and overlap integral approaches are described below. The Fresnel coefficients are defined according to Macleod (1986).

2.3.1 Scattering Matrix Formalism.

We follow the formalism of Haus (1984). At some reference plane, in general, there are (due to scattering) both incident and reflected light waves. If we characterize the incident waves (inputs) by normalized amplitudes $a_i$, and the reflected waves (outputs) by normalized amplitudes $b_i$, where the $i$'s refer to the reference plane (port) in question, then the net power flowing into the port is (see Fig. 2.6)

$$P_i = a_ia_i^* - b_ib_i^*$$

Normalization is required to make the definitions universal for different impedances. If the outputs are linearly related to the inputs, a matrix formalism can be developed to
express the outputs as weighted combinations of the inputs. For example, for a two-port junction such as a partially transmissive mirror, we have

\[
\begin{bmatrix}
  b_1 \\
  b_2
\end{bmatrix} = \begin{bmatrix}
  S_{11} & S_{12} \\
  S_{21} & S_{22}
\end{bmatrix} \begin{bmatrix}
  a_1 \\
  a_2
\end{bmatrix},
\]

(2.7)

Fig. 2.6: Generic scattering junction illustrating the inputs and outputs for various ports.

where the $S_{ij}$ are called the \textit{scattering coefficients} and matrix $[S]$ thus becomes the \textit{scattering matrix}. The scattering coefficients have direct physical significance: they represent the ratio of a normalized output amplitude to a normalized input amplitude. The squared magnitudes of the scattering coefficients $|S_{ij}|^2$ denote the fraction of power appearing at the port $i$ due to the power entering port $j$. The diagonal terms of the matrix are the respective complex amplitude coefficients. The off-diagonal elements stand for the complex output at one port due to the input at another - in other words, transfer functions. For the general external cavity configuration shown in Fig. 2.4 such a linear
wave scattering formalism would result in the explicit expression for the effective amplitude reflection coefficient (Coldren and Koch 1984b),

$$r_{\text{eff}}(z,\lambda) = S_{11} + \frac{S_{12}S_{21}r_2^2}{1 - S_{12}r_2^2}$$  \hspace{1cm} (2.8)

where \( r_2 = S_{11} = -S_{22} \), \( r_3 \) and \( r_2 = S_{12} \) and \( r'_2 = S_{21} \) are the amplitude reflection and transmission coefficients at the corresponding dielectric boundaries, and \( \xi^2 = \exp(\alpha z - 2i\beta z) \) denotes the propagation phase accumulation and field amplitude losses for a round trip in the external cavity, including absorption, diffraction and mode re-excitation. The expression for the transmission coefficient would also require the knowledge of matrix \( S \) and the outcoupled medium mode re-excitation coefficient (Fig. 2.5).

In this approach the losses in the external cavity and those due to the laser cavity mode re-excitation, which influence the effective reflection and transmission coefficients, require proper evaluation, especially in the ESEC butt-coupling region \( z \sim z_R \). For example, Coldren and Koch (1984a) approximated the EC return amplitude level \( |r_2 \xi^2| \) from Gaussian diffraction in the far-field and stated that for small tilts of the external mirror this factor is reduced by a small constant independent of the EC length. However, as we demonstrate in Chapter 5, the outcoupling efficiency from the ESEC strongly depends on the angular misalignment and separation between the ESEC mirrors 2 and 3 (Fig. 2.5a).
2.3.2 Overlap Integral Approach.

A more accurate treatment of the passive EC would involve the consecutive evaluation of the fractional contributions to the reflectance/transmittance made by the laser field that is delayed by $p$-round trips within the external cavity and incident onto the laser mirror 2 in $-z$ direction or, respectively, onto the external mirror 3 in $+z$ direction. This direct evaluation is based on the **modal fields overlap integral** and takes multiple reflections within the EC into account. Thus, it provides a convenient alternative to the scattering matrix formalism. For example, an amplitude reflection coefficient for the compound output mirror (see Fig. 2.5b) is written as

$$r_{\text{eff}}(\lambda, z) = r_2 - \frac{1 - r_3^2}{r_2} \sum_{p=1}^{\infty} C_{LL,p} \{ -r_2 r_3 \exp(-i\Phi) \}^p$$

(2.9)

Here $C_{LL,p}$ is the field overlap integral taken at the LD output facet between the laser mode emanating from the laser diode with itself after $p$-round trips inside the external etalon of length $z$ and $\Phi = 2kz$. It can be easily verified that Eq. (2.8) is a special case of Eq.(2.9) under the assumption of a single reflection inside the EC ($p=1$) and $C_{LL,1} \exp(-i\Phi) = \xi^2$.

The practical difference in applying Eq. (2.9) versus Eq. (2.8) arises from the expressions chosen to represent the eigenfunctions of the external cavity. Kim and Hsieh (1992) calculated the complex coupling coefficient by applying the open resonator formalism developed by Vainstein (1963), based on a rigorous theory of diffraction at the open end of the resonator. Regarding an external cavity as an unfolded open resonator...
with rectangular mirrors, eigenmodes of the LD waveguide structure are expressed as products of complex cosine distributions in orthogonal directions. The frequency of the oscillations in general is not equal to the resonator frequency: \( k \Delta z = \pi (m/2 + q) \), where \( m \) is a large integer and \( q \) is a small correction within a range \( |q| < 0.5 \) (Vainstein 1963).

The correction term \( q = q' + iq'' \) results in an additional phase shift of the eigenmode in the round-trip propagation time, as well as the fractional decrease of the energy of the eigenmode. The overlap integral for the \( n \)th round-trip is a complex function of separation distance \( z \) and the near-field beam size and was calculated analytically using complex cosine eigenfunctions. For long “open resonators” \( (z \to \infty) \) this approach was pointed out to pose some problems because the amplitude of \( C_{LL,p} \) does not decay to zero. That is, as \( z \to \infty \) we would expect zero feedback to the laser diode.

Voumard et al. (1977) also treated an EC as an open resonator. However, in this case the field amplitude coupling coefficients were approximated.

2.4 NOVEL BUTT-COUPLING MODEL EMPLOYING AN EFFECTIVE MIRROR

The butt-coupling model (BCM) that we use to analyze the ESEC was first discussed by Karioja and Howe (1996). It was subsequently enhanced (Sidorin and Howe 1997a) to explain the results of coupling experiments in the near field. This model is based on the Gaussian mode overlap integral and is neither restricted in the external
cavity length, nor in the feedback levels, and it takes coherence properties of the external reflections into account.

2.4.1 Concept of an Effective Mirror in the Model.

Following Kogelnik (1964) and Joyce and DeLoach (1984), a small angular misalignment is introduced into the model by an addition of a tilt phase angle into the Gaussian field. In accordance with Hall et al. (1979), a transverse misalignment is handled by a transverse off-set of the Gaussian field. Building on this, we also account for LD astigmatism by introducing a longitudinal off-set into the transverse component of the Gaussian field that is normal to pn-junction plane of the LD. The placement of an arbitrary (matching) refractive index material into the external cavity as well as the placement of a potting material around the laser is also handled by the model.

- Due to the Gaussian approximation of the LD eigenmode (see Appendix A), the model allows us to analytically calculate the effective Fresnel amplitude reflection coefficient for the compound mirror \( r_{\text{ef}}(\lambda, z) \), Fig. 2.5b and Eq. (2.9), and forms a basis for the modeling of feedback effects on the operational performance of the laser diode (see Chapter 4).

- Using a reasonable approximation of the eigenmodes of the outcoupled medium to the right of the compound mirror (Fig. 2.5a; in our case - fiber eigenmodes, see Appendix A) the effective Fresnel amplitude transmission coefficient for that mirror
\( \tau_{\text{eff}}(\lambda, z) \) is also obtained in closed form. This forms a foundation for the evaluation of the direct end-coupling efficiency into the waveguide or fiber (see Chapter 3).

- The amplitude reflection (transmission) coefficients for the linearly-polarized mode at the small angles of incidence \( \theta \sim 1^\circ \) are approximated by those for a linearly-polarized plane wave at normal incidence. This is undoubtedly justified within the butt-coupling region \( z \sim z_R \), where the wavefront remains essentially plane.

In the enhanced butt-coupling model we consider \( C_{12} \) - the coupling coefficient, or overlap, integral between modes 1 and 2 - to be a complex quantity of the form:

\[
C_{12} = \gamma \cdot \exp(-i\Delta)
\]

(2.10)

where \( \gamma \) is an overlap integral amplitude and \( \exp(-i\Delta) \) is its phase-modification factor. With no misalignments between the LD and the SMF, parameters \( \gamma \) and \( \Delta \) depend on the length of the external cavity and the LD and SMF modal waist sizes.

We re-write Eq. (A.1.3) for the normalized Gaussian mode of the LD that propagates in the \( z \)-direction with a tilt, \( \theta \), and a transverse off-set, \( \delta \), with respect to a chosen \( z \)-axis, and include possible LD-astigmatism, \( \varepsilon_z \):

\[
\Psi(x, z) = A_X(z) \cdot \exp\left\{ -\frac{(x - \delta_X)^2}{w_X^2(z + \varepsilon_z)} \right\} \exp\left\{ -ik \frac{(x - \delta_X)^2}{2R_X(z + \varepsilon_z)} \right\} \times
\]

\[
\times \exp\{ i k \Theta_X \cdot (x - \delta_X) \} \exp\{ -i[k \cdot (z + \varepsilon_z) - \varphi(z + \varepsilon_z)] \}
\]

(2.11)
where \( A_X(z) = \left(\frac{2}{\pi}\right)^{\frac{1}{4}} \cdot w_x^{-\frac{1}{2}}(z + \varepsilon_z) \) is the amplitude, \( k = \frac{2\pi n}{\lambda} \) is the wavenumber, \( w_x(z) \) is the beam spot size in the \( z \)-plane, and \( R_x(z) \) is the wavefront radius in the same plane. An expression for the field along the \( y \)-direction (perpendicular to \( x \)) is obtained by replacing \( x \) with \( y \) everywhere in (2.11) and setting \( \varepsilon_z = 0 \).

The field coupling coefficient \( c_{12}(x,z) \) between modes \( \Psi_1(x,z) \) and \( \Psi_2(x,z) \) in any \( z \)-plane is given by (A.3.6) with a similar expression for the coupling in \( y \)-direction. The evaluation of the field coupling coefficients for the Gaussian fields is greatly simplified by using the relation

\[
\int_{-\infty}^{\infty} \exp(-ax^2 - 2bx - c) \, dx = (\pi/a)^{1/2} \exp(b^2/a - c) \quad (2.12)
\]

(Abramowitz and Stegun 1965) that gives rise to

\[
c_{12}(x,z) = \left(\frac{2}{w_{1,x}(z)w_{2,x}(z)}\right)^{1/2} \left(\frac{1}{a}\right)^{1/2} \cdot \exp(b^2/a - c) \quad (2.13)
\]

where

\[
a = (w_{1,x}^{-2}(z) + w_{2,x}^{-2}(z)) + ik(R_{1,x}^{-1}(z) - R_{2,x}^{-1}(z))/2;
\]

\[
b = -\delta_x / w_{2,x}^2(z) + ik(\delta_x / R_{2,x}(z) + \Theta_x) / 2;
\]

\[
c = (\delta_x / w_{2,x}(z))^2 - ik(\delta_x^2 / R_{2,x}(z) + 2\Theta_x \delta_x) / 2.
\]

The total coupling coefficient for the fields is calculated then as a product of two directional coefficients \( c_{12}(x,z) \) and \( c_{12}(y,z) \) according to (A.3.5).

Now it is easy to compute the optical parameters of the external cavity formed by the laser and fiber facets. The effective Fresnel amplitude reflection coefficient of this
etalon, \( r_{\text{eff}} \), is calculated according to (2.9). The effective power reflection coefficient of the compound output mirror is obtained by squaring \( r_{\text{eff}} \). If \( |C_{LL,p}| \) were used in (2.9) instead of the complex quantity \( C_{LL,p} \), then the information about the additional phase change upon reflection from the etalon, which is discussed in Chapter 3, would be lost.

Similarly, the following can be obtained for the effective power transmission coefficient, which describes the total laser power coupled into the SMF eigenmode:

\[
T_{\text{eff}} = t_{\text{eff}} t_{\text{eff}}^* = \left\{ \sqrt{(1 - r_2^2)(1 - r_3^2)} \sum_{l=1}^{\infty} C_{LF,l} [-r_2 r_3 \exp(-i2kz)] \right\} \times \text{c.c.} \quad (2.14)
\]

where \( C_{LF,l} \) is the Gaussian beam overlap integral of the SMF-field and the LD-field that has traversed the separation, \( z \), between the LD and the SMF an odd number of times \( l \). This integral is calculated in the plane of the SMF facet (see discussion in Appendix B).

### 2.4.2 Phenomenological Description of the Laser Diode.

In our linear analysis we are concerned only with LDs having slightly doped (or undoped) active regions - thus we simplify our model of the gain mechanism by considering only the electron density \( N \). We start with the general singlemode rate equations for the carrier density \( N \) and the photon density \( N_{\text{ph}} \):

\[
\frac{dN}{dt} = \frac{I}{qV} \frac{N}{\tau_{sp}} - v_{pr} g N_{\text{ph}}
\]

\[
\frac{dN_{\text{ph}}}{dt} = \Gamma v_{pr} g N_{\text{ph}} + \Gamma \frac{\gamma_{sp}}{\tau_{sp}} N - \frac{N_{\text{ph}}}{\tau_{ph}}
\]
where $\eta_i$ is the internal quantum efficiency, $I = I(t)$ is the pumping current, $q$ is electronic charge, $v_g$ is the group velocity of light, $g$ is the modal gain, $\Gamma \approx 0.5$ is a confinement factor, $\tau_{sp}$ is the spontaneous emission lifetime $\sim 3 \cdot 10^{-9}$ s, $\gamma_{sp}$ is the spontaneous emission factor $\sim 10^{-4}$ and $\tau_{ph}$ is the photon lifetime. It can be shown that the steady-state total output power of the LD that is directly end-coupled into the ESEC (Fig. 2.5a) is given by

$$P_{int,E} = P_1 + P_2 = \frac{I - I_{thr,E}}{q} \eta_d \hbar \nu$$

(2.15)

where subscript ‘E’ denotes the presence of the ESEC, $\eta_d$ is the differential quantum efficiency of the LD (assumed unaffected by the feedback), $q$ is the elementary charge, $\hbar$ is Plank’s constant, $I$ is the drive current and the threshold current (Kressel 1988) is expressed as

$$I_{thr,E} = C_{thr} \left\{ \alpha_{int} d + \ln \left[ \left( R_1 R_{eff} \right)^{1/2} \right] \right\}$$

(2.16)

Here $\alpha_{int}$, being the internal loss rate, includes scattering losses, $d$ is the LD’s cavity length and $C_{thr}$ is a geometric factor depending on the active layer parameters, cavity length and the internal quantum efficiency of the LD. Eq.(2.16) implies a linear dependence between threshold current and total loss, which is a reasonable assumption for GaAs-based LDs that exhibit negligible nonradiative recombination. (For long wavelength lasers, $\lambda \sim 1.3 - 1.6 \mu m$, the addition of an Auger recombination term would be required to produce the correct relationship.)

The threshold gain condition in the presence of the ESEC is written as

$$\Gamma_{g_{thr,E}}(z, \lambda) = \alpha_{int} + \alpha_{rad} = \alpha_{int} - \ln[r_{eff} (z, \lambda)] / d$$

(2.17a)
where $\Gamma$ is the confinement factor, $\beta$ is the propagation constant and $\phi_{\text{eff}}$ is the phase of the effective reflection coefficient given by (2.9). In our analysis we neglect the slight mode pulling introduced by the presence of the ESEC, as seen from the threshold condition on phase (2.17b) and discussed in Sec. 3.1. Eq. (2.16) gives only the cavity loss parameters necessary to calculate the threshold gain. To estimate the material gain spectral distribution, we used the approach developed in Appendix C.

2.4.3 Validity of Butt-Coupling Model.

Having outlined the model, we need to emphasize the following.

- The model is only valid for the LD in a steady-state regime. This requirement is imposed by the necessity to match boundary conditions for EM-fields through the use of Fresnel coefficients. Thus analysis of the dynamic performance of the LD might be restricted to time scales that are much greater than the round trip propagation time within the compound cavity: $t \gg c/(n_d d + n_z z)$.

- The model is valid only above the threshold (Eq. 2.15). As a result, it might break down at the point $z=0$. Indeed, for the symmetric external cavity ($r_2 = r_1$), for example, $r_{\text{eff}}(z = 0, \lambda) = 0$ and there is no lasing; thus our mathematical results do not have any physical significance at the point $z=0$. 

\[ 2\beta d - \phi_{\text{eff}} = 2\pi m \]  
\[ (2.17b) \]
In the approach used here, the coupled-cavity aspects of the problem are contained entirely in the wavelength-dependent threshold gain (Eq. 2.17a). This oversimplifies the problem, since the system behavior is then governed by single values for the average photon density and current density, when in fact these quantities have different values in the two cavities (LD cavity and ESEC). Having made the assumption that the ESEC can be treated as a linear effective mirror, we require that once the system is above the threshold the light level in the ESEC is too low to saturate any gain in the ESEC. Thus an "effective mirror" treatment should be valid provided that the ESEC is not too close to its own threshold. But this is completely realized since the ESEC considered is passive (no gain). Another assumption imposed by the use of single-cavity rate equations in the butt-coupling model is that the current (carrier) and loss distributions are considered to be uniform throughout the whole system.

2.5 EXPERIMENTAL TECHNIQUE

For the experimental investigation of coupling and feedback effects we realized an ESEC LD via butt-coupling a high-power LD (HPLD) into a SMF, Figs. 2.5. The parameters of our experimental system are presented in Table 2.1.

Optical feedback is provided by a single-mode fiber (SMF) that is directly end-coupled to a AlGaAs Fabry-Perot high-power laser diode (SDL 5400C/5410C). Optical feedback is varied by precise positioning of the cleaved front fiber facet relative to the
HPLD. The SMF is mounted on tilting and rotating stages that are attached to a nanopositioning XYZ-translator. Reflections from the back end of the fiber are eliminated by angle-cleaving. (It should be noted that feedback from the far end of our

![Diagram of experimental setup](image)

**Fig. 2.7:** *Experimental setup: direct end-coupling of high-power laser diode (HPLD) into a single-mode fiber (SMF). PC: personal computer.*

SMF, which is ~1m long, would contribute to the LD operation *incoherently* under most circumstances.) The formed external cavity serves as an output coupler for the butt-coupled HPLD and is characterized by the effective coefficients, \( r_{\text{eff}} \) and \( t_{\text{eff}} \) (Eqs. 2.9 and
2.14). The coupling coefficient $C_{ll,p}$, that will be discussed in Section 3.1, acts as a complex-valued attenuation factor that adjust the proportion of each etalon partial wave that is spatially coupled back to the HPLD cavity. A thermoelectric cooler maintained the laser package at a constant temperature. The diode drive current is also kept constant during the experiment. The laser spectrum is observed directly using an optical spectrum analyzer (HP70950A) with a resolution of 0.08 nm. The corresponding variations of output power are monitored with a photodiode. The initial adjustments consist of transverse, angular and longitudinal alignment of the fiber with respect to the HPLD by maximizing the power coupled into the fiber.
Reflectance coefficients:

- $R_1 = r_1^2$
- $R_2 = r_2^2$
- $R_3 = r_3^2$

R, = r,^ 95%
R^, = r^, 4%
R, = r,^ 4%

Refractive indices:
- LD’s active layer $n_D$ 3.6
- medium in EC $n_z$ 1

LD cavity length $d$ 750 $\mu m$

Wavelength (solitary regime) $\lambda_0$ ~845 nm

Modal waists (Gaussian approximation):
- LD mode, parallel to pn-junction $w_{0,LR}$ 1.7 $\mu m$
  normal to pn-junction $w_{0,LR}$ 0.7 $\mu m$
- SMF mode $w_{0,F}$ 2.55 $\mu m$

Transverse and longitudinal misalignment increments $\Delta x, \Delta y, \Delta z$ ~20 nm

Angular misalignment increment $\Delta \theta_{x,y}$ $\leq 0.01 \text{rad}$

LD internal loss $\alpha_{\text{int}}$ 2 cm$^{-1}$

Slope of PI-characteristic $0.99 \text{ W/A}$

Threshold Current $I_{\text{thr}}$ 25 mA

Driving Current $I$ 75 mA

Table 2.1: Parameters of components used for modeling and experiments (unless noted otherwise), measured or specified by the LD manufacturer (SDL, Inc.)
CHAPTER 3.

ANALYSIS OF LASER DIODE-TO-FIBER BUTT-COUPLING

In this Chapter we discuss several aspects of LD-to-SMF direct end-coupling. The discussion is facilitated by using the effective (compound) mirror that was introduced in Chapter 2 as a way to characterize direct end-coupling:

(1) The complex nature of the field overlap integral is emphasized. Its phase factor (Sec. 3.1), which is traditionally neglected due to concern with power coupling efficiency, affects the power coupling at extremely short separations of the coupled elements. This is confirmed by our experiments (Sec. 3.3.3).

(2) Both the reflectance and transmittance of the compound mirror formed by the LD output and SMF input facets are considered in our representation of butt-coupled LD and SMF as an ESEC LD (Sec. 3.1). In all external cavity LD designs reported to date, the external mirror is used only as a reflector.

(3) LD-to-SMF butt-coupling cannot be viewed as an imaging process; hence coupling into SMF and feedback to the LD-cavity are not complementary due to the fact that the overlap of modes that occur at the LD facet and SMF facet is quite different (Sec. 3.1).
(4) Finally, due to the modulation of feedback that results when the ESEC length $z$ is varied, the threshold current for the ESEC LD is deeply modulated versus $z$. This effect has not been previously considered in the technical literature.

3.1 EXTREMELY-SHORT EXTERNAL CAVITY CHARACTERIZATION

The variation of the amplitude, $\gamma_p$, and phase, $\Delta_p$, of the overlap integral $C_{LL,p}$ (Eqs. 2.9 and 2.10) versus the length of the external cavity that is formed when the LD and SMF described in Table 2.1 are butt-coupled is illustrated in Fig. 3.1 for the case of zero misalignments and $p=1$. At very small values of $z$ the amplitude parameter $\gamma_1$, approaches unity while the phase, $\Delta_1$, approaches zero so that $|C_{LL,1}|$ approaches unity, which should be expected (we obtain the maximum coupling efficiency in this case). On the other hand, both parameters approach zero in the limit of large separation between the laser diode and the fiber (for practical purposes butt-coupling efficiency is negligible when $z \geq 10^3 \mu m$). This corresponds to the zero butt-coupling efficiency in the limit $z \to \infty$. Thus, our butt-coupling model exhibits an obvious advantage over the open-resonator approach (Kim and Hsieh 1992), which does not adequately describe the coupling efficiency in the limit of large $z$.

The complex nature of the overlap integral ($\Delta \neq 0$) affects not only the power coupling in the near-field (Sec. 3.3.3); its crucial influence on the ESEC LD operational
characteristics can also be understood from the following argument. Following the idea of Osmundsen and Gade (1983), we introduce the complex feedback parameter:

\[ \zeta \equiv \frac{r_2}{r_{\text{eff}}} = \zeta_0 \exp(i\phi_\zeta) \tag{3.1} \]

Then the steady-state threshold condition for the compound cavity laser diode, Eq. (2.17a), can be re-written as

\[ \exp[(g-\alpha)d] = \frac{\exp(i\phi_d)}{r_1r_2}\zeta \tag{3.2} \]

where \( \phi_d = \omega c/2n_d d \) is the solitary laser cavity round trip phase accumulation, \( c \) is the speed of light in the vacuum and \( \omega \) is the lasing frequency. Eqs. 3.1 and 3.2 clearly explain the physical meaning of the feedback parameter \( \zeta \): \( \ln \zeta_0 \) represents the additional gain required for the compound cavity laser to oscillate in a given mode under feedback while its phase \( \phi_\zeta \) denotes the spectrum shift relative to the case of the zero feedback.

This amount of this mode pulling, caused by the presence of the effective compound mirror, is indicated by the phase angle of \( r_{\text{eff}}(\lambda) \) in the polar plot inset of Fig. 3.2. This Figure demonstrates the variation of the compound mirror reflectance, calculated at \( \lambda = 845\,\text{nm} \) according to Eq. (2.9) for a symmetric ESEC having length \( z \leq 15\mu m \). The reflectance exhibits an oscillatory behavior with a periodicity of \( \lambda/2 \) between two adjacent extrema. The maxima of \( R_{\text{eff}}(\lambda) \) occur at anti-resonances of the external etalon.
Fig. 3.1: Behavior of the coupling coefficient (overlap integral) $C_{LL,\lambda}$ between LD modes at the entrance mirror of the ESEC (mirror 2 in Fig. 2.5a), compared for the case of $\Delta_{1} = 0$ (real $C_{LL,\lambda}$) and $\Delta_{1} \neq 0$ (complex $C_{LL,\lambda}$). Phase is presented in units of $\pi$. Coupling parameters: single reflection, zero misalignments. The Rayleigh range ($z \leq 10\mu m$) is clearly seen to be the region in which there is significant difference in the real and complex forms of the overlap integral.

(i.e., compound mirror). The exponential decay of the maximum feedback strength due to the change in the complex overlap integral $C_{LL,p}$ can be observed from the envelope of $R_{ef}(\lambda)$.
Fig. 3.2: Effective reflectance \( R_{\text{eff}} = |r_{\text{eff}}|^2 \) of the compound mirror of the ESEC LD versus \( z \), calculated for \( R_1 = 0.95, R_2 = R_3 = 0.04, n_z = 1 \). The corresponding polar plot for \( r_{\text{eff}} \) is shown in the inset. The counter-clockwise direction of the locus of \( r_{\text{eff}} \), versus increasing \( z \), is indicated with an arrow.

Using Eqs. (2.9, 2.10) and setting \( p = l \) (single reflection within the ESEC) and \( \cos(\Phi + \Delta_l) = \pm 1 \), we obtain approximate expressions for the envelope of the extrema of \( R_{\text{eff}}(\lambda, z) \):

\[
R_{\text{eff}}^* (\lambda, z) = \left[ \sqrt{R_2} \pm \sqrt{R_3 (1 - R_3)} \cdot \gamma_1 (\lambda, z) \right]^2
\]  

(3.3)
Two points, $z = 0$ and $z = \infty$, characterize the extrema of the external cavity configuration and correspond to $R_{\text{eff}} = 0$ (for symmetric ESEC, see Sec. 2.4.3) and $R_{\text{eff}} = R_2$ (no feedback).

The transmittance of the ESEC is a functional characteristic that is novel to our analysis of SEC LDs - it characterizes the coupling into the eigenmode of the medium outside the external mirror 3 in Fig. (2.5a), i.e. the coupling into the SMF-mode (Eq. 2.14). Because of the losses that are quantified by the partial modal coupling coefficients $C_{\text{L}L_p}$ and $C_{\text{L}F_I}$, the power reflection and power transmission coefficients of the compound mirror do not sum to unity (Fig. 3.3).

![Graph showing the effective transmittance of a compound mirror](image)

**Fig. 3.3:** Effective transmittance of the compound mirror due to butt-coupling LD into SMF (see Table 2.1 for configuration parameters). $T_{\text{eff}}$ and $R_{\text{eff}}$ do not sum up to unity due to the internal loss on coupling.
3.2 THRESHOLD CONDITION AND THRESHOLD CURRENT IN STEADY-STATE

Starting with the requirement on round-trip propagation for single-mode oscillation and expressing the effective reflection coefficient of the compound mirror (Eq. 2.9) as

\[ r_{\text{eff}} = |r_{\text{eff}}| \exp(i \phi_{\text{eff}}), \]

we easily arrive at the threshold magnitude and phase equations (2.17a) and (2.17b), respectively. The explicit wavelength dependence of the threshold gain is discussed below. It can be seen from the phase condition again that the oscillation frequency is "pulled" by the presence of the compound mirror (Fig. 3.2, inset). Eq. (2.17a) clearly indicates that the modulation of the compound mirror's effective reflection coefficient results in a modulation of the amplitude threshold condition through the modulation of the radiation loss. This, in turn, sets the corresponding threshold carrier densities and threshold current. (The variation of the radiation loss, corresponding to an ESEC length change of \( \lambda/2 \) for different initial values of \( z \) is discussed later in Sec. 4.1.2, where we treat the spectrum of the ESEC LD).

The threshold current \( I_{\text{thr}} \) of a semiconductor laser is proportional to the volume of the active region \( V \) and the recombination rate \( R(n_{\text{thr}}) \), which in turn is a nonlinear function of the carrier density at threshold \( n_{\text{thr}} \):

\[ I_{\text{thr}} = qVR(n_{\text{thr}}) = qV\left(A n_{\text{thr}} + Bn_{\text{thr}}^2 + Cn_{\text{thr}}^3\right), \]

where \( q \) is the electronic charge. In the above expression the small contribution of stimulated emission to \( I_{\text{thr}} \) was omitted, as well as any possible leakage current.
Coefficients $A$ and $C$ describe non-radiative recombination due to traps, or surface states, and the Auger process, respectively. $B$ is the radiative recombination coefficient. In our model we neglect non-radiative recombination, as was mentioned in Sec. 2.4.2. Assuming a linear relationship between the gain and carrier density, we arrive at Eq. 2.16 for threshold current. Using an idea presented by Olsson and Dutta (1984) useful to normalize the threshold current variation due to the feedback from the ESEC, we indirectly evaluate the external feedback via an expression

$$\frac{I_{\text{thr},E}}{I_{\text{thr},0}} = \frac{2d\alpha_{\text{int}} - \ln\left(R_1 R_{\text{eff}}\right)}{2d\alpha_{\text{int}} - \ln\left(R_1 R_2\right)}$$

(3.5)

where the subindex '0' refers to the absence of the ESEC (i.e., a solitary LD). Rewriting Eq.(3.5), we find that

$$R_{\text{eff}} = \exp\left\{\left(\frac{I_{\text{thr},E}}{I_{\text{thr},0}} - 1\right)(\ln R_1 - 2d\alpha_{\text{int}}) + \frac{I_{\text{thr},E}}{I_{\text{thr},0}} \ln R_2\right\}.$$  

(3.6)

Substituting from Eq. (3.6) into Eq. (3.1) we estimate the feedback parameter $\zeta$ and thus the strength of the feedback to the lasing mode. This method of estimating the feedback strength is useful, especially under the condition of extremely-short butt-coupling separation distances, which cause $I_{\text{thr},E}$ to be significantly changed versus $I_{\text{thr},0}$, as described below. We suggest another advantage of the normalization expressed as Eq. (3.5): since the active region volume of the LD often is not known precisely, it allows us to compare how different types of ESEC LDs are affected by the coherent external feedback that obtains in an ESEC LD or SEC LD configuration.
An analysis of how the threshold current depends on the composition of the LD was previously reported (Temkin et al. 1986, Sigg 1993). It was found that the thickness of the LD active layer could be estimated from the relation between this thickness and the confinement factor, Γ, given by Botez (1981). We are not concerned with composition analysis in our work. Instead, we would like to emphasize that the distinguishing feature of the ESEC configuration is that the threshold current undergoes deep modulation (~several tens of percent) around the value of $I_{\text{thr},0}$ as the length of ESEC is varied. For comparison, in previous analyses (Kuwahara 1980a, Kuwahara et al. 1980b, Sigg 1993) the reported changes in threshold current typically did not exceed several percent and no deep modulation was observed, because no periodic variation of feedback was provided experimentally. Fig. 3.4 shows the computed and experimentally measured dependence of $I_{\text{thr},E}$ on external cavity length $z$ for the ESEC LD specified in Table 2.1. The threshold was experimentally defined at the point at which lasing started, as monitored with an optical spectrum analyzer. Good agreement between the calculated and experimental data is obtained for coherent feedback. In the limit $z \to \infty$, modulation of $I_{\text{thr},E}$ versus $z$ asymptotically decreases and $I_{\text{thr},E} \to I_{\text{thr},0}$, as should be expected. In addition to the indirect evaluation of the feedback strength (Eq. 3.6), the threshold current modulation results in significant spectral selection in the ESEC LD output. These considerations, together with the significant depth of $I_{\text{thr},E}$ modulation, lead us to the conclusion that in an analytical development based on threshold condition we must not
neglect the emission wavelength shift, as was done by Kawano et al. (1986) and Sigg (1993). That is the reason for including the explicit wavelength dependence in Eq. (2.17).

![Fig. 3.4: Normalized threshold current variation versus external cavity length, simulated by the butt-coupling model. Circles in the inset represent experimental data. See Table 2.1 for parameters used.](image)

### 3.3 OUTPUT POWER AND COUPLED POWER IN STEADY-STATE.

In estimating the ESEC LD output power according to (2.15) the variation of the emission wavelength (Chap. 4) is disregarded, since we are concerned only with the total power coupled into the SMF.
3.3.1 Differential Quantum Efficiency and Alignment of the ESEC.

To perform the power output calculations, we first must estimate the differential and internal quantum efficiencies, \( \eta_d \) and \( \eta_{\text{int}} \), respectively, based on the parameters of the LD in the solitary regime:

\[
\eta_d = \frac{q}{h\nu} \frac{dP_{\text{int}}}{dl} = \frac{q}{h\nu} \frac{dP_1}{dl} + \frac{q}{h\nu} \frac{dP_2}{dl} = \eta_{d1} + \eta_{d2}
\]

(3.7)

and

\[
\eta_{\text{int}} = \eta_d \frac{\alpha_{\text{int}} + \alpha_{\text{rad}}}{\alpha_{\text{rad}}}
\]

(3.8)

where

\[
\rho_p = \frac{P_1}{P_2} = \frac{R_2}{R_1} \frac{1 - R_1}{1 - R_2}
\]

(3.9)

is the ratio of the solitary LD outputs through mirrors 1 and 2 (Ettenberg et al. 1971), see Fig. 2.5a, \( \frac{dP_{1,2}}{dl} \) are the slopes of the PI-characteristics for the outputs through mirrors 1 and 2 respectively and \( \alpha_{\text{rad}} = -\frac{1}{d} \ln(r_1r_2) \) is the radiation loss of the LD oscillation cavity. Defining \( \eta_{\text{int}} \) as the fraction of injected carriers that recombine radiatively within the active region and assuming that it is not modified by the external feedback, we can see that \( \eta_d \) undergoes modulation versus external cavity length in the presence of the external feedback due to the influence of the variable reflectance of the external Fabry-
Perot etalon on $\alpha_{rd}$. This modulation directly results in the variation of the partial differential quantum efficiencies

$$\eta_{d1} = \frac{\rho}{\rho + 1} \eta_d, \quad \eta_{d2} = \frac{1}{\rho + 1} \eta_d,$$

(3.10)

and the corresponding PI-characteristic slopes ($dP_1/dI$ and $dP_2/dI$). The variation of these PI-slopes offers an interesting way of characterizing the feedback strength and, therefore, the longitudinal alignment of (i.e., length of) the external cavity within increments of $\lambda/4$. Indeed, in unison with the compound mirror reflectance, values of $\eta_{d1}$ and $\eta_{d2}$ are maximized when separation $z \rightarrow (2m + 1)\lambda/4$, and minimized when $z \rightarrow 2m\lambda/4$ (for constant driving current, temperature and misalignment). The realization of the alignment technique requires, however, two power readings at different drive current values for each length value $z$. Another possible difficulty would be due to the strong asymmetry of the LD cavity ($R_1/R_2 \sim 19$, Table 2.1) design used with high-output-power LDs. This would decrease the sensitivity of the proposed alignment technique when power readings are performed via the output from mirror 1 (Fig. 2.5a), since in this case $P_1 \ll P_2$.

### 3.3.2 Hysteresis of PI-Curve

The PI-curve measured for the ESEC LD (Table 2.1) shows hysteresis. In addition, the output power exhibits undulations, as depicted in Fig. 3.5, at a fixed LD-to-SMF distance when the dc-driving current is changed, depending on the direction of current scan. This
situation was earlier observed by Lang and Kobayashi (1980) for an external cavity LD configuration such as that shown in Fig. 2.4 which used a highly reflective external mirror and long external cavity (~ 1cm). They explained such behavior as resulting from multi-stable external cavity LD operation. The proposed physical mechanism included the variation of cavity optical path length, which is caused by the refractive index variation due to the active region temperature change with current. As can be seen from Fig. 3.5, threshold current in this particular case is reduced in the presence of ESEC relative to the solitary LD value of 25 mA (Table 2.1), which indicates strong feedback and a LD-to-SMF separation $z \sim (2m+1)\lambda/4$. This hysteresis phenomenon strongly

![Graph](image)

**Fig.3.5:** Hysteresis is observed in the $P-I$-curve of a LD that is coupled to a SMF at $z=$const. The average slope is reduced compared to that for the solitary LD (Table 2.1) due to the presence of the ESEC. The reduced threshold current indicates strong feedback ($R_{eff} > R_2$).
depends on the feedback level and is easily destroyed by slightly varying the ESEC length \( z \).

### 3.3.3 Coupling in the Near Field.

The measured power coupled to the SMF was compared with predictions based on the butt-coupling model (Eqs. 2.14...2.16). The results are shown in Fig. 3.6 (a,b) for angular misalignments of ~10 and ~50 mrad, respectively. The computed variation of the coupled power as a function of separation, \( z \), exhibits similar-shaped fluctuations that occur at regular intervals, determined by half the emission wavelength as expected. We note that the variation of the measured coupled power shows a degree of repeatable asymmetry in the regions of maxima (see. Fig. 3.6a), which is well predicted by the model. This asymmetry is not caused by an angular misalignment of the LD and SMF facets, i.e., a Fabry-Perot etalon with mirrors that form a slight wedge, since the initial angular misalignment has already been included into the model, see Eq.(2.11). (The etalon wedge causes Fizeau fringes to occur in the intensity distributions at the laser and fiber facets (Kinosita 1953)). To demonstrate that this asymmetry is explained by the complex nature of the overlap integral, we compare the predictions of the butt-coupling model when both real and complex forms of the overlap integral are used (see Fig. 3.7).
Fig. 3.6: Butt-coupling model prediction (thick) and experimental data (thin) of power coupled to SMF for angular and transverse misalignments, respectively: a) ~10 mrad, ~20 nm; b) ~50 mrad, ~20 nm.
The asymmetry of the individual peaks of the theoretical curve are present when the complex form of the overlap integral is used, i.e., when \( \Delta_n \neq 0 \) in Eq.(2.10). We also note from Fig. 3.7 that another effect of the phase modification introduced with \( \Delta_n \) is the shift in the positions of the extrema of the coupled power curve relative to those obtained when the phase modification is neglected. Other calculated operational characteristics of the extremely-short external cavity LD, such as differential quantum efficiency and threshold current that were discussed earlier, also undergo similar shifts compared to the case when \( \Delta_n = 0 \). These shifts are not significant.

**Fig. 3.7:** Comparison of butt-coupling model predictions for real (\( \Delta_n = 0 \)) and complex (\( \Delta_n \neq 0 \)) coupling coefficients for \(-10 \text{ mrad angular and } \sim 20 \text{ nm transverse misalignments.} \)**
from the practical point of view, however, since they were not resolved experimentally.

It can be also seen from Fig. 3.6 that under small misalignments and within the range of $z \leq z_r$, the regular variation of the coupled power versus separation presents a distortion in the form of sharp spikes. This behavior can be understood from Fig. 3.8, which presents all characteristics of the ESEC LD discussed above versus ESEC reflectance. Spikes are caused by ESEC LD operation under conditions that cause a low-reflectance of the compound mirror ($R_{cf} < 2\%$) to be realized. When this occurs, the output power variation caused by changes of external cavity reflectance is extremely strong (Karioja and Howe 1996). The influence of the reflection coefficients of the LD output and SMF input facets and various misalignments on the power coupled to the SMF will be discussed in Chapter 5.
EC is "absent": \( R_{\text{eff}} = R_2 \)
\[ 2z = (2m+1)\lambda/4 \]

Fig. 3.8: Dependence of different parameters of the ESEC butt-coupled LD (see Table 2.1) on the effective reflectance of the compound mirror: power outputs through mirrors 1 and 2 (\( P_1 \) and \( P_2 \)); threshold current (\( I_{\text{th}} \)), power coupled into the SMF (\( P_3 \)) and differential quantum efficiency (\( \eta_2 \)).
CHAPTER 4.
SPECTRAL FEEDBACK EFFECTS.

In this Chapter we investigate two feedback effects that arise when a laser diode (LD) and a single-mode fiber (SMF) are directly end-coupled at extremely-short, but variable, separations. As mentioned in Chapter 2, this configuration comprises an extremely-short-external-cavity (ESEC) as "seen" by the LD. The origins of the feedback to the laser cavity are the Fresnel reflections from front and rear end fiber facets as well as backscattering within the fiber (Dandridge and Miles 1981). In our analysis we neglect the latter due to its small contribution (< 0.01%, Dandridge and Miles 1981) and short length of the fiber (~1 m) considered. Two major feedback effects that can be controlled by varying the ESEC length are: tuning of the operational wavelength of the ESEC LD and minimizing the relative intensity noise (RIN) of the output cw light beam. We shall limit our discussion of these effects to the steady-state.

The following points regarding spectral tuning and RIN will be made:

(1) Both effects considered are periodic with ESEC length due to modulation of the ESEC reflectance/transmittance with period \( z \approx \lambda_0 / 2 \) and the dynamic range of these modulations depends on the feedback strength;

(2) Tuning is characterized by either multi- or singlemode output spectra, depending on the feedback strength. The dynamic range of the available feedback is defined by the value of the overlap integral \( C_{LL,p} \) (Fig. 3.1) and it is controlled within this range by
varying the ESEC length $z$;

(3) the spectral output linewidth (relative to that of the solitary LD) will not be reduced by introduction of an ESEC, partly because this does not increase the photon lifetime and because it does not decouple LD resonant frequency from the refractive index variation;

(4) the wavelength tuning range is not constant, but depends nonlinearly on the ESEC length $z$;

(5) RIN in the case of singlemode tuning is lower than that for multimode tuning.

4.1 SPECTRAL TUNING

The quality of the direct end-coupling system cannot be evaluated in terms of coupling efficiency only. It is well known that optical feedback strongly influences the steady-state output power of the laser as well as its dynamic properties and emission spectrum (Salathe 1979, Lang 1980, Fleming and Mooradian 1981, Dandridge and Miles 1981, Lin et al. 1984, Cassidy 1984, Sidorin and Howe 1997a). Several attempts have been made to benefit from the feedback that occurs in a butt-coupling configuration (these will be discussed in Chap. 6). Coldren and Koch (1984a, 1984b, 1984c) used a simple scattering matrix formalism (see Chap. 2) to outline the design procedures for integrated multi-element semiconductor lasers. In the following Sections we apply the earlier developed butt-coupling model (Chap. 2) to characterize the optical feedback influence on ESEC LD spectral and noise properties in the steady-state. The effect of this
feedback on ESEC LD power characteristics was discussed in Chap. 3.

4.1.1 Wavelength Tuning Experiment

In this Section we describe the dependence of the butt-coupled LD’s output wavelength and modal structure on external cavity length (Sidorin and Howe 1997b).

The tuning procedure is quite straightforward (see Sec. 2.5). By adjusting the separation between the LD and the SMF one forces the lasing to hop to a neighboring longitudinal mode of the LD. This occurs while keeping the driving current and the temperature constant (to control the tuning within the LD’s intermodal separation in a quasi-continuous regime it would be necessary to vary the temperature and/or current). Depending on the initial length of the ESEC, two major types of wavelength tuning are observed when working with a simple Fabry-Perot high-power LD (Table 2.1).

Fig. 4.1 presents typical experimentally observed and calculated wavelength tuning curves for two different conditions. For relatively large separations between the LD and SMF (z ~ tens of μm) feedback is weak. In this case the external etalon’s reflectance maxima and the shape of the lasing medium’s gain spectrum collaborate to cause single-mode operation (Fig. 4.1b), provided that the local maximum of the external etalon’s reflectance versus frequency is sufficiently narrow. At shorter separations the
Fig. 4.1: Wavelength tuning in (a) multimode regime (initial separation $z \leq 10 \mu m$) and (b) singlemode regime (initial $z \approx 30...50 \mu m$): experiment (thick line) and modeling (thin line). The output spectra at several tuning points is shown in the insets. Scan increment $\Delta z = 60 \text{nm}$. 
Fig. 4.2: a) Singlemode wavelength tuning (experimental curve) with increased z-resolution of \( \Delta z \approx 40 \text{ nm} \). Corresponding spectra are shown in b). Multimode lasing occurs in the transition region 'f..j' of the tuning curve.
feedback conditions allow to simultaneous support several LD cavity modes and multimode operation occurs, that is, a packet of ~10 to 15 adjacent longitudinal modes is scanned across a significant range of more than 10 nm, Fig. 4.1a. The number of longitudinal modes that lase simultaneously in this case decreases with an increase of z. The ESEC LD output power, $P_3$, and wavelength variations versus $z$ are nearly synchronous since they are both related to the reflectance of the ESEC.

The vertical "transition regions" in both the multimode and singlemode tuning regimes correspond to simultaneous multimode lasing at both ends of the tuning range spectrum (Fig. 4.1b, point e, and Fig. 4.1a, point j). The output spectra at points a and f are analogous to those at points d and j, respectively. The error bars shown in Fig. 4.1 correspond to the standard deviation obtained as a result of multiple experiments. It should be pointed out that in the regime of multimode operation ($z \leq 15 \mu m$) this uncertainty is higher than that for single mode operation. The explanation stems from the fact that the change in longitudinal separation, necessary to switch the dominantly lasing mode of the laser cavity to the neighboring one, depends nonlinearly on $z$ (see Chapter 5). A clear visualization of the increased instability of the spectral behavior that occurs in the vertical “transition” regions of the wavelength tuning curve can be obtained by measuring the singlemode regime tuning curve with increased $z$-scan resolution. The result of that measurement is presented in Fig 4.2 (a,b). Here the region ‘f...i’ corresponds to multimode lasing and it occupies a significant part of the tuning range.
Fig. 4.2: Modulation of the radiation loss at the lasing threshold in extremely-short external cavity configuration. Zero transverse and angular misalignments are used for this simulation.

(a) initial separation $z_0 = 6\lambda$
(b) initial separation $z_0 = 60\lambda$
(c) spectral cross-sections, corresponding to $z_0 = 6\lambda$
(d) spectral cross-sections, corresponding to $z_0 = 60\lambda$

$A: z = z_0 \quad B: z = z_0 + 4\lambda/18 \quad C: z = z_0 + 7\lambda/18 \quad D: z = z_0 + \lambda/2$
The change from relatively smooth tuning (points 'a...f') to multimode-hopping (points 'g...j') is associated with the increased noise. This phenomenon is considered in Sec.4.3.

4.1.2 Discussion of Output Spectral Structure and Tuning Simulations

The physical mechanism responsible for the change in the structure of the ESEC LD’s output spectrum (from multimode to singlemode oscillations) due to the change in $z$ can be understood from the following two arguments.

a) As seen from a comparison of Figs. 4.3(a,c) and 4.3(b,d) the curvature of the minima of the spectral radiation loss distribution increases with increasing ESEC length. Correspondingly, the number of ESEC LD cavity modes contained within one loss period (Fig. 4.4), which is given by the ratio of optical lengths $n_d d/n_z z$ (Fig. 2.5), decreases with ESEC length. Thus the margin of loss from the strongest among the currently lasing modes $\lambda_i$ to the neighboring ones at $\lambda_{i\pm k}$ increases with $z$. This, together with the roll-off of the material gain spectrum $g(\lambda)$ provides the observed increase in the ratio $P_i/P_{i\pm k}$ of output powers in modes $i$ and $i \pm k$, Fig. 4.4. Our experimental observations are in excellent qualitative agreement with the coupled-cavity LD design predictions of Coldren and Koch (1984a) who specified that the margin loss (under the approximation of constant loss within the ESEC) for adjacent modes is maximized for small LD cavity length $d$ and large ESEC length $z$: $\Delta \alpha_{i,\pm 1} \sim z^2/d^3$. The gain envelope roll-off $\Delta g(\lambda)$, see Fig. 4.4, was also found to be maximized for minimum ESEC length: $\Delta g_{i,\pm 1} \sim z^{-2}$. 
Thus, we conclude that for single-mode operation (tuning) $z$ should be chosen as large as possible subject to maintaining sufficient $\Delta g(\lambda)$ under all anticipated conditions.

b) The change in the FWHM of the transmission peaks of the ESEC is another reason for the variation of the output spectrum (since the measured output spectral distribution applies to light coupled into the SMF upon transmission through the ESEC, Fig. 2.7). Indeed, the finesse $F$ of the Fabry-Perot etalon (that is comprised of identical mirrors $a$ and $b$, $r_a = r_b = r$, and that has optical length $n_z z$) is defined as the ratio of the etalon's free spectral range to the fringe halfwidth (Macleod 1986),

$$F = \frac{\Delta \lambda}{\delta \lambda_{\text{1/2}}} \approx \frac{\pi r}{(1 - r^2)}$$ (4.1)

Using the expression for the free spectral range, $\Delta \lambda = \lambda^2 \cos \theta / 2n_z z$ (where and $\theta$ is the angle of propagation of the light in the etalon relative to its optical axis), and assuming no loss and the paraxial plane wave propagation, we conclude that the FWHM of the ESEC transmission peaks is defined by

$$\delta \lambda_{\text{1/2}} \approx \frac{(1 - r_z^2) \lambda^2}{2 \pi r_z n_z} \frac{1}{z} \approx \frac{1}{z},$$ (4.2)

which partly explains the transition from the multi- toward the single-mode spectrum when $z$ is increased.
To perform the wavelength-tuning simulations we used the butt-coupling model (outlined in Chapter 2) together with a rough numerical estimate of the gain spectral distribution for the SDL 5400C HPLD active medium. The latter was carried out using certain assumptions about the laser structure that are based on the guidance provided by the manufacturer and the traditional functional form of the gain spectrum (see Appendix C). The simulations allow us to qualitatively track only the strongest mode of the lasing distribution in steady-state, since the model is based on singlemode rate equations (see Sec. 2.4.2).

The exact multi-modal transient behavior, that is not a subject of current research, can be obtained by incorporating the multimode rate equations in the butt-coupling model. The required multimode equations are
\[
\begin{align*}
\frac{dN}{dt} &= \eta_i \frac{I}{qV} - N \frac{1}{\tau_p} - n g_m N_{ph,m} \\
\frac{dN_{ph,m}}{dt} &= \frac{\gamma_{sp}}{\tau_{sp}} N + n g_m (g_m - \alpha_m)
\end{align*}
\]

where subindex 'm' denotes the mth lasing mode and other variables retain their traditional definitions. These single-cavity rate equations fully incorporate all coupled-cavity effects in the dependence of the threshold gains on wavelength - the limitations imposed by this were discussed in Sec. 2.4.3.

Another way to perform transient analysis - which is based on a comprehensive scattering junction algorithm - was demonstrated by Coldren and Koch (1984c). It differs from the analysis based on single-cavity rate equations described above in that neither of the coupled cavities is assumed to be linear. In this approach the rate-equations, the propagation phase on each transit between the cavity boundaries and appropriate scattering relations at the cavities' boundaries are considered in each of the coupled cavities separately. As a result, this algorithm avoids approximations of the single-cavity rate equations by keeping separate track of losses and coupled powers in each cavity. It also allows us to obtain power densities as a function of position along the device, so that non-uniformity of the gain and carrier distribution along the laser cavity can be taken into account.

Oscillation occurs in the compound cavity mode with the lowest threshold gain. However, the spectral reflectance peak of the ESEC does not, in general, coincide with the mode supported by the solitary LD cavity. For a given set of cavity parameters we
find the lowest threshold mode numerically (see Fig. 4.1). An ESEC bandwidth that is narrow compared to the solitary LD mode spacing and a large ratio of external feedback ($R_3$) to the LD output facet feedback ($R_2$) would result in a nearly linear tuning curve. Our case of $R_2 \sim R_3$ and low finesse of the ESEC ($F \sim 1$, see Eq. 4.1) gives a more nonlinear tuning curve that tends toward a staircase (Fig. 4.2). It has been suggested that overall tuning fidelity be characterized by the rms residual of a linear fit to the measured curve (Zorabedian 1995b).

### 4.1.3 Linewidth

We start with the Shawlow-Townes expression for the linewidth $\delta \nu$ for semiconductor lasers, measured at FWHM (Yariv 1975, Henry 1982)

$$\delta \nu = k_1 \frac{\hbar \Omega_m (BW_c)^2}{P_m} n_{sp} \left(1 + \alpha^2 \right)$$

where $\nu_m$ is the lasing mode frequency, $P_m$ is the power in that mode, $BW_c$ is the bandwidth (FWHM) of the laser cavity in question, $n_{sp}$ is the spontaneous emission factor, $'1'$ represents the spontaneous emission noise contribution, $\alpha^2$ is the linewidth enhancement due to the carrier noise contribution and $k_1$ is a constant. $BW_c$ relates to the photon lifetime within the cavity and, consequently, to the cavity loss:

$$BW_c \propto \frac{1}{\tau_{ph}} = v_g (\alpha_{int} + \alpha_{rad}).$$

Then, keeping all parameters in Eq. (4.3) constant, except $BW_c$, and using Eq. (2.17a) one can express the linewidth change due to the
presence of the ESEC relative to the solitary LD case as

$$
\rho_u = \frac{\delta u_E}{\delta u_0} = \left[ \frac{\alpha_{\text{int}} - \frac{1}{2d} \ln\left(R_1 R_{\text{eff}}\right)}{\alpha_{\text{int}} - \frac{1}{2d} \ln(R_1 R_2)} \right]^2 \frac{P_{\text{out},0}}{P_{\text{out},E}} \quad (4.4)
$$

where the variables and subindices retain their customary definitions. Taking typical experimental values from Table 2.1 and \( z \sim 10\mu m \) we estimate the limits for modulation of \( \rho_u \) due to change in ESEC length \( z \) to be on the order of \( 0.65 \leq \rho_u \leq 2.4 \). This
demonstrates that for the ESEC LD in question the linewidth of the output spectrum practically is not changed compared to that for the solitary LD. We did not try to obtain an experimental verification for this conclusion. However, in the regime of multimode
tuning the FWHM of the output spectral distribution was observed to be modulated with a half-wavelength periodicity, see Fig. 4.5. It is worth noting that, in the presence of an ESEC, the laser frequency retains its strong dependence on the semiconductor refractive index (compared with corresponding de-coupling in the case of long external cavities). Hence, the refractive index fluctuations contribute to the linewidth of the ESEC LD as significantly as in the case of a solitary LD. Indeed, the resonant frequency of order \( m \) is expressed as

\[
\nu_m = mc/2(n_d d + n_z z)
\]  

Then

\[
\frac{\partial \nu_m}{\partial n_d} = -\frac{\nu_m}{n_d} \left[ \frac{n_z z}{n_d d + 1} \right]^{-1}
\]

and the relative change in the mode frequency due to the changes in the refractive index is reduced by a factor of \( \left[ \frac{n_z z}{n_d d + 1} \right] \sim 1 \) for the ESEC and no improvement is seen over the solitary LD.

### 4.1.4 Wavelength Tuning Range.

Our goal here is to demonstrate that the wavelength tuning range, achievable with an ESEC LD realized via butt-coupling, is a nonlinear function of the external cavity length.

Initially, for simplicity, we shall ignore the nonlinear variation of the carrier density in the gain medium due to the modulation of the threshold condition versus the
ESEC length and, therefore, its influence on the spectral properties of the material gain. Plane wave propagation is assumed within the ESEC. The separations between the modes, supported by the LD’s cavity of length \( d \), is given by

\[
\delta \lambda = \frac{\lambda^2}{2n_{gr}d}
\]  

(4.7)

![Figure 4.6: Tuning range, calculated using different methods. Experimental data shown in scatter plot.](image)

Fig. 4.6: Tuning range, calculated using different methods. Experimental data shown in scatter plot.

where \( n_{gr} = n_g - \lambda (\partial n_g / \partial \lambda) \) is the group effective index, and \( n_g \) is the active medium’s effective index at \( \lambda \). Coincidence of a mode of the LD cavity and a mode of the ESEC can be achieved not only by tuning the length of the ESEC, but can also result
from a change in the optical length of the LD’s cavity by, for example, a change in temperature (Cassidy et al. 1991, Ruprecht and Brandenberger 1992). Assuming that such a resonant condition has been achieved, a small change in the external cavity length would result, for constant mode number, in a change of the external cavity resonant wavelength. When this wavelength change corresponds to that in Eq. (4.7), the resonant condition is satisfied for the neighboring mode of the LD’s cavity and emission shifts to that mode. The corresponding change in external cavity length \( \delta z \) is estimated from the fact that, in resonance of order \( m \) with the lasing wavelength, the ESEC length \( z \) is directly proportional to that wavelength, \( n_z z = m\lambda \), and therefore

\[
\delta z = z \frac{\delta \lambda}{\lambda} = \frac{\lambda}{2n'_p d} z.
\] (4.8)

The sequence of lasing mode shifts continues until the length of the external cavity is changed by \( \lambda/2 \). When this occurs, the initial LD mode is again resonant with the external cavity and the ESEC LD emits at the original wavelength. We define the tuning range \( \Delta \lambda \) to be the difference between the extreme values of ESEC LD lasing wavelength that are achievable within one period of ESEC length tuning (\( \Delta z = \lambda/2 \)). This range is clearly a function of the external cavity length \( z \) and is given by (using Eq. 4.8 and setting \( \Delta z = \lambda/2 \))

\[
\Delta \lambda = \left( \frac{\Delta z}{\delta z} - 1 \right) \delta \lambda = \left( \frac{\lambda}{2\delta z} - 1 \right) \delta \lambda = \left( \frac{\lambda^2}{2z} - \delta \lambda \right)
\] (4.9)

The "-1" term is present in the first part of Eq. (4.9) due to the fact that, when changing
the ESEC length, the last increment of \( \delta z \) returns the lasing wavelength to its original value.

Next, we remove the previous simplification and include the effect of the gain medium presence and, using the butt-coupling model, numerically calculate the feasible tuning range. Fig. 4.6 shows the result of this analysis and compares it with a plot of Eq.(4.9) and with the experimental data for the configuration specified in Table 2.1. It can be seen that by excluding the gain effect one would significantly overestimate \( \Delta \lambda (z) \).

It is apparent that a decrease in the amount of feedback to the LD's cavity, whether it results from increasing the separation \( z \) or lowering SMF's facet reflectance \( R_3 \), would lead to a general nonlinear decrease of the tuning range \( \Delta \lambda (z) \). The fact that the two mirrors that form the external etalon have similar reflectance and that they are closely spaced causes the net reflectance of the etalon to be highly modulated as the spacing is changed (Sec. 5.2). This large change in net etalon reflectance is the key to the achievement of a large tuning range.
4.3 RELATIVE INTENSITY NOISE

Expressing the internal electric field of the laser as \( E(t) = E'(t)\exp(i\omega_0 t) + cc \), where the amplitude \( E'(t) \) is given by \( E'(t) = (E_0 + a_n(t))\exp(i(\phi_0 + \phi_n(t))) \), we obtain

\[
E(t) = 2(E_0 + a_n(t))\cos(\omega_0 t + \phi_0 + \phi_n)
\] (4.10)

Here, the random variables \( a_n \) and \( \phi_n \) represent the amplitude fluctuations (AM-noise) and phase fluctuations (PM-noise) of the LD field, respectively. Expressing the LD output power as

\[
P(t) = P_0 + \delta P_0(t) = \varepsilon_0(c/2\eta_d d)\ln[1/\eta_0 \gamma_2](E_0 + a_n(t))^2
\] (4.11)

where \( P_0 \) is the average power, we introduce frequency fluctuations (FM-noise) and laser power fluctuations (IM-noise) as

\[
\delta \omega = d\phi_n/dt
\] (4.12)

and

\[
\delta P_0(t) \approx 2\varepsilon_0(c/2\eta_d d)\ln[1/\eta_0 \gamma_2]E_0 a_n(t)
\] (4.13)

The laser power fluctuations \( \delta P_0(t) \) are proportional to the LD AM-noise as long as \( E_0 \gg a_n \), as can be seen from (4.13).

Another measure used to conveniently represent the IM-noise of the LD is the relative intensity noise (RIN), defined as the ratio of the mean-square of the power fluctuation (noise) in a 1 Hz slot bandwidth to the square of the average cw output power,

\[
RIN = \langle \delta P_0(t)^2 \rangle / P_0^2
\] (4.14)
RIN is measured by focusing the cw laser output beam onto a photodetector and routing the resulting photocurrent to both an rf-spectrum analyzer and a dc-voltmeter (see Fig.2.7). The average photocurrent corresponds to $P_0$ while the rms fluctuations of the photocurrent are proportional to $\left\langle \delta P_0(t)^2 \right\rangle^{1/2}$. The mean square noise power $P_n(f)$ in the photocurrent at frequency $f$ was measured via the spectrum analyzer using a $\Delta f = 30$ kHz slot bandwidth that was centered at a specific video frequency. This quantity is normalized to a 1 Hz bandwidth by dividing it by $\Delta f$ (such a normalization assumes uncorrelated spectral noise components). Taking an appropriate system frequency response $s(f)$ into account, the spectral RIN distribution is given by

$$RIN(f) = 10 \cdot \log_{10} \frac{P_n(f)}{P_{dc} s(f) \Delta f}$$  \hspace{1cm} (4.15)$$

where $P_{dc}$ is obtained by squaring the mean photocurrent sensed by the dc-voltmeter.

All noise measurements were performed within the frequency region of 1 to 10 MHz (that approximately corresponds to the bandwidth of readout channels employed in optical data recording). Theoretically, the RIN for the laser without feedback should decrease with increasing bias current above threshold (McCumber 1966). This dependence can be clearly seen in Fig. 4.7(a).

The two operational regimes of tuning, multimode and singlemode (see Sec. 4.2.1), of the ESEC LD realized by butt-coupling (see Table 2.1) exhibit quite different RIN behavior. Fig. 4.7(b,c) demonstrates the results of RIN measurements on our ESEC
LD at 1 MHz (these results are representative of those at other frequencies within the considered region). The RIN undergoes significant increase at separations $z$ that correspond to the beginnings of new wavelength tuning periods ($2z \approx (2m+1)\lambda/2$; the 'vertical transition regions' in Figures 4.1 and 4.2). Fig. 4.7b corresponds to clean singlemode operation with the side-mode suppression of more than 30 dB. On average, singlemode tuning is found to be less noisy along the linear slope of the tuning curve than the corresponding multimode case (Fig. 4.7c), except at the beginning of the tuning periods where modes at opposite ends of the tuning range lase simultaneously. Although RIN is generally higher in the multimode regime, the effect of the feedback on the increase in RIN is found to be reduced in the multimode case. Additional insight can be obtained by comparing the statistical characteristics of the ESEC LD RIN, Fig. 4.7d, to the RIN of the solitary LD, Fig. 4.7a. The excessive RIN, observed in the ESEC LD compared to the solitary laser, is induced because the gain and refractive index are changed by carrier density fluctuations due to the optical feedback. Thus we would expect the reduction of this noise with a decrease of the feedback light. Indeed, viewing the reduction of $R_{\text{eff}}$ as attenuation of feedback, we observe that the RIN dependence on $z$ is similar to that of $R_{\text{eff}}$ (compare Figs. 4.7(b,c) and 3.2).
Fig. 4.7: RIN measurement, performed for the ESEC LD realized via butt-coupling into a SMF (see Table 2.1). a) solitary LD; butt-coupled LD: b) singlemode tuning, c) multimode tuning, d) statistics for singlemode (s) and multimode (m) tuning.
CHAPTER 5.
TOLERANCES AND STABILITY

The butt-coupling model, introduced in Chapter 2, successfully predicts the dependence of the coupling efficiency on both the axial separation and transverse misalignments between the laser diode and the fiber. The closed-form nature of the solution for the coupling efficiency as a function of various alignment parameters is an advantage of this model which is due to the use of a Gaussian approximation for all coupled modes. It is not necessary to appeal to numerical techniques to obtain a desired result. In this Chapter we discuss the use of the model to provide the mechanical tolerance and alignment analysis required for optoelectronic package design.

5.1 ALIGNMENT TOLERANCES

5.1.1 Angular, Transverse and Longitudinal Misalignments: Influence on Coupling Efficiency.

Fig. 5.1 shows the calculated contours of coupling efficiency versus longitudinal and angular misalignments (a,b) as well as longitudinal and transverse ones (c,d) when ESEC lengths vary between 8 and 25 μm in the coupling system specified in Table 2.1. Only the right half of the contour map is shown, since the left half is the mirror image of the right one. Maximum coupling efficiency corresponds to the point of no misalignments (not shown) and is equal to approximately 43% for the case of an AR-coated (thick lines) or non-AR-coated SMF facet.
Fig. 5.1: Degradation of coupling efficiency versus misalignments. In the plane of pn-junction:
(a) angular $\theta_x$, (c) transverse $\Delta X$; Normal to the plane of pn-junction: (b) angular $\theta_y$, (d) transverse $\Delta Y$; and longitudinal ($Z$).
$R_3=R_2=4\%$ (thin lines) and $R_3=0.1\%, R_2=4\%$ (thick lines). Units: $Z, \Delta X, \Delta Y$ - microns; $\theta_x, \theta_y$ - degrees. Assumptions: (a,b) zero transverse misalignment, (c,d) zero angular misalignment.
It can be seen that when working at $2z_R \leq z \leq 3z_R$, $z_R \approx 5\mu m$, the -1dB alignment tolerances are approximately $\pm 1\mu m$ in both transverse planes. However, the difference in LD output beam divergence angles becomes apparent from the fact that the $x$-plane angular tolerance is smaller than the corresponding $y$-plane one. It is also worth noting that at these lengths of the ESEC the AR-coating of the SMF facet does not significantly affect the coupling stability with respect to positioning along the $z$-axis, in comparison with shorter separations where AR-coating becomes crucial (Karioja and Howe 1996). Karioja and Howe also modeled the ESEC filled with matching gel. Although this solution does not seem to be practical in the non-laboratory environment, it would result in a decrease of the LD beam divergence, a decrease of the effective ESEC reflectance $R_{\text{eff}}$ and an increase of the ESEC length. These changes, in turn, lead to some increase of the longitudinal alignment tolerance and a decrease of the angular ones. The effect of the $R_{\text{eff}}$ reduction is that the ESEC LD operates in the low-backreflection portion of the $P_3$ versus $R_{\text{eff}}$ curve (see Fig. 3.8, $R_{\text{eff}}<2\%$), where the feedback to the LD is extremely sensitive to the slightest change in $R_{\text{eff}}$ and the power coupled into the SMF is less sensitive to the variation of the ESEC transmission.

5.1.2 Axial Tolerances and Stability of Short-External-Cavity GaAlAs Laser Diode for Use as a Tunable Single-Mode Source.

The rough etalon analysis, presented in Sec. 4.1.4, which neglects the spectral dependencies of the radiation loss $\alpha_{\text{rad}}(\lambda)$ and material gain $g(\lambda)$ of the ESEC LD,
Fig. 5.2: Axial tolerance $\delta z$ on EC length required to maintain the operation of the ESEC LD in the same single longitudinal mode. Solid line represents a logarithmic fit to several numerical data points.

Fig. 5.3: Two consecutive experimental scans of a single period of the (singlemode) tuning curve, performed at $\sim 40$ $\mu$m separation with $60$-nm scan increments.
predicts a linearly increasing axial mechanical tolerance with increase of \( z \) as the ESEC LD maintains the same (single) oscillating mode operation, i.e. \( \delta z \propto z \), see Eq.(4.8). However, considering the modulation of the threshold current (and, therefore, the carrier density), Fig. 3.5, that is reflected by the threshold condition variation (Sec. 3.2) due to the change in \( z \), we reason that \( \delta z \) depends on \( z \) nonlinearly. Indeed, the threshold loss margin between the adjacent modes increases with an increase of the EC length, \( \Delta \alpha_{i,\pm 1} \propto z \) (Coldren and Koch 1984a). Thus, as \( z \) increases, it would require a larger change in \( R_{\text{eff}} \) to overcome this loss margin, i.e., to hop from \( \lambda_i \) to a neighboring \( \lambda_{i\pm 1} \) and, according to the Eq.(2,9), bigger change \( \delta z = z_{i\pm 1} - z_i \) (the mode hop occurs when \( R_{\text{eff}}(\lambda_i, z) \) practically equals \( R_{\text{eff}}(\lambda_{i\pm 1}, z) \)). Figs. 4.3(c,d) demonstrate complete qualitative consistency with the offered reasoning. A numerical estimate of \( \delta z(z) \) that is shown in Fig. 5.2 leads to the conclusion that, in the singlemode tuning regime, the stability of an ESEC LD should be higher. This is confirmed by our experimental observations as well.

Tuning due to the change of EC length \( z \) occurs in the form of consecutive mode-hops between the modes supported by the ESEC LD cavity. When working in a singlemode tuning regime (\( z \sim \) tens of \( \mu \text{m} \)) , we resolve almost every resonant mode of the laser cavity with satisfactory stability. The typical characteristic “stair-case” tuning behavior for singlemode tuning is shown in Fig. 5.3 and 4.2(a). Although we did not
investigate the complex engineering associated with stable and reliable ESEC LD wavelength tuning, these observed results indicate that robust tuning can be achieved.

5.2 CHOICE OF MIRRORS' REFLECTANCES.

The behavior of the power characteristics (LD output power $P_2$, as well as the power coupled into the SMF, $P_3$) of the ESEC LD critically depends not only on the ESEC length $z$, but also on the relative values of $R_2$ and $R_3$. (Generally, $R_3$ would represent the effective reflectance, produced by both ends of the SMF, unless the feedback from the rear end is eliminated or the length of the SMF exceeds half the coherence length of the LD light). Indeed, all three parameters affect the values of the back-coupling and out-coupling coefficients ($C_{LL}$ and $C_{LF}$, respectively) and thus the reflectance and transmittance of the effective compound mirror (Eqs. 2.9 and 2.14).

Symmetry of the ESEC (i.e., $R_2 = R_3$) leads to the deepest modulation of its reflectance $R_{\text{eff}}$ and, as a result, to the deepest modulation of the output power $P_2$ and the power coupled into the SMF $P_3$ (Sidorin and Howe 1998). Indeed, using Eq.(3.3) for the envelopes of the effective reflectance of the compound LD mirror, we define the contrast of the modulation of $R_{\text{eff}}(\lambda,z)$ due to change in $z$ in the traditional way as

$$V_r = \frac{R_{\text{eff}}^+(\lambda,z) - R_{\text{eff}}^-(\lambda,z)}{R_{\text{eff}}^+(\lambda,z) + R_{\text{eff}}^-(\lambda,z)}.$$  (5.1)
Then, denoting $R_3 = (\text{const.}) \times R_2$ and $x = (\text{const.}) \times (1 - R_2) \cdot \gamma_1(z)$, and neglecting the dependence of $\gamma_1$ on $z$ (Fig. 5 of Sidorin and Howe, 1997a), we arrive at the anticipated result that $V(x)$ has its only maximum at $x=1$, which corresponds to $R_2=R_3$. Consequently, from Eqs. (2.14, 2.15, 2.16, 2.17a), it follows that the modulation of the LD output power $P_2$ and power $P_3$ coupled into the SMF would be maximized in this case, see Fig. 5.4. As a result,

![Graph](image)

*Fig. 5.4: Power coupled from HPLD to SMF in direct end-coupling configuration, for different SMF facet reflectances. $R_2=4\%$."

the tolerances on axial positioning of the SMF with respect to the LD are the tightest, from the coupling point of view, when the ESEC is symmetric. The wavelength tuning
range is obviously widened in the case of a symmetric ESEC, since the threshold condition exhibits maximum modulation in this case.

The maxima of the power, $P_3$, coupled into the SMF, which occur in the vicinity of $z = (2m + 1)\lambda/4$ ($m \geq 0$ is an integer), will not be affected from the practical point of view in the limit of $R_3 \to 0$. Under this condition, due to the low initial reflectance of the SMF facet, $R_3$, $\left(\frac{dP_3}{dR_3}\right) = \left(\frac{d(P_2T_{eff})}{dR_3}\right) \to 0$. Fig. 5.4 illustrates this point as well. However, when butt-coupling to a high-refractive index waveguide (e.g., KTP), an AR-coating will increase the coupling somewhat in the region $z \leq z_R$.

5.3 PACKAGING ISSUES RELATED TO PIGTAILING THE FIBER

The purpose of packaging is to ensure the reliability of the finished module in all operational conditions. Indeed, the packaged device has to allow electrical, optical, thermal and mechanical interconnections while providing immunity to mechanical shocks, temperature variations and protection from the environment. Although we are not concerned with packaging per se in this work, it's worth mentioning some aspects of the packaging process: optomechanical design, coupling tolerances, optical alignment, device attachment and module encapsulating. Coupling tolerances were considered in Sec.5.1; below we refer to some of the remaining issues (Karioja 1996 and references therein).

Optomechanical construction has to provide means for device alignment during the assembling process. In the case of a butt-coupled LD and SMF a combination of
cylindrical and planar constructions, that reflect the geometry of butt-coupled components, or an optical bench, would be applicable. This would assure the proper connection of both planar and circularly-symmetric components (Foley et al. 1990). Kinematic principles should be applied in the optomechanics for integrated optics packaging to escape from overconstraints in device attachment and, therefore, the occurrence of distortion.

Optical alignment techniques are divided into two groups: a) active alignment, based on maximization of coupled power, and b) passive alignment, based on the use of mechanical alignment structures (grooves, bumps, holes) or patterned alignment marks. The costly active technique, which can be automated and is commercially applied to fiber pigtailed LD packaging, results in better packaging quality. The simpler passive technique, which results in higher insertion loss, has lower yield of packaged modules. One of the promising passive techniques is the flip-chip bonder, where the use of the alignment patterns is possible both on the top and on the bottom of the device. To date passive alignment that is accomplished by solder reflow (due to surface-tension forces), in conjunction with the Si-micromachined V-grooves enables ~ 0.5 \( \mu m \) accuracy in the lateral alignment of coupled components.

The solution of the device attachment problem in optoelectronic packaging should take into account the coefficients of linear thermal expansion of the devices in question. Attachment is done by (1) adhesive bonding (thermocured and UV-cured, the latter being is less rigid), (2) soldering (SnPb-based solders and low temperature solder-
glasses) or (3) welding (a Nd:YAG laser is used to weld metals while a CO₂-laser is used to weld glasses).

Finally, *module encapsulation* is necessary to comply with the requirements of high reliability, high optical stability and long operating lifetime, especially in telecommunication applications. Hermetic sealing may be provided with metal-metal, glass-glass and metal-glass bonds.
CHAPTER 6.

BUTT-COUPLING AND EXTREMELY-SHORT-EXTERNAL-CAVITY LASER DIODES: APPLICATIONS.

6.1 OVERVIEW

Previous research on SEC LDs, as well as our work with ESEC LDs (reported in previous Chapters), show that composite cavity LDs are extremely susceptible to perturbations in the external cavity length (whatever the cause). However, this sensitivity of the composite LD to its external cavity parameters has two useful consequences - output power variation on one hand (Chap. 3) and the variation of the oscillation frequency on the other hand (Chap. 4). Thus, one class of potential applications is based on sensing the change in these two major parameters. An alternative approach would be to introduce controlled changes in the ESEC to influence the wavelength/power.

a) SEC InGaAsP and GaAs LDs have proved useful as singlemode sources in sensitive spectrometers (Nakagawa and Shimizu 1987, Ventrudo and Cassidy 1990, Lee et al 1991) and have been employed in studies aimed at the detection of various chemical components (Cassidy and Bonell 1988, Bruce and Cassidy 1990, Zhu and Cassidy 1997). To achieve high sensitivity, harmonic and FM modulation of the tunable source are employed.
b) Significant effort has been expended to improve control of the operational characteristics of SEC LDs, their construction and sensitivity to changes in the external feedback, as the following three examples illustrate.

A simple system that extends the continuous tuning range of the SEC LD was investigated by Ruprecht and Brandenberger (1992). It tunes the $m$th order lasing mode by varying the temperature and/or drive current of the LD and prevents it from hopping to the $(m \pm 1)$th order by adjustment of the external cavity length.

Ventrudo and Cassidy (1993) proposed a scheme to control the longitudinal mode of a InGaAsP LD by using an interference fringe pattern in the far field that is formed by the light emitted from the front and rear LD facets. The signal-to-noise ratio of a discrimination signal derived from these fringes was demonstrated to be higher than for the traditional voltage control signal; the external cavity was stabilized much faster due to the wider detection bandwidth.

Uenishi et al. demonstrated optical fabrication techniques by micromachining in silicon (1995) and nickel (1996) to manufacture planar external mirrors for the tunable SEC LD.

e) Few examples of applications that utilize an ESEC LD have been demonstrated so far. All systems reported to date sense the variation of the ESEC LD output power in response to an external disturbance. Prototype magnetic and acoustic sensor schemes were reported as early as in 1983 by Miles et al. Subsequently a flying optical head for optical data storage was demonstrated (Ukita et al. 1989), where the ESEC was formed
by the surface of a phase change recording medium and a LD that was attached to an air bearing slider. (In this demonstration the data signals and tracking error signals read from sampled tracking servo marks were detected.) More recently, GaAs-based integration was realized to construct an ESEC LD displacement sensor for micromechanical photonic devices by the same group (Ukita et al. 1994). The integration technology used in this latter work significantly reduced the need for optical alignment.

New and/or additional applications of ESEC LDs can be realized if either the construction of the device is improved and/or simplified, or if its operational characteristics are better controlled. In the sequel we discuss two novel systems - an electronically tunable ESEC LD and an improved light delivery system. In Sec. 6.2 we present the results of our work on a wavelength-tunable hybrid laser diode that operates at a center wavelength of 980 nm in a novel ESEC configuration. Here we employ a micromachined, electronically tunable external interference filter as a spectrally variable reflector to realize a miniature (hybrid multi-chip module) ESEC tunable laser diode. The demonstration of a prototype of this device suggests its potential application in dense wavelength division multiplexed (DWDM) optical communications. In Sec. 6.3 we consider an alternative way of delivering LD light to the write/read objective of an optical recording head. This may be beneficial in optical recording applications where the system requires a large field of view in object space or, equivalently, small magnification imaging of the LD source plane onto the storage medium.
6.2 DEMONSTRATION OF A WAVELENGTH TUNABLE EXTREMELY-SHORT-EXTERNAL-CAVITY HYBRID LASER DIODE USING AN ELECTROSTATICALLY TUNABLE SILICON MICROMACHINED FABRY-PEROT INTERFEROMETER.

The basic idea of this experiment is to butt-couple a novel micro-electro-mechanical system (MEMS) and a LD to realize a compact, high performance and mass producible tunable LD. Several approaches have been taken to build micro-optical MEMS devices (Cassidy et al. 1991, Aratani et al. 1994, Uenishi et al. 1995 and 1996, Kiang et al. 1996). Movable micromirrors, used in previous (almost assembly-free) implementations of this technique, are not commercially available at the moment. The micromachined tunable Fabry-Perot interferometer (TFPI) discussed here, however, represents mature technology, considering its use in a commercial CO₂-sensor, manufactured by Vaisala Oy (Ref.).

The ESEC LD device studied is comprised of a high-power laser diode (HPLD) that is closely spaced (butt-coupled) to a TFPI, Fig. 6.1. The experiments performed are similar to those described in previous Chapters. In the present case, the extremely-short-external-cavity is formed by the output facet of the HPLD and the external TFPI. A separate confinement heterostructure quantum well InGaAs/GaInAsP/GaInP high-power laser (Asonen et al. 1994), emitting at ~980 nm in a solitary regime with an anti-reflection coating (R₂~5%) on the output facet, serves as a gain element that is held at constant temperature and biased at a constant current level ~30% above its threshold current.
Fig. 6.1: A high-power laser diode (HPLD) directly end-coupled to a tunable Fabry-Perot interferometer (TFPI). 1,2 - LD mirrors; AR - antireflection coating; z - separation distance.

The movable mirror of the micromachined TFPI is separated from the HPLD output facet by initial distance $z = z_0$, which establishes the initial feedback into the LD's cavity. The minimal separation $z_0 \approx 25 \mu m$ between the HPLD and TFPI is limited by the geometry of the present experiment (mounts of the LD and TFPI require special design). There is no significant truncation of the laser beam in transmission through TFPI's clear aperture (diameter $\sim 750 \mu m$) at such short distance. When electrostatically tuned, the TFPI acts like an optical sweeping filter, shifting the spectral distribution of its reflectance and transmittance. Also, the separation, $z$, between the LD and TFPI is a nonlinear function of the voltage applied to the TFPI (Blomberg et al. 1996).
The TFPI used in our experiments was optimized to provide selective and strong feedback in the 1 μm-spectral region in the first interference order. Fig. 6.2a presents the relative variation of the TFPI reflectance spectrum versus applied voltage. The region of adjustable reflectance of the TFPI corresponding to the applied voltage range of 3.5 to approximately 5.5 V (see Fig. 6.2b), was used to obtain the anticipated tuning effect. There are two mechanisms leading to the observed wavelength tuning. On one hand, this tuning results from the variation in the spectral position of the TFPI reflectance minimum versus its driving voltage, Fig. 6.2a. On the other hand, starting at fixed initial separation $z_0$ between the HPLD and TFPI, a specific voltage that is applied to the TFPI causes the separation $z_0$ to change to a unique value $z$ by moving an upper mirror of TFPI toward its lower mirror. This effect causes $z$ to vary by as much as ~70 nm. (The variation of $z$ is defined by the operational characteristics of TFPI, see Blomberg et al. 1996.) These two mechanisms affect the optical characteristics of the compound mirror of the hybrid laser cavity in an extremely nonlinear fashion. As a result, depending on the initial separation between the HPLD and the TFPI, different modes of tuning were observed: i) multimode tuning (packet of ~10 modes tuned simultaneously across the range of several nm), ii) double mode generation at the opposite ends of the tuning range (separated by several nm), and iii) quasi-single-mode tuning.

Stable adjustment and, therefore, repeatable tuning, in the quasi-singlemode regime was observed primarily within a TFPI working range of ~3.8 to 4.8 V. Scanning over the working range of the TFPI with a precision of ~0.05 V revealed a quasi-
continuous (step-wise, via mode-hopping to the adjacent modes of the hybrid LD) wavelength tuning over a region of ~4 nm with the FWHM of the spectral distribution equal to ~0.3 nm (Fig. 6.3). A simple estimate of intermodal separation for the considered LD shows that we tuned ~3 longitudinal modes simultaneously. A partial explanation for this stems from the fact that in its present design the TFPI has a quite broad reflectance spectrum in the 1st order - approximately 30 nm, as can be seen from Fig.6.2.

Continuous tuning, which could be achieved by the simultaneous adjustment of TFPI voltage and temperature and/or drive current of the HPLD, was not a subject of this research.

Fig. 6.2: (a) The minimum of the measured TFPI reflectance spectrum undergoes a 'blue shift' when the applied voltage is increased; (b) the adjustable TFPI reflectance region from 3.5...5 V (shown for λ ~ 979nm.)
Fig. 6.3: Wavelength tuning across ~4 nm range, achieved with the hybrid LD. The corresponding output spectrum variation is shown to the right. FWHM of spectral distribution at every point was measured to be ~0.3 nm.

6.3 USING AN OPTICAL FIBER FOR LIGHT DELIVERY TO THE WRITE/READ OBJECTIVE IN OPTICAL RECORDING.

A traditional way of collecting light from a laser diode (LD) source is to use a lens system. In many cases additional elements, such as beam circularizing and astigmatic optics, are required for proper device operation. Below we analyze the use of LD-to-SMF butt-coupling in optical recording. Specifically, we determine what fraction of the power $P_2$, that emanates from a moderately high output power LD (Fig. 6.4a) can be delivered to a write/read objective via a singlemode fiber that is butt-coupled to this LD. The system
studied consists of an edge-emitting LD that is butt-coupled to a SMF and an infinity-conjugate, aberration-free circularly symmetric collimator lens that receives the light from the uncoupled end of the SMF (Fig. 6.4b). The efficiency of this light collecting system is compared to that obtained by using only the collimator lens to directly capture the light from the same LD, Fig. 6.4c. In both cases it is assumed that all the light captured by the collimator is delivered to the write/read objective lens. The results of this work show that in a practical system (which exhibits reasonable LD-to-SMF separation and alignment tolerances) more power can be delivered to the write/read objective by the system that employs an intermediate SMF (Fig. 6.4b) if the numerical aperture (NA) of the collimator lens is on the order of $\sim 0.11$ or less.

The LD considered in this study is index-guided and nominally emits up to 50 mW of CW power at wavelength $\lambda \sim 845$ nm into a lowest spatial mode (well approximated as an elliptical-Gaussian distribution) that exhibits full-width at half-maximum power angular spreads in the far-field of approximately $\Theta_x \times \Theta_y \approx 10.6^\circ \times 26^\circ$. (The corresponding beam waist radii, defined at the $e^{-2}$ power levels, are inferred from far-field measurements to be about $1.7 \mu m \times 0.7 \mu m$ in the planes parallel and perpendicular to the pn-junction of the LD, respectively.) Astigmatism of this LD is small ($< 3$ microns) and dependent on drive current. All measurements were performed with a LD having the following parameters: threshold current $I_{th} \sim 23$ mA, P-I-slope $\sim 0.83$ W/A at $T=20.1$ °C and drive current $I=75$ mA and a SMF with an uncoated flat input facet.
We define the butt-coupling efficiency $\eta_{bc}$ as the fraction of the solitary LD light output power $P_2$ that appears at the output end of the butt-coupled SMF that is axially separated from the LD by distance $z$. $\eta_{bc} = P_1/P_2$. Fig. 6.5 contains plots of $\eta_{bc}$ as a function of $\omega_f$, the waist radius of the SMF modal field Gaussian distribution (Marcuse 1979) for several values of $z = (2m+1)\lambda/4$, $m$ - integer. We note that these $z$ values are those that produce maximum coupling (see Chapter 4). No transverse or angular misalignments between the LD and SMF are assumed in Fig. 6.5. The results of two simulations are presented - for no astigmatism and 10 $\mu m$-astigmatism in the LD beam, respectively. From Fig. 6.5 one can see that for experimentally reasonable values of minimum separation $z \approx 10 \mu m$ (see Chap. 3) and LD astigmatism $\sim 2\mu m$, $\eta_{bc,\text{max}} \sim 43\%$ can be achieved for the coupling of the LD in question to the SMF, if the SMF modal field waist radius were chosen to be $\omega_f \sim 1.7 \mu m$. The power transfer comparison for the two systems described earlier is given in Fig. 6.6., which contains plots of the quantity $P_1/P_2$ for the configurations shown in Fig. 6.4(b,c). These curves were obtained via the butt-coupling model described in Chap. 2; the analysis used to produce them as well as their practical implementations will now be discussed. Consider a circular aperture, that is normal to and centered on the axis of propagation of an elliptical Gaussian beam. We start with representing this Gaussian field (normalized to unit power) in the angular space $(\phi_x, \phi_y)$:
Fig. 6.4: Experimental configurations: (a) solitary laser diode, LD; $P_2$ - output power; (b) light delivery system employing a singlemode fiber (SMF) that is butt-coupled to the LD; $L$ - collimating lens; butt-coupling efficiency is defined as $\eta_{BC} = P_3/P_2$; $P_4$ - total power collected; (c) traditional way to collect light from the LD.
Fig. 6.5: Efficiency of LD-to-SMF butt-coupling versus the SMF modal waist radius for zero LD astigmatism (solid) and 10μm-astigmatism (dashed); LD parameters are described in text. LD-to-SMF separation is defined according to $z = (2m + 1) \frac{\lambda}{4}$; $m=0,20,40,60$ and 100 (curves a,b,c,d,e, respectively).

$$\Psi(\phi_x, \phi_y) = A_x \exp\left(-\frac{\phi_x^2}{\phi_{x,\epsilon}^2}\right) A_y \exp\left(-\frac{\phi_y^2}{\phi_{y,\epsilon}^2}\right) \times \text{(phase term)}, \quad (6.1)$$

where $\phi_{x,\epsilon}$ and $\phi_{y,\epsilon}$ are the angles that correspond to $e^{-1}$ field amplitude level in the planes parallel to LD pn-junction and normal to it, respectively, and $A_{x(y)} = \left(\frac{2}{\pi}\right)^{\frac{1}{4}} \left(\frac{1}{\phi_{x(y),\epsilon}}\right)^{\frac{1}{2}}$ is the amplitude. The fraction of power in the Gaussian beam that is collected by the circular aperture is obtained by integration.
\[ P_{\text{per}}(\Theta_{\text{NA}}) = 4 \int_{\phi_x = 0}^{\Theta_{\text{HM}}} \int_{\phi_y = 0}^{\Theta_{\text{NM}}} \Psi(\phi_x, \phi_y) \cdot \Psi^*(\phi_x, \phi_y) d\phi_x d\phi_y, \]  

and is easily shown to be

\[ P_{\text{per}}(\Theta_{\text{NA}}) = \text{erf} \left( \Theta_{\text{NA}} \sqrt{-\ln 0.5 \left( \frac{\Theta_{\text{HM}}^2}{4} \right)} \right) \cdot \text{erf} \left( \Theta_{\text{NA}} \sqrt{-\ln 0.5 \cdot \left( \frac{\Theta_{\text{NM}}^2}{4} \right)} \right), \]  

where \( \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt \), \( \Theta_{X,Y} \) are the full-width angles of the far-field Gaussian beam divergence at half-maximum power levels, and \( 2\Theta_{\text{HM}} \) is the full angle subtended by the aperture at the waist of the Gaussian beam. The solid curve in Fig. 6.6a shows the fraction of the LD output power, \( P_1 \), that is collected by an infinity-conjugate circularly symmetric lens, focused directly on the LD output facet, versus the NA of that lens within the range \( NA \leq 0.16 \). The dashed curves in the figure indicate how this power transfer versus collimator NA is affected by placing a perfectly aligned, butt-coupled SMF having \( \omega_f \sim 2.4 \mu m \) between the LD and the lens (the lens is focused on the output facet of the SMF in this latter case). The cases of perfect alignment and moderate misalignment (angular and transverse) of the butt-coupled SMF are considered together with negligible LD astigmatism. The curves labeled \( a\ldots d \) correspond to the same values of LD-to-SMF separation, \( z \), as the identically labeled curves in Fig. 6.5. It can be seen that when the reasonable value of \( z \approx 10 \lambda \) (8.7 \( \mu m \)) together with moderate misalignments are used, higher LD power transfer is achieved via the system that employs an intermediate SMF when the collimator \( NA \leq 0.11 \). This occurs because the
fiber intercepts the laser output beam at a distance that is on the order of the beam’s Rayleigh range, where the angular beam spread is relatively small.

Fig. 6.6a was experimentally verified using the LD described above and a SMF with cut-off wavelength $\lambda_c \sim 770\text{nm}$ and a modal waist radius $\omega_f \sim 2.4\mu\text{m}$ (measured at $\lambda \sim 845\text{ nm}$ in the far field via the adjustable slit technique, suggested by Prof. Roland V. Shack). The collecting aperture used had diameter $D_{ap} = 11\text{ mm}$ (Fig. 6.4 (b,c)). The collecting aperture NA was varied by changing the separation $t$. Alignment of the butt-coupled SMF to the LD was maintained as butt-coupling spacing was varied. The results

![Graph](image)

**Fig. 6.6:** (a) Power transfer comparison for two configurations: curve L - traditional collecting lens, Fig. 6.4c; curves (a,b,c,d) - intermediate SMF employed; LD-to-SMF separation values $z$ correspond to those of the similarly labeled curves in Fig. 6.5. (b) Experimental verification of power transfer efficiency as a function of numerical aperture: L - aperture only, Fig. 6.4c; (1,2,3) - intermediate SMF employed, independent experiments ($z < 3, 9$ and $15\mu\text{m}$, respectively). Every third experimental point is shown. Typical LD-to-SMF misalignments: angular $\leq 3^\circ$, transverse $\leq 100\text{nm}$. 
of the experimentally measured power transfer are given in Fig. 6.6b. This Figure clearly illustrates the power transfer advantages obtained by using a butt-coupled SMF to first collect LD light that is subsequently captured by a low NA collimating lens ($NA \leq 0.11$).

Earlier we mentioned that a low NA collimator could be used to realize an optical storage write/read head that exhibits a large object field of view (this follows since the magnification at which the LD source plane is imaged onto the storage medium is given by the ratio of the collimator NA to the write/read objective NA). Such a head would be useful if an array of laser sources having relatively large separations, e.g., a few tens of microns or more, were to be imaged onto the storage medium. For example, an $8 \times 1$ array of LDs having a total length of $350\mu m$ ($50\mu m$ between adjacent devices) could be imaged onto a $\sim 60\mu m$ long stripe via a NA=0.6 objective if a NA=0.1 collimator lens is used. Such an arrangement could be used for simultaneous write/read of multiple data tracks on the storage medium, or for electronically tracking a single data track if an appropriate angular skew of the imaged linear stripe of focused laser spots to the data track direction is used. (The electronic tracking function might be realized, for example, by selecting that one of the eight imaged sources which is currently producing a maximum playback signal.)

Another advantage of using a SMF to route the light from a LD to the object plane of the collimator lens is that the light emanating from the output facet of the SMF is circularly symmetric and contains no astigmatism; this obviates the need to incorporate any anamorphic elements in the optical head. Furthermore, replacement of the LD(s) used
in the recording system may be simplified if a fiber coupled head is employed. Finally, if an integrated array of LDs, or a number of discrete LDs, is to be imaged via intermediate butt-coupled fibers, then the surface defined by the output facets of the multiple fiber(s) can be made non-planar. This surface can be shaped to compensate the Petzval curvature of the high NA write/read objective, thereby improving its off-axis imaging performance and/or simplifying its design.
CHAPTER 7.
CONCLUSION

7.1 SUMMARY OF RESULTS

To recapitulate the work described in this dissertation I shall concentrate on the major results that were achieved and will focus on their novelty when appropriate.

In this dissertation we have reported the analysis and realization of a wavelength tunable Fabry-Perot laser diode, based on the idea of butt-coupling a laser diode to an external reflector.

- A simple butt-coupling model, which is based on the modal overlap integral formalism and includes multiple reflections within the external cavity, was developed and found very effective in describing the problem of variable coupling.
- For the first time, near-field measurements confirmed the importance of the phase factor of the overlap integral.
- The useful output of the extremely-short external cavity laser diode (ESEC LD), realized by butt-coupling a laser diode to either a singlemode fiber or to a micromachined Fabry-Perot filter, was outcoupled through the extremely-short-external cavity. Thus the ESEC was employed both in reflection and transmission (compared to its employment in reflection only, as has been reported thus far).
- For the first time, to the best of my knowledge, repeatable tunability has been realized via the variation of an extremely-short gap between butt-coupled components. The
mechanical tolerances involved in the realization of an extremely-short-external-cavity (ESEC) tunable device have been found to be very tight.

- To explain and predict the experimentally observed LD frequency tuning, the variation of the gain spectra for the laser diode active material has been taken into consideration.

- All feedback effects achieved via LD source butt-coupling have been characterized by their highly nonlinear dependence on the ESEC length. These effects are maximized when ESEC length is less than, or on the order of, the Rayleigh range of the laser beam.

- Wavelength tuning was realized in the multimode as well as singlemode regimes.

- In the singlemode tuning regime the spectral linewidth is essentially the same as that of the solitary laser diode - thus the initial choice of the laser source is crucial, depending on the application.

- The tunable, extremely-short-external-cavity LD was realized in two independent configurations that admit to hybrid (multi-module) fabrication:

  1. by butt-coupling to a singlemode optical fiber, with variable laser diode-to-fiber separation;

  2. by butt-coupling to a novel electrostatically tuned spectral filter at a fixed distance.

A several-nm range of tuning was exhibited by each of these systems.
• RIN of the ESEC LD output light was found to be reduced (and essentially the same as that of the solitary LD) when the ESEC LD is operated in the singlemode tuning regime.

• In addition, we demonstrated the potential advantages of employing laser diode-to-singlemode butt-coupling, relative to a traditional collecting lens, in light delivery to the read/write objective in an optical recording head that exhibits a large object plane field of view (i.e., low numerical aperture collimating lens).

Perhaps the most important aspect of the work presented here is that it provides a research tool that can be used to facilitate the design of extremely-short external cavity laser diodes, which in many ways are technologically novel laser sources.

7.2 FUTURE WORK.

A number of additional questions - experimental and theoretical - must be addressed to achieve extremely-short external cavity laser diodes useful for a wide variety of applications.

• In the work reported herein, no attempts have been made to reduce the relative intensity noise figures. Very high frequency modulation of the drive current might be useful in this regard.
• An accurate analytic determination of the material gain spectrum variation versus feedback is required to facilitate the design of integrated ESEC LDs that utilize both bulk and (single)-quantum-well LDs.

• We only studied operation of ESEC LDs in the steady-state regime. This work should be extended to the study of modulated ESEC LDs, especially at the frequencies of interest in optical communications.

• ESEC LDs based on DFB/DBR laser diodes should be studied to determine their tuning characteristics. The motivation here is the hope that this ESEC LD will output tuned light having the same narrow spectral line as an isolated DFB/DBR LD.

• Realization of a “blue-laser” source, based on the frequency doubling in a butt-coupled, nonlinear quasi-phase-matched waveguide, would be a logical continuation of the present work.

• And, of course, the fabrication of practical ESEC LD devices requires that means be devised to achieve stable and repeatable butt-coupling and packaging.
APPENDIX A

FUNDAMENTAL MODES OF LASER DIODE AND FIBER:
APPROXIMATIONS AND COUPLING COEFFICIENTS

A.1 OPTICAL FIELD OF A DOUBLE-HETEROSTRUCTURE
INJECTION LASER

The use of double-heterostructure (DH) injection lasers that operate in the fundamental mode as the signal source in different applications (e.g., optical communications, integrated optics or optical data storage systems) requires that the emission be coupled into other optical component (such as an optical fiber, waveguide or the lens). The techniques for coupling and the resulting coupling efficiency depend on the field pattern of the DH laser. The far-field emission pattern has generally been described by giving the beam divergence as the full angle between the half-power (3 dB) points. In the plane of the laser junction (xz-plane) the beam divergence $\Theta_x$ (or, equivalently, $\Theta_z$) has been reported to have values of $\sim 10^\circ$. In the plane perpendicular to the laser junction, the beam divergence $\Theta_y$ (or $\Theta_\perp$) strongly depends on the structural composition of the laser as well as the active region thickness (Casey et al. 1973). However, typical commercially available laser diodes that operate in the fundamental mode are characterized by $\Theta_y \sim 30^\circ$ (SDL 1994).

Analytical descriptions for the far-field of the emitted light beam of a laser diode, based on Maxwell's equations, are available in the literature (Casey et al. 1973). These
representations agree well with the measured intensity patterns. However, owing to their mathematical complexity they are seldom used for actual design calculations. Instead, a simple Gaussian model of the laser diode beam has been used extensively in the studies concerning coupling efficiency between a diode and an optical fiber (Joyce and DeLoach 1984, Karstensen 1988, Karioja and Howe 1996). Another model, the Lorentzian-Gaussian, approximates the laser diode field in the plane normal to the junction by the Lorentzian function, while keeping the Gaussian description of the beam in the other plane (Dumke 1975, Naqwi 1990).

The simple Gaussian model originates from one of the exact solutions of the parabolic wave equation, which was derived from the Helmholtz equation after omitting the second derivative term with respect to the \( z \) coordinate (Simon 1983). The omission is allowable only when the beam cross section varies slowly as it propagates. For elliptical beams generated by actual devices, this condition is not satisfied due to the large beam divergence angle \( \Theta_r \sim 30^\circ \). In addition, there is a discontinuity between the Gaussian distribution and the internal guided mode of laser resonator at the laser facet.

The Lorentzian distribution (used in the Lorentzian-Gaussian model) is a solution of the scalar diffraction integral (Dumke 1975). As a result this model may contain all the errors introduced in the scalar theory of diffraction, in which light is treated as a disturbance that is incident on a finite aperture in an infinite opaque screen (Goodman 1968). Strictly speaking, laser diodes never meet this condition. Indeed, the standard Kirchoff diffraction theory cannot be applicable to the case of light emanating from the
DH laser diode, since the “aperture” (cleaved edge of the dielectric structure) is itself a “source” of electromagnetic radiation. Furthermore, to obtain an explicit solution of the diffraction integral, additional simplifications were made (Dumke 1975, Naqwi 1990): (a) the thickness of the laser diode active layer is infinitesimally small and (b) the obliquity factor in the diffraction integral is negligible. However it is known that the omission of the obliquity factor is allowed only in the paraxial region, that is much smaller than the cone determined by the beam divergence angles $\Theta_x$ and $\Theta_y$.

From the discussion above it can be seen that the two models, established under different assumptions, are only approximations to the field distributions emitted by actual laser diodes. Conventional curve-fitting techniques, used to approximate the experimental data on the laser diode optical irradiance distribution, show that a somewhat better match is given by the Gaussian model (Li 1992) in both planes. At the same time the Gaussian model simplifies the calculations, allowing one to treat the distributions in $xz$- and $yz$-planes in a similar fashion.

Thus we choose to regard the 2-dimensional optical mode profile of the laser diode generally as an elliptical $TEM_{mn}$ mode (normalized for unit power) that in rectangular geometry is given by

$$TEM_{mn} = \Psi_{mn}(x,y) = \psi_m(x)\psi_n(y)$$ (A.1.1)

with field amplitude distribution in the $x$-direction in a given $z$-plane

$$\psi_m(x,z) = \left(\frac{2}{\pi w_x(z) \cdot 2^n \cdot m!}\right)^{1/2} H_m\left(\sqrt{2} \frac{x}{w_x(z)}\right) \exp\left(-\frac{x^2}{w_x^2(z)} - ik \frac{x^2}{2R_x(x)}\right)$$ (A.1.2)
$H_m(x,z)$ are Hermite polynomials, $m$ and $n$ are the transverse mode numbers, $k = 2\pi/\lambda$ is the wavenumber, $R(z)$ is the radius of curvature of the phase front and $w(z)$ is the corresponding beam radius. For the fundamental Gaussian mode amplitude distribution, $m=n=0$, (A.1.2) reduces to

$$\psi(x) = \left( \frac{2}{\pi w_x} \right)^{1/2} \exp \left( -\frac{x^2}{w_x^2} - i k \frac{x^2}{2R_x} \right)$$

(A.1.3)

where we have omitted the $z$-dependence that modifies the modal profile on propagation. The field amplitude distribution in $y$-direction is written in a similar fashion by replacing $x$ with $y$ everywhere.

According to (A.1.3), the optical field satisfies a separability condition in transverse rectangular coordinates. This separable nature of the field would be preserved during transmission through a thin spherical lens, whose transfer function is given by

$$\exp \left[ -i \frac{k}{2f} (x^2 + y^2) \right]$$

(A.1.4)

Separability would be also be preserved during the passage through a thick lens, if it is not strongly decentered with respect to the beam (Goodman 1968).

### A.2 FUNDAMENTAL MODE OF A SINGLE-MODE FIBER

The shape of the fundamental $LP_{01}$ mode of a circularly symmetric step-index singlemode fiber (SMF) is similar to a Gaussian shape. To find the best Gaussian
approximation in this case, it is generally preferred to choose the Gaussian field that leads to the maximum coupling efficiency into a $LP_{01}$ mode.

As discussed by Marcuse (1979), for $0.8 \leq \lambda/\lambda_c \leq 2$, where $\lambda_c$ is the cut-off wavelength for the ideal step-index SMF, the $LP_{01}$ mode can be approximated with a good accuracy by the Gaussian distribution with waist (or modal field radius) $w_0 = a[0.65 + 1.619 V^{-1/2} + 2.879 V^{-6}]$. Here $V = ak\sqrt{n_{core}^2 - n_{cladding}^2}$ is the normalized thickness of the ideal step-index SMF, $a$ is the SMF core radius and $k$ is a wavenumber. For the Gaussian approximation in the case of graded-core fibers or fibers with cladding variations one can always use the parameters of the equivalent step-index fiber, calculated by various methods (Jeunhomme 1990).

A.3 COUPLING COEFFICIENTS FOR OPTICAL MODES: OVERLAP INTEGRAL

When a mode emanating from a guiding structure such as a laser resonator, is launched into another system, such as a waveguide, it excites a set of eigenmodes of that system. As the mode parameters of the two systems will, in general, not be matched, a single spatial mode laser beam will couple to several modes of the waveguide. The basic idea of calculating the coupling efficiency between two modal fields via the overlap integral between them was introduced by Kogelnik (1964) for spherical mirror resonators. Here we generalize it:
Let \((E_i, H_i)\) and \((E_j, H_j)\) be two different electromagnetic fields, normalized in such a way that

\[ \int_{S_i} n_i \cdot (E_i \times H_i) dS_i = 1 \quad (i=1,2) \quad \text{(A.3.1)} \]

where \(n_i\) is the unit vector on the \(i\)th mode axis and the integration is extended over the mode transverse section \(S_i\). The following relation connecting the modal field amplitudes \(A_1\) and \(A_2\) can be obtained in a given overlap plane:

\[ A_2 = A_1 \int_{S_1} (E_1 \times H_2^*) \cdot n_2 dS_2 = A_1 C_{12} \quad \text{(A.3.2)} \]

where the quantity

\[ C_{12} = \int_{S_2} (E_1 \times H_2^*) \cdot n_2 dS_2 \quad \text{(A.3.3)} \]

is called the overlap integral and gives the information about the matching of the two fields. Using the weak guiding approximation for the waveguide mode \((E_2, H_2)\) (i.e., \(n_{\text{core}} - n_{\text{cladding}} \ll 1\)) and plane wave approximation for the free-space mode \((E_1, H_1)\), one can simplify (A.3.3) by operating the normalized scalar transverse components of only the electric fields 1 and 2 in the overlap plane, \(\Psi_{1,2}\) (the transverse magnetic components are automatically matched approximately). In this case \(C_{12}\) assumes the simple form

\[ C_{12} = \int_{s_1} \Psi_1 \Psi_2^* dS_2 \quad \text{(A.3.4)} \]
Now, using the transverse \((x,y)\) Gaussian field distribution according to (A.1.1) and (A.1.2) and appealing to the orthogonality of the modal functions, the coupling coefficient (A.3.4) between two modes \(\Psi_{mn}\) and \(\Phi_{pq}\) can be written in a given \(z\)-plane as

\[ C_{\Psi\Phi} = c_{mp} \cdot c_{nq} \quad \text{(A.3.5)} \]

where

\[ c_{np}(x) = \int_{-\infty}^{\infty} \overline{\psi}_m(x) \phi_p(x) dx \quad \text{(A.3.6)} \]

as well as the corresponding expression for \(c_{nq}(y)\).

The presented approach has an interesting consequence: it can be easily seen that no coupling takes place between odd and even modes, i.e.

\[ c_{mp} = 0 \quad \text{for } m+p \text{ odd} \]

since the integrand in (A.3.6) becomes an odd function of its argument.
APPENDIX B

CHOICE OF THE OVERLAP PLANE.

As stated earlier, butt-coupling efficiency into a fiber depends on a variety of factors, including the modal overlap factor \( C_{LF,p} = C_{LF,p}(z,\theta,\delta) \) and the reflectances of the facets involved. To better understand the effect of the modal overlap on efficiency, we first investigate the variation of the coupling efficiency with respect to the position of the plane in which the overlap is considered.

In the case of lens coupling the following approach to calculation of the overlap integral is traditionally adopted. First, diffraction theory is applied to the field distribution at the laser facet to obtain the one at the entrance pupil of the optical system. Then the field in the exit pupil is determined by a transformation of the entrance pupil field. This transformation is directed by the ideal paraxial properties of the optical system and the coherent optical transfer function (which describes optical system aberrations). The field at the image plane (in our case - at the plane of the fiber entrance facet) is set, again, by applying diffraction theory to that one at the exit pupil plane. Finally, the power coupling efficiency is found using the square modulus of the field overlap integral of the image field distribution and the mode profile of the receiving fiber.

Such a description of the coupling efficiency calculation is conceptually convenient since it directly corresponds to the propagation of light through the optical
system from the source to the receiver. Although this suggests that the overlap integral
calculation should be carried out in the surface of physical coupling - on the input facet of
the receiver - in the case of lens coupling this computation can be performed in any other
plane within the optical system, provided that propagation from the laser and fiber facets
to the plane of interest satisfies the Fraunhofer approximation (Goodman 1968). Then the
fields obtained by propagating between the planes under consideration are related via a
Fourier Transform.

Indeed, in such a case the field overlap integrals for normalized fields \( \psi_n, \psi_m \) at
planes 1 and 2 are:

\[
\eta_1 = \iint \psi_n^* \psi_m \, dx \, dy,
\]
and

\[
\eta_2 = \iint FT(\psi_n) \, FT(\psi_m^*) \, dx_2 \, dy_2.
\]

Then, using Parseval's theorem (Goodman 1968):

\[
\int f(\alpha) g(\alpha)^* \, d\alpha = \int F(\beta) G(\beta)^* \, d\beta
\]  
(B.1)

and

\[
\int |f(\alpha)|^2 \, d\alpha = \int |F(\beta)|^2 \, d\beta
\]  
(B.2)

where \( F(\beta) = FT\{f(\alpha)\} \), \( G(\beta) = FT\{g(\alpha)\} \), we arrive at \( \eta_1 = \eta_2 \). Thus, the overlap
integral is shown to be an invariant of the lens-coupling system (at least in the paraxial
approximation).

For butt-coupling, however, the distance \( z \) between the laser and the fiber facets
does not satisfy the Fraunhofer assumption, which is \( z_{fr} \gg \pi (x_a^2 + y_a^2) / \lambda \) (Goodman
1968), since \( x_a \sim 3 \, \mu m \) and \( y_a \sim 1 \, \mu m \) are the dimensions of the cross-section of the
active laser layer. Because effective butt-coupling occurs at \( z_{bc} \leq 50 \ \mu m \) (Karioja and Howe 1996, Sidorin and Howe 1997), one can see that \( z_{fr} \gg z_{bc} \). Under these conditions the field distribution in a plane \( a \) cannot be described as a Fourier Transform of the field in a plane \( b \) (both planes are separated by \( z \leq z_{bc} \)). Under these conditions the overlap integral becomes the function of the overlap plane position.

To demonstrate the significance of the correct choice of the overlap plane, we calculated the butt-coupling efficiency using the butt-coupling model for the system described in Chap. 2 under the approximations considered in Appendix A. The results are presented in Fig. B1, where the coupling efficiency is defined as the ratio of the power coupled into the fiber to the power radiated by the butt-coupled laser output facet, \( \eta_{cou} = P_1 / P_2 \), see Fig.(2.6). Graphs \( L \) and \( F \) correspond to the calculation of the overlap between the laser and the fiber modes at different planes within the ESEC. \( L \) denotes the plane coincident with the output facet of the LD, while \( F \) corresponds to the overlap plane that lies at the SMF facet. Relative differences between the coupling efficiencies for the \( L, F \) and \( I \) cases (where \( I \) describes an intermediate overlap plane) normalized to that one for \( F \), are also presented.

For the demonstrated results \( I \) was selected to be in the middle of the ESEC. The error in determining the coupling efficiency, as well as the magnitude of the coupled power, is clearly dependent on the choice of the position of the overlap plane. This error
can be as high as 10% for \( z_{bc} \sim 20\lambda \). Changes in the characteristics of the Gaussian field on propagation between the fiber and laser would explain this significant difference.

![Figure B1](image)

**Fig. B1:** Efficiency of coupling between the LD (SDL5400) and SMF (\( w_f = 2.55\mu m \)), calculated in different overlap planes (L: LD facet, I: intermediate plane, F: SMF facet). Error, normalized to the F-plane calculation is shown in the inset. Misalignment parameters: \( \Delta \theta_x = \Delta \theta_y \approx 2^\circ, \delta_x = \delta_y \approx 20nm \).

Indeed, because of the nonlinear behavior of the orthogonal wavefront radii of the laser beam (which are, in general, different due to laser beam’s ellipticity and astigmatism), the corresponding radial phase undergoes significant changes within the butt-coupling region. The analogous phase terms for the fiber mode change similarly; the only difference is that the modal \( x \)- and \( y \)-distributions are equal due to rotational symmetry of the fiber mode.
As a result, the behavior of the overlap integral $C_{LF,p}$ and therefore the coupling efficiency differ depending on the choice of the overlap plane.

In view of these considerations we take the modal overlap integral in the SMF's facet plane, since physical coupling occurs in that plane.
APPENDIX C

THE MATERIAL GAIN SPECTRUM ESTIMATE

- We define the material gain per unit length as the proportional growth of the photon density $N_{ph}$ as it propagates along some direction in the crystal, and use the group velocity $v_{gr}$ to transform the spatial growth to the growth in time:

$$g = \frac{1}{N_{ph}} \frac{dN_{ph}}{dz} = \frac{1}{v_{gr} N_{ph}} \frac{dN_{ph}}{dt} = \frac{R_{stim}}{v_{gr} N_{ph}}$$

(C.1)

where $R_{stim}$ is the stimulated emission rate.

Using Fermi's Golden Rule (Kittel 1986) for $R_{stim}$ we obtain for the transition energy $E_{21}$

$$g(E_{21}) = \frac{2\pi}{\hbar} \left| H'_{31} \right|^2 \rho_r(E_{21}) \cdot (f_2 - f_1)$$

(C.2)

where $H'_{31}$ is the spatial overlap of the initial and final electron wavefunctions, or matrix element (in units of energy), $\rho_r$ is the reduced density of states (density of transition pairs per unit transition energy), $(f_2 - f_1)$ is the Fermi factor and $\hbar = 2\pi\hbar$ is Planck's constant. The matrix element was shown (Kittel 1986) to be dependent on the electromagnetic field vector potential $A_0$ and the transition matrix element $|M_r|^2$, that contains the polarization dependence of the electron-field interaction and restricts the types of states that can interact:
where $q$ is the electron charge and $m_0$ is the electron mass.

- The next step is to express the matrix element $|H'_{21}|$ in terms of the photon density $N_{ph}$. This can be done by relating the energy density of the time-harmonic electric field to the photon density

$$
\frac{1}{2} n_{gr}^2 \varepsilon_0 |E^2| = \hbar \omega N_{ph}
$$

(C.4)

where $n_{gr}$ is the active medium group refractive index and $\varepsilon_0$ is the electrical permittivity of vacuum. Using (C.4) and recalling that the electric field relates to the derivative of the vector potential, we rewrite (C.3) as

$$
|H'_{21}| = \frac{q^2 \hbar}{2n_{gr} \varepsilon_0 m_0^2 \omega} |M_T|^2 N_{ph}
$$

(C.5)

- Assuming a bulk Al$_x$Ga$_{1-x}$As active layer, $x \sim 1\%$, and neglecting the presence of light-holes, the reduced density of states can be expressed as

$$
\rho_r (E_{21}) = \frac{\sqrt{E_{21} - E_g}}{2\pi^2} \left[ \frac{2m_r}{\hbar^2} \right]^{3/2}
$$

(C.6)
where \( m_r \approx \frac{m_e m_h}{m_e + m_h} \) is the reduced mass, \( m_e = 0.067 m_0 \) is the effective mass of electron and \( m_h = 0.55 m_0 \) is the effective mass of heavy holes in GaAs (Palik 1985).

Also, assuming the parabolic band approximation (Kittel 1986),

\[
E_{21} = E_g + \frac{\hbar^2 k^2}{2 m_r} \tag{C.7}
\]

and (Jani et al. 1985)

\[
E_g = 1.424 + 1.247 x, \tag{C.8}
\]

energy values being measured in eV.

- Observing momentum conservation (k-selection rule), the transition matrix element \( |M_r|^2 \) for a given polarization is taken to be a constant that can be inferred from experimental measurements; for TE-polarization it is equal to (Jani et al. 1985)

\[
|M_r|^2 = \frac{1}{3} \left[ 29.83 + 2.85 x \right] \frac{m_0}{2} \tag{C.9}
\]

- In addition, neglecting lineshape broadening, (C.2) is finally re-written with the help of (C.5), (C.6) and (C.9) as

\[
g(E_{21}) = g_{max}(E_{21})(f_2 - f_1) \tag{C.10}
\]

where \( g_{max}(E_{21}) = \frac{\pi q^2 \hbar}{\eta \varepsilon_0 c m_0^2} \frac{1}{h \nu_{21}} |M_r(E_{21})|^2 \rho_r(E_{21}) \) is the maximum gain.
In estimating the Fermi factor the carriers are treated as an ideal Fermi gas in 3D and the following approximation was used for the chemical potential $\mu$:

$$\beta \mu \approx \ln \nu + K_1 \ln(\nu K_2 + 1) + K_3 \nu$$  \hspace{1cm} (C.11)

with $K_1=4.8966851$, $K_2=0.04496457$ and $K_3=0.1333760$ valid for $\nu \leq 50$, where

$$\beta = \frac{1}{k_B T}, \quad \nu_i = \frac{2}{\sqrt{\pi}} \frac{N_i \beta^{3/2}}{A_i}, \quad A_i = \frac{1}{2\pi^2} \left( \frac{2m_i}{\hbar^2} \right)^{3/2}, \quad k_B \text{ is the Boltzmann constant, } N_i \text{ is the carrier concentration, and } i \text{ implies a particular type of carrier (Haug and Koch 1990).}$$

Fig. C.1 illustrates the gain spectrum shift dependence on the threshold condition.

---

**Fig. C1:** Change in the gain spectrum of a AlGaAs-LD. Two extreme points of threshold condition modulation are shown: in this example these correspond to $I_{\text{thr}}=19\, \text{mA}$ and $I_{\text{thr}}=35\, \text{mA}$.
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