Spatial and Spectral Brightness Enhancement
of High Power Semiconductor Lasers

by

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Biographical Sketch

The author was born in San Antonio, Texas. He attended the University of Texas at Austin, and graduated with a Bachelor of Science degree in electrical and computer engineering. He graduated with honors with foci in electromagnetics and solid-state devices. He began doctoral studies in optics at the University of Rochester's The Institute of Optics in 2007. He was awarded a GAANN Fellowship and Horton Fellowship. He pursued his research in spatial and spectral brightness enhancement of high-power, broad-area, semiconductor lasers under the direction of Dr. John R. Marciante.

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Abstract

The performance of high-power broad-area diode lasers is inhibited by beam filamentation induced by free-carrier-based self-focusing. The resulting beam degradation limits their usage in high-brightness, high-power applications such as pumping fiber lasers, and laser cutting, welding, or marking. Finite-difference propagation method simulations via RSoft’s BeamPROP commercial simulation suite and a custom-built MATLAB code were used for the study and design of laser cavities that suppress or avoid filamentation. BeamPROP was used to design a tapered, passive, multi-mode interference cavity for the creation of a self-phase-locking laser array, which is comprised of many single-mode gain elements coupled to a wide output coupler to avoid damage from local high optical intensities. MATLAB simulations were used to study the effects of longitudinal and lateral cavity confinement on lateral beam quality in conventional broad-area lasers. This simulation was expanded to design a laser with lateral gain and index prescription that is predicted to operate at or above state-of-the-art powers while being efficiently coupled to conventional telecom single-mode optical fibers. Experimentally, a commercial broad-area laser was coupled in the far-field to a single-mode fiber Bragg grating to provide grating-stabilized single-mode laser feedback resulting in measured spectral narrowing for efficient pump absorption. Additionally a 19 GHz-span, spatially resolved, self-heterodyne measurement was made of a broad-area laser to study the evolution/devolution of the mode content of the emitted laser beam with increasing power levels.
Contributors and Funding Sources

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List of Symbols and Abbreviations

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| $\alpha$ | Absorption value or gain-index coupling coefficient/
|        | linewidth enhancement factor |
| $\%$  | Percent |
| $^\circ$ | Degree |
| $\mu$ | Symbol for the prefix micro- meaning $10^{-6}$ or cartesian direction offset |
| 2-D   | Two dimensional |
| A     | Unit of measure Amperes |
| B     | Spontaneous emission coefficient |
| BAL   | Broad area laser |
| BPM   | Beam Propagation Method |
| C     | Celsius |
| c     | Prefix for centi- $10^{-2}$ or the speed of light |
| CBC   | Coherent beam combining/combination |
| clad  | Cladding |
| COD   | Catastrophic optical damage |
| $D$   | diffusion constant |
| $d$   | Gain layer thickness |
| DBR   | Distributed Bragg reflector |
| DCF   | Dual clad fiber |
| $D_{zGH}$ | Goos–Hänchen shift value |
| E     | Electric field |
| EDFA  | Erbium doped fiber amplifier |
| Eqn.  | Equation |
| FA    | Fast-axis cylinder |
| FBG   | Fiber Bragg grating |
| FF    | Far-field |
| FFT   | Fast Fourier transform |
| Fig.  | Figure |
| FP    | Fabry–Pérot |
| FWHM  | Full width half-maximum |
| G     | Prefix for giga- $10^9$ |
| $g$   | Small signal gain |
| GaAs  | Gallium Arsenide |
\( h \)  
Planck's constant divided by 2\( \pi \)

\( J \)  
Injected current density

\( k \)  
Optical propagation constant

\( k_0 \)  
Vacuum wave vector

LP  
A mode in linear polarization form followed by order indicators

\( m \)  
Meters or prefix milli- meaning 10^-3

\( M^2 \)  
Beam quality metric, m-squared

MMI  
Multi-mode interference

MOPA  
Master oscillator power amplifier

\( N \)  
Free-carrier density

\( n \)  
Variable for refractive index or prefix meaning nano- 10^-9

\( N_0 \)  
Transparency free-carrier density

NF  
Near-field

\( n_r \)  
Variable for cladding index

Pol. Cont.  
Polarization controller

\( q \)  
absolute value of the charge of an electron

RF  
Radio frequency

RMS  
Root mean square

SCOWL  
Slab-coupled optical waveguide laser

SM  
Single-mode

SMA  
SubMiniature version A connector for coaxial RF cables

SMF-28  
Designation for a common telecom single-mode optical fiber

TIR  
Total internal reflection

VBG  
Volume Bragg grating

\( W \)  
Unit of measure Watt/s

\( W \) or \( w \)  
Waveguide full width

\( w_0 \)  
Unperturbed waveguide full width

\( x,y,z \)  
Variable for orthogonal Cartesian coordinates

\( X,Z \)  
Variable for normalized coordinates for x and z

\( x0 \)  
Unperturbed x coordinate

\( \alpha_{eff} \)  
Effective absorption value

\( \Gamma \)  
Transverse confinement factor

\( \Delta \)  
Capital delta used to indicate a change in a variable

\( \Delta \nu \)  
Separation frequency

\( \theta \)  
Variable for geometric or phase angle

\( \theta_c \)  
Critical angle for total internal reflection

\( \lambda \)  
Variable for wavelength
\( \pi \) Pi, ratio of a circle's circumference to its diameter
\( \sigma \) Standard deviation
\( \nu \) Frequency
\( \omega \) Angular frequency
Chapter 1: Introduction to Broad-Area Laser Brightness

I. Background

Semiconductor diode lasers, demonstrated in parallel by Robert Hall at General Electric and Marshall Nathan at IBM in 1962, have a number of distinct properties that offer dramatic benefits and challenges when compared to other lasing media [1, 2]. Since the invention of the laser diode, lithographic manufacturing techniques shared with the well-funded computer chip industry, as well as the laser diode's compact size and high electrical-to-optical efficiencies, have pushed this source into a world desiring coherent light [3]. The utility of the laser diode has driven the number of devices manufactured annually to orders of magnitude greater than that of other lasers. Diode lasers have supplanted other, bulkier, light sources, in applications ranging from consumer optical data storage to the optical pumping of other lasers [4, 5].

While high temperatures have historically been a limiting factor for laser diodes, requiring the first such diodes to be cooled with liquid nitrogen to achieve sufficient gain for lasing, optical power density is presently the limiting factor for prominently useful diode lasers [2, 6]. Semiconductor lasers manufactured by commercial manufactures such as nLight have achieved wall-plug efficiencies as high as 76% for water-cooled devices [7]. The cross-sectional waveguide dimensions of single-mode devices tend to be around 1.3-μm tall and 5-μm wide. The 5-μm width limits the device from operating
with multiple lateral modes. The 1.3-µm height is preferred for a number of additional reasons involving the control of electric field interaction with the gain, efficient electrical pumping of the gain, and lithographic economic pressures to avoid long vertical growth times during manufacture. This small cross-sectional area causes single-mode laser diodes to reach the limits of catastrophic damage due to high optical field intensities. The electric field is enhanced around defects in the crystal such as the lasing facets [8]. Facet passivation techniques have been developed which push the catastrophic optical damage (COD) limits to ~1 Watt for single-mode diodes, but the desire for drastic increases in output power have required that dimensions of laser diodes be pushed beyond the conventional single-mode laser diode regime [9].

The simplest method for bypassing the COD limit is to create a wider device. This device is referred to as a broad-area laser (BAL). Widening the device causes the lateral waveguide, and thus the laser, to be able to support multiple modes. Higher-order spatial modes have lower brightness, at the same output power, than the fundamental mode, partially defeating the benefits of progressing to higher power. When the beam deviates from its approximately lowest-order Gaussian profile, it can no longer be focused as finely, causing degraded irradiance and resolution performance in welding, marking, and cutting applications. Additionally, the ability to couple light into single-mode waveguides, for example an optical fiber laser, decreases with multi-mode behavior. In other gain media, this problem is often overcome by adding a simple spatial filter or utilizing an unstable resonator cavity, however, this is not sufficient in semiconductor gain media. In semiconductor laser material, the refractive index has a
relatively large dependence on the free-carrier density, equivalent to the density of excited atoms in a conventional laser medium. This free-carrier density is proportional to the gain when used in a laser cavity and changes laterally across the cavity with saturation of the gain from a propagating beam. As the absorption peak of the material is pushed to higher energy, the Kramers-Kronig relation (in a form as it pertains to refractive index)

\[
n_1(\omega) = 1 + \left( \frac{2}{\pi} \right) P \int_0^\infty \frac{\omega' n_2(\omega')}{\omega'^2 - \omega^2} d\omega' \\
n_2(\omega) = \left( -\frac{2}{\pi} \right) P \int_0^\infty \frac{\omega n_1(\omega')}{\omega'^2 - \omega^2} d\omega' \tag{1.1}
\]

describes a shift in the refractive index that follows the shift in the band-gap absorption peak, shown pictorially in Figure 1.1. In this equation, \( n_1 \) and \( n_2 \) are the real and imaginary parts of the refractive index, respectively, and the \( P \) represents the Cauchy principal value. The optical absorption coefficient is related to the imaginary refractive index by

\[
\alpha(\omega) = \frac{2n_2(\omega)\omega}{c} \tag{1.2}
\]

This leads to a reduction of the refractive index in areas of high free-carrier density for slightly sub-bandgap light, with a more drastic affect the closer the light is to the original bandgap energy [10].
Fig. 1.1. An increase in free-carrier density shifts the absorption at the bandgap of a semiconductor to higher energy. By the Kramers-Kronig relation, the refractive index of the material shifts along with the absorption peak, lowering the refractive index of the material to the lower photon energy side of the peak.

A peaked beam profile, such as a Gaussian, propagating in this pumped medium will extract more free carriers toward the center of the peak through stimulated emission, thereby raising the refractive index where free-carriers are depleted. The result is a material of gradient index that focuses light passing through it. Focused light, however, will create a stronger gradient index and thus a stronger lens leading to a runaway process until the degree of focusing balances with diffraction. The resulting small beam leaves a large volume of unsaturated gain media available to generate other such small beams that interact chaotically with one another in a process called filamentation [11]. Filament generation is depicted in Figure 1.2.
Fig. 1.2. Centrally saturated free-carriers create a focusing refractive index profile that modifies the fundamental electric field distribution from that represented by the broad-shaped dashed line to that of the narrow-shaped solid line. This leaves large gain (above lasing threshold) to be utilized by small perturbations (i.e. from spontaneous emission or crystal imperfections) in a multi-mode supporting waveguide.

II. High Spatial Brightness Design

There have been a number of methods attempting a scalable means of creating high-power, high-quality beams from broad-area semiconductor lasers. Monolithic techniques add complication to the lithographic process, but result in a robust and compact system, while external techniques for modifying conventional BAL behavior have the advantage of being tested and modified during the build process. Dente created a BAL with high beam quality by selectively removing a semicircle from one of the
semiconductor facets creating a monolithic unstable cavity, but powers only reached 600 mW before filamentation occurs [12]. Ultimately, these techniques fail due to the ability of strong gain-index coupling to significantly perturb the propagating beam within one pass through the cavity, causing degradation of even the most pristine feedback seeds into chaos before once again reaching the filter. Two tapered schemes have seen commercial success. One such tapered laser includes a single-mode laser section to seed a tapered section, which allows free diffraction while increasing in power. The reflection off of the broad cavity facet then partially couples back to the single-mode section creating a bulk spatial filtering effect [13]. Gain extracted during the otherwise free diffraction in the lateral dimension, as well as oppositely curved wave fronts from the broad reflector, reduce the tendency of filamentation within the laser. The other tapered design is the tapered master oscillator power amplifier (MOPA) which is similar to the previously described design, but the laser cavity is lithographically written into the single mode section of the device and the tapered section serves only as an amplifier external to the laser cavity. In addition to extracting gain while diffracting, this design benefits from not having a backward propagating beam in the broad-area section, which would otherwise enhance the free-carrier lens formation [14].

Other techniques for improving BAL beam quality show greater potential to scale with power. The slab coupled optical waveguide laser (SCOWL) uses large single-mode areas in two dimensions to reduce interaction between the electric field and the gain in addition to coupling unwanted higher-order modes into a lossy external cavity [16]. Though each SCOWL still ends up being restricted to relatively low powers, their
symmetrical beams are desirable for practical implementation of the lasers, and the slab coupled modes can be used to phase lock an array of SCOWLS on the same chip. One of the more interesting attempts to make a filamentation-free BAL is the angled-grating distributed feedback laser (α-DFB), also depicted in Figure 1.3 (c). This laser utilized an angle cavity with respect to the facet and a refractive index grating along the length of this tilted cavity. The desired k-vectors corresponding to plane-wave propagation are directed at the reflective facets to form a laser cavity while undesired perturbative k-vectors are nominally unaffected by the grating and quickly exit the cavity. This laser has benefits over lump filtering methods in that undesired spatial components of the light are stripped in a distributed fashion before they have experienced the gain of a full pass through the cavity, drastically reducing their ability to perturb the system [17].

External techniques for achieving high brightness BALs involve creating an external cavity for the broad-area gain medium with some form of filtering element included. This filtering is often in the form of mirrors placed in the far-field emission pattern that have had their lateral extent limited so that they only provide feedback to nearly a single lateral mode of the laser cavity [15]. In most cases, only a single lobe of a twin-lobed higher-order mode is fed back into the cavity; however experiments with double-lobed feedback have shown drastic improvement in beam quality and maximum operating power over the single-lobed case [15]. The field of coherent beam combination also often falls within the scope of external-cavity high-brightness lasers [18]. In passive coherent beam combination, a number of small emitters are placed within a cavity which requires a fixed phase-relation between the emitters in order to reduce the loss of
feedback. This inter-element phase-locking is achieved by making sure the case where the lowest loss occurs is one in which each emitter feeds back to all of the emitters in the system [19]. However, despite the potential simplicity of a passive system, active control of the relative phases of the emitters has seen the most success at the cost of the extensive, continuous monitoring of the phases in question [18].

Sample Filamentation-Suppression Designs

Fig. 1.3. Pictorial representations of past attempts at filamentation suppression in BALs. From left to right a) shows an unstable cavity reflecting facet, b) represents either a tapered cavity or MOPA configuration, and c) shows the α-DFB laser.

II. High Spectral Brightness Design

The multi-mode nature of high-power diode lasers makes the development of a single grating for all lateral modes (modes of differing k-vectors) difficult. For applications such as marking and welding, a narrow and stable emission spectrum at a
material absorption peak allows for more controlled surface heating. For optical pumping, a narrow and stable pump means the ability to create a physically smaller or lower concentration gain medium for pump absorption. Like the spatial problem, spectral control has filtering methods both internal and external to the diode. Internally, a distributed Bragg reflector (DBR) can be written into the device to narrow the spectrum, but the semiconductor refractive index near lasing wavelengths changes drastically with temperature and this causes shifts in the grating resonance and thus the emission wavelength [20]. An external-cavity volume Bragg grating (VBG) can also be used to stabilized and narrow a BAL’s spectral operation [21]. Using a VBG has the benefit of being more stable with respect to temperature, but requires additional optical alignment compared to an on chip solution.

### III. Content Preface

This thesis covers a broad range of topics with the purpose of understanding and offering means of improving the brightness of laser diode systems with a focus on improving beam quality at powers higher than are achievable by single mode diodes. Chapter 2 covers the computational tools and the physics described by them. Chapter 3 contains the modeling results of tapered multi-mode interference coupling for potential use in obtaining broad-area powers and power densities from single-mode laser gain structures with good beam quality. Chapter 4 inspects, through computational modeling, the effects of cavity confinement on the power and brightness of simple BALs. Chapter 5 uses computational modeling to pose a solution to a power-limited, filamentation-free
BAL design through the understanding of the impact of internal refractive-index profiles on the design. Chapter 6 covers experimental exploration of the use of off-axis far-field fiber Bragg grating (FBG) feedback to a broad-area laser and provides foundation for a provisionally patentable idea for narrowing and stabilizing BAL spectrum and improving brightness. Chapter 7 describes the passive probing of the spatial and spectral mode structure of a BAL via self-heterodyne RF detection of mode beating for the purpose of understanding the interplay between waveguide modes and filamentation. Chapter 8 will offer conclusions and branches of research revealed in the course of this work.

REFERENCES


Chapter 2: Computational Tools and Methods

I. Introduction

The costs of state-of-the-art experiments can often drastically outstrip funding sources. Additionally, it is financially unwise to undergo costly experiments without a theoretical foundation that indicates some successful outcome. In some cases this foundation can be obtained analytically, but when problems become too dynamic and complex, as is the case for filamentation in broad-area semiconductor lasers, modern scientist turn to computational methods for solving problems.

II. RSoft’s BeamPROP

Chapter 3 of this dissertation involves the design of a multi-mode interference (MMI) coupler for use in coherent beam combination of a number of single-mode gain regions into a wave-guided laser without exceeding the flux densities that limit single-mode devices, while simultaneously maintaining beam quality. To do this, a commercial tool called BeamPROP made by RSoft was used. BeamPROP has a CAD interface for describing waveguide structures. For this work, two-dimensional analysis was sufficient since the third dimension is constrained to be single mode by the physical structure of the semiconductor growth process. BeamPROP uses the finite-different beam propagation method (FD-BPM) for simulating optical propagation in waveguides. For multi-mode design, RSoft recommends the use of higher-order Padé approximation, which includes additional Taylor expansion terms in the one-directional beam propagation equation in
order to more accurately represent non-paraxial propagation. Critical dimensions of lateral and longitudinal step sizes were decreased to the point where differences in step sizes were negligible. BeamPROP's feature of being able to add statistical variations to the designed structure were used to simulate manufacturing imperfections [1].

II. Custom MATLAB BPM

For Chapters 4 and 5 of this work, the options from available commercial code were not sufficient to model all of the relevant physics of the problem, namely spatially saturable gain and the related free-carrier index changes. Therefore, custom code was written within MATLAB to include these effects and allow any desired aspect of the simulation to be modified and understood. The basic structure of the code is a Fox-Li based, split-step, Fourier BPM [2]. Forward and backward traveling wavefronts are propagated in a simulated cavity described by the equations

\[
\frac{\partial E_f}{\partial z} = i \frac{\partial^2 E_f}{\partial x^2} + E_f \left[ \frac{1}{2} (1-i\alpha)g(N) - \frac{\alpha_{\text{int}}}{2} \right] \tag{2.1}
\]

\[
-\frac{\partial E_b}{\partial z} = i \frac{\partial^2 E_b}{\partial x^2} + E_b \left[ \frac{1}{2} (1-i\alpha)g(N) - \frac{\alpha_{\text{int}}}{2} \right] \tag{2.2}
\]

where \( k = n_{\text{eff}}*k_0 \), \( \Gamma \) is the transverse confinement factor, \( \alpha \) is the linewidth-enhancement factor, \( \alpha_{\text{int}} \) is the internal loss, and \( g(N) \) is the local carrier-dependent gain defined by the equation \( g(N) = a(N-N_0) \), where \( a \) is the gain cross-section and \( N_0 \) is the transparency carrier density. When propagated in the cavity, these forward and backward traveling
waves are coupled to one another by facet reflections, as well as their effects on the carrier density and thus the gain and refractive index. The carrier density distribution coupling these two waves is described by

\[
D \frac{\partial^2 N(x, z)}{\partial x^2} = - \frac{J(x, z)}{qd} + \frac{N(x, z)}{\tau_{nr}} + BN^2(x, z) + \frac{\Gamma g(N)}{\hbar \omega} \left( |E_f|^2 + |E_b|^2 \right)
\]  

(2.3)

where \( D \) is the diffusion constant, \( J(x, z) \) is the injected current density, \( q \) is the absolute value of the charge of an electron, \( d \) is the gain layer thickness, \( \tau_{nr} \) is the non-radiative lifetime, \( B \) is the spontaneous-emission coefficient [3]. The algorithm for solving this system is depicted in block-diagram form in Fig. 2.1.

**BPM Block Diagram**

- Start from noise (constant amplitude, random phase)
- FFT of the electric field
- Electric field propagation in Fourier space
- Inverse FFT to real space
- Solve carrier diffusion equation to find carrier density
- Determine the effects on the complex refractive index and add the effects of any fixed waveguide
- Multiply by the effects of the spatially varying complex refractive index for the effects of gain
- Repeat for each longitudinal step
- Apply cavity facet boundary and repeat for opposite traveling wave

**Fig. 2.1.** Workflow of BAL simulation.
When utilizing a simulation, it is important to verify that the results mimic reality using understandable and verified test cases. For this BPM code, the free-space propagation was tested to check that the results for a Gaussian input matched those analytically predicted. The values of the free-carriers and thus gain were verified to saturate to values above transparency in a lasing configuration. The gain medium was checked to ensure that it properly photo-bleached in the absence of electrical pumping. With the addition of a free-carrier refractive-index term, the simulated propagating beam was verified to self-focus.

Fig. 2.2. BAL simulated emission was shown to resemble commercial BAL specification. The solid line represents Alfalight diode specifications, while the dashed line is determined by BAL simulation using available parameters for modern devices.

The simulation is designed to model a BAL, so comparing the simulation output to a commercial BAL laser is of critical value. In fact, without such validation, the
simulations cannot be made to reliably predict physics, let alone be used for specific device design. To do this validation, the simulation must be made three dimensional by attributing the profile of a slab waveguide to the transverse (vertical) dimension of the device. Using commercially reported parameters for broad-area lasers (expanded upon in Chapter 3) the simulation produced an emission of typical commercial divergence angle as well as a current vs. power that closely matches commercial specifications, shown in Figure 2.2. Small differences may be accounted for in the uncertainty of a few parameters obtained across the literature from multiple devices, as not all of the required parameters are given for any single device (likely to protect intellectual property). Additional confidence was developed in the model’s ability to recreate the highly asymmetric, two-lobed emission of the tailored BAL experimentally demonstrated by Yariv et al. [4]. With the addition of a predicted index step due to thermal refractive-index changes at higher powers, the simulation of Yariv's BAL failed similarly to the experimental device. This strong correlation between the model and this complex device significantly enhanced the model’s veracity.

In Chapter 4, statistical variation in current and refractive index were included to emulate manufacturing imperfections. Additionally, a two-dimensional, finite-difference thermal model of the system was included with resistive and optical sources of heat [5]. The results of this model were integrated into the optical model by starting the BAL system at low current (sub-threshold) and running the simulation until it stabilized. At this point the thermal refractive-index profile is determined and updated in the BAL split-step section. Current is then slightly increased and this process repeats until the
desired operating current is reached. This is represented in the algorithm diagram by the dashed box. This is done to represent a system where free-carrier refractive-index changes occur much faster than thermal changes.

III. Box Model of BAL

Broad-area laser modes are often compared to an analytic “Box Model” [6]. This radically simplified description of BALs represents their modal structure purely as sinusoids terminating abruptly at the waveguide boundaries. Note that such a model cannot predict complicated physics, such as filamentation dynamics. Lateral modes are distributed spectrally by the equation

\[ \omega_{mp} = \omega_{m0} + \frac{\pi c \lambda}{4n^2W^2} p^2 \]  (2.4)

Where \( m \) represents a longitudinal mode index for an angular frequency \( \omega \) and \( p \) the lateral mode index [6]. The speed of light is represented by \( c \), \( \lambda \) is the vacuum wavelength, \( n \) is the center refractive index, and \( W \) is the width of the waveguide. This Box Model is used to predict spatial and spectral patterns for the beat frequencies between modes in a self-heterodyne experiment by Stelmakh and Vasilyev [6]. In this work, mode spectral-width is included heuristically as the precise mechanisms are neither included nor germane to this analysis. The present work reintroduces the modeling of longitudinal modes omitted of Stelmakh and Vasilyev. Specifically, Chapter 7 extends their work to increased operating currents and recognizes that inter-longitudinal-mode beating is relevant at radio frequencies well below the longitudinal mode spacing. The
model is primarily used to accentuate the differences between the model and a physical device.

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Chapter 3: Tapered Multi-Mode Interference Beam Combiner for Self-Organized Array Lasing

I. Introduction

Semiconductor lasers are highly desirable for their high efficiency, compact size, high reliability, and ability to convert electrons directly into photons. However, effects such as thermal rollover, catastrophic optical damage, and other nonlinear effects limit the laser power that can be produced by semiconductor lasers [1]. Coherent beam combining (CBC) via evanescent wave coupling [2], common resonator coupling [3], injection locking [4], and self-organizing [5] methods can reduce the power demand and heat generated by any individual laser by combining the output of multiple lasers into a single coherent beam. In this chapter, a self-organizing cavity is proposed which uses a tapered planar multi-mode interference (MMI) coupler to coherently combine single-mode semiconductor lasers into the fundamental mode of a wide-output waveguide.

The principles behind an MMI coupler are similar to those of the Talbot effect [6]. The nearly free-space propagation of light in the multi-mode region generates scaled self-images of the input at various lengths down the multi-mode region due to the periodicity induced by the reflecting walls of the region. This effect can be used to create a power splitting/combining device that can serve as part of a semiconductor laser-array cavity, as shown in Fig. 3.1. When inputs with the correct phase relation are applied to the MMI, the power in each of the ports of an Nx1 coupler will combine from the multiple port side into the opposing single port provided the length is chosen properly.
Upon reflection at the output coupler, the power will redistribute among the N ports after propagating through the MMI region once again. This redistribution provides each gain element feedback from the other gain elements, coupling all of the elements together. When used as part of the laser cavity, only the wavelength and phase relations that provide the proper coupling between opposing ends of the MMI region will allow sufficient feedback to reach lasing threshold. This is the concept of a self-organized laser array [5], and has resulted in recent work using MMI coherent beam combining [7-10].

**Self-Organized MMI Laser Schematic**

![Self-Organized MMI Laser Schematic](image)

Fig. 3.1. Schematic of a 1x4 self-organized MMI laser architecture.

A successfully combined laser will still have a problem with the intensity of light at the output coupler causing catastrophic optical damage; the power at the output is N-times higher than each individual element yet has the same beam size. To compensate
for this shortcoming, a tapered MMI region is proposed to allow for a wider output coupler. Fig. 3.2 shows this modified version, tapered in the manner relevant to this work. This solution offers rugged, monolithic (non-free-space) CBC while avoiding catastrophic optical damage at the combined output and maintaining fundamental mode output.

**Tapered MMI Coupler Dimensions**

![Tapered MMI Coupler Dimensions Diagram]

Fig. 3.2. Schematic of a 1x4 tapered MMI coupler as described in this work. It is important to keep in mind that in all representations of MMI couplers presented, the vertical and horizontal scales are significantly different.

The remainder of this chapter is organized as follows. The physical design and modeling of this device are described in Section II. The physical operation of the device is described in Section III. The performance attributes of this device, particularly with
respect to practical fabrication and operation issues are described in Section IV. A discussion and concluding remarks are provided in Section V.

II. Numerical Model

Beam propagation in two dimensions is described by

$$\frac{\partial E(x, z)}{\partial z} = \frac{i}{4\pi} \frac{\lambda}{n_r} \frac{\partial^2 E}{\partial x^2} + \frac{i2\pi n_r}{\lambda} \left( \frac{n^2(x, z) - n_r^2}{2n_r} \right) E \quad (3.1)$$

where $E$ is the electric field, $z$ is the axial dimension, $x$ is the transverse dimension, $n_r$ is a reference index, $n(x,z)$ is the spatially resolved refractive index structure that defines the waveguide, and $\lambda$ is the free space wavelength. This differs from Eqn. 2.1 in that Eqn. 2.1 includes the complex contributions of gain while Eqn. 3.1 explicitly shows the effects of a passive waveguide. To underscore the inherent scaling of such the proposed MMI device, consider normalizing the spatial coordinates by defining $Z = z/(n_r/\lambda)$ and $X = x/\lambda(n_r/\lambda)$. Letting $n_c$ be the cladding index, assuming a small index step $\Delta n(x,z)$ in the core, and normalizing the spatial coordinates yields an equation that is only depends on the relative refractive index step:

$$\frac{\partial E}{\partial Z} = \frac{i}{4\pi} \frac{\partial^2 E}{\partial X^2} + i2\pi \left( \frac{\Delta n(x, z)}{n_{clad}} \right) E \quad (3.2)$$

This equation clearly shows that any waveguide can be scaled in dimension by the factor $(\lambda/n_r)$ provided the index step $\Delta n/n_r$ remains constant. Such a realization allows the selection of all physical factors with impunity without losing generality of the analysis. A specific example demonstrating this effect will be presented in Section III.
The MMI waveguide couplers were modeled in 2-D using the beam propagation method and RSoft’s commercial package [11] (described in Chapter 2) to compute Eqn. (3.1). Fully transparent boundary conditions and 4\textsuperscript{th}-order Padé approximations were used with computation steps of 0.1 microns in the transverse direction and 1 micron in the propagation direction. The MMI waveguide couplers are of a 1xN form. The N number ports are 5-microns wide to match the mode size of commercial single-mode laser diodes. The single-port waveguide is N-times wider than the opposing N ports. The step above ambient index used is 0.01, which is easily attainable in a rib waveguide, over a base index of unity used for generalized analysis. The design wavelength was also chosen to be 1 micron for generality, and lossless transmission was assumed.

The width of the MMI section at the multi-port end of the waveguide is selected to be nominally 50 microns per port. Selecting a narrower MMI section by allowing the narrow ports to be closer together will result in a shorter device; however, placing the ports too close together will cause undesirable coupling between the ports prior to entering the MMI region. A linear taper is used to change the width of the MMI region to a larger size at the single port-side with the intent to maintain peak intensity comparable to that of the multi-port gain elements across the MMI, giving the MMI region a flared appearance.

Multiple tapered MMI structures were studied, with 1x2, 1x4, and 1x8 geometries. The N ports were distributed with equal spacing about the center of the MMI region. When the port spacing was allowed to vary to optimize transmission, the port pitch was changed to 51.2, 50.6, and 50.3 microns for 1x2, 1x4, and 1x8 couplers,
respectively. The flared width and coupler length were varied in each design to find the maximum transmission of the fundamental mode launched in the wide output port. Though initially modeled for transmission from 1 to N ports, the system exhibits natural reciprocity, as is demonstrated in Section IV.

III. Device Physics

Modeling the 1x2, 1x4, and 1x8 tapered MMI couplers all followed the same method. The number of ports and their initial pitch determines the width of the multi-port side of the device. The width of the MMI region at the single-port side was varied and the optimum length was found for each width. The term “flare ratio” is used to describe the ratio of the width of the MMI waveguide of the single-port side to that of the multi-port side. The transmission of the device is specified as single-mode transmission and is defined by the ratio of power in the fundamental mode at the output of the device to the total power launched into the input of the device. The power in the fundamental mode at the output is determined by a mode overlap integral of the propagated complex field at the output with the fundamental mode of the output waveguide.

Fig. 3.3 (solid) shows the fundamental mode transmission for the 1x8 coupler optimized at various flare ratios. The maximum simulated value for the 1x8 coupler was found to be at a flare ratio of 5 with a fundamental mode transmission of 98%. Although not plotted, the maximum transmission values for the 1x4 and 1x2 couplers were also around 98% at flare ratios of 2.63 and 1.5 respectively. These results demonstrate that
the optimum flare ratio for coupling to an Nx5 micron waveguide is not N, thus implying that the taper is not performing an adiabatic transformation. In this 1-to-N configuration, the remaining power is radiated out of the coupler at the narrow end of the MMI region. In an N-to-1 configuration ~1.5% of the power is radiated from the waveguide, with the remaining power coupling into higher order modes of the broad-area waveguide.

![Optimum Flare-Ratio Design Plot](image)

**Fig. 3.** Simulated maximized fundamental mode transmission (solid) and length required to maximize the transmission (dashed) as a function of flare ratio for a 1x8 flared MMI coupler. The flare ratio is the unit-less ratio of the lateral width of the single-port side of the MMI to that of the multi-port side.

Fig. 3.4 (a) shows an intensity map of light in a 1x8 tapered MMI coupler when light is launched into the fundamental mode of the wide port. Fig. 3.4(b) shows an intensity map of light in a standard 1x8 MMI coupler when excited in the same manner. Fig. 3.4(c) shows the same image of the tapered MMI coupler where the dimensions have
been skewed so that the boundaries of the MMI region match those of the rectangular MMI coupler. This results in the two patterns being nearly identical. This could suggest adiabaticity or geometrical similarity, but additional details presented later indicate the latter.

**Comparison Between Conventional and Tapered Multi-Mode Interference**

![Intensity Maps](image)

Fig. 3.4. Intensity maps of (a) flared and (b) (continued on the next page) standard 1x8 MMI couplers. (c) (continued on the next page) A skewed intensity map of the flared coupler in (a) with a resulting pattern that matches the standard coupler in (b).

For the 1x8 coupler, the optimum length as a function of the flare ratio is shown in Fig. 3.3 (dotted). This plot shows a linear relation, which means a specific angle of the sidewalls is required for optimum transmission. Fig. 3.5 shows the optimized flare ratio plotted as a function of the number of ports in the multi-port end of the MMI coupler. Although these data points fall in nearly a straight line, the slope (~0.75) is not the unity
value that would be expected from an adiabatic process; doubling the number of ports and thus the width of the broad-area port does not result in a doubling of the flare ratio.

Fig. 3.4. (b,c) Continued.
Similar calculations were performed for a 1x8 MMI coupler with an exponential taper. Fig. 3.6 shows the peak fundamental mode transmission as a function of flare ratio by optimizing the length of the device at each flare ratio. The length of the MMI section at the simulated maximum transmission was 43.6 mm at a flare ratio of 2.5. The fundamental mode transmission efficiency peaks at 60%, far lower than that of the linearly tapered MMI coupler, with a significant amount of the remaining power radiated out of the waveguide at the narrow end of the taper in a 1-to-N configuration. In the opposite N-to-1 configuration, significant fractions of the remaining power either couple into higher-order even modes or radiate out of the waveguide at the broad-area waveguide junction. The results of the exponential taper simulations further prove that
the widening of the single self-image at the output coupler side of the MMI is not the result of an adiabatic process.

Exponentially Tapered Optimum Flare Ratio

Fig. 3.6. Simulated fraction of power transmitted into the fundamental mode of the 40-micron-wide port of a 1x8 exponentially flared MMI coupler.

Free-space emission from a discrete array of emitters was simulated by turning the simulation around, launching light into the 8 ports of the multi-port side of the device with proper the phase relations, and removing the waveguide edges in the multi-mode section of the device. Fig. 3.7 shows the intensity map of the emitter array for the tapered and non-tapered MMI geometries for which the diffraction emission lobes are clearly visible. Using the free-space angle of the first emission lobe, one can calculate that inserting the waveguide edge causes total internal reflection of the first lobe so that it crosses the central lobe at the maximum efficiency length, as depicted in Fig. 3.7. Lobes at higher diffraction orders experience multiple reflections at the total internal reflection
interfaces to also arrive at the same location. The linear scaling shown in Fig. 3.3 (dotted) is the result of this folding process, which constrains the angle of the waveguide walls, while the resulting diffracted beam size constrains the optimal flare ratio for the coupler, as shown in Fig. 3.3 (solid). Taken together, these data show that the tapered device is folding the far field of the system rather than adiabatically stretching the coherent MMI propagation behavior.
Fig. 3.7. Intensity map of free space propagation with MMI overlay for (a) a tapered MMI, and (b) a standard MMI. The MMI boundary lines are overlaid to show that when the lobes are reflected at an imposed boundary they will converge on the single-port output.
IV. Performance and Tolerances

Further simulations were carried out to determine other performance characteristics of the 1x8 coupler. In these simulations, the entire structure was flipped about the axis perpendicular to the direction of propagation in order to demonstrate the reciprocity of the system. The coupler, now in an 8x1 configuration, was excited with uniform power across the eight ports using the output phase distribution obtained from the 1x8 case. The phases of the launched waves, relative to the innermost pair, are symmetrical about the axis of propagation and are 0, -\(\pi/20\), -\(3\pi/20\), -\(6\pi/20\) radians from the innermost to the outermost pairs respectively. Analysis of these launch phases reveals the pattern 0 : \(\Delta\theta\) : 3\(\Delta\theta\) : 6\(\Delta\theta\), which is the same pattern as that of a standard MMI coupler, though with a different numerical value for \(\Delta\theta\).

The 8x1 transmission as a function of wavelength is shown in Fig. 3.8. The transmission spectrum is centered on the design wavelength with a ~10 nm full-width half-maximum. The device can be designed for other operating wavelengths, allowing the coupler to control the feedback wavelength and thereby the lasing frequency of the semiconductor laser array. The resulting shape of the curve will provide wavelength selectability in a lasing system by providing progressively higher cavity loss in the system for wavelengths further from the transmission peak. No other comparable maxima were obtained between 0.4 and 2 micron wavelengths when using a 3 nm separation of data points across the range.
In a typical MMI, the balance of power in the ports affects the overall transmission of the structure because the design depends on the coherent addition of each input. This issue may be particularly detrimental when using this coupler with a laser array where input powers cannot be ideally controlled. Fig. 3.9 shows the change in transmission of the total injected power after the powers of individual ports are varied. Although two different ports were varied in Fig. 3.9 (a) and (b), the results are nearly identical. Moderate fluctuations in a single coupled device have little performance impact on the coupler. For example, a 30% change in power in the center left port causes only a 0.4% loss in transmission efficiency. Should a single laser element completely fail, it would affect the output by an approximately 12% loss in one-way efficiency of the remaining power being injected into the coupler. The majority of this lost power is
radiated out of the waveguide but a small fraction resides in a higher-order odd mode of the broad-area waveguide. This result is similar to that of standard MMI couplers that have been simulated in the course of this study. Further, the transmission efficiency as a function of power imbalance is of the same form predicted by the analytical expression for beam combining [12]. This analytic model predicts that a missing element in the coupler results in 87.5% transmission efficiency for the remaining elements.

**Single-Element Fault Tolerances**

![Diagram](image)

Fig. 3.9. Fraction of fundamental-mode power transmitted by the 8x1 flared MMI when (a) the power in the leftmost port is varied, and (b) (continued on the next page) the power in the port just left of center is varied.
Fig. 3.9 (b) Continued.

Fabrication imperfections of such waveguide devices may also impact the tapered MMI performance. Such scattering will affect the ability of a laser cavity made with this MMI to self-organize into a coherently combined array. The lithographic resolution of the waveguide fabrication process was simulated by dividing the waveguides into a grid whose dimensions are determined by the resolution parameter. The effect of lithographic roughness was simulated by adding a perturbation function to both the position and width of the waveguide at each point in the propagation direction \( z \). This perturbation function \( h(z) \) is determined by lithographic roughness and correlation length parameters. The autocorrelation function \( R(u) \) is defined as:

\[
R(u) = \int_{-\infty}^{\infty} h(z)h(z-u)dz \quad (3.3)
\]
Where the autocorrelation function is at its maximum when \( u = 0 \). For two positions along the \( z \) direction, \( z \) and \( z + u \), \( R(u) \) describes the degree to which the positions are correlated. A useful model for the autocorrelation function in the waveguide fabrication process is [13]:

\[
R(u) = \sigma^2 e^{-|u|/D}
\]

(3.4)

Where \( \sigma = \sqrt{R(0)} \) is the rms deviation and \( D \) is the correlation length. Within the correlation length, the function \( h(z) \) is not changing randomly. The transverse position and width of the waveguide are perturbed by functions \( \Delta x(z) \) and \( \Delta w(z) \), which are generated using the correlation function. These functions are added to the nominal values resulting in asymmetrically perturbed final waveguide positions [13]:

\[
x(z) = x_0(z) + \Delta x(z) \\
w(z) = w_0(z) + \Delta w(z)
\]

(3.5)

Using a 0.25-micron resolution and a 1-micron correlation length, the transmission as a function of roughness was simulated and the results are plotted in Fig. 3.10. This figure spans the range from state-of-the-art waveguide processing (10 nm rms deviation) to 100 nm rms deviation [14]. The transmission stays above 95% until a 70 nm rms deviation is reached, which is seven times worse than state-of-the-art. This data suggests state-of-the-art processing sidewall roughness will have little impact on the performance of the MMI coupler.
Fig. 3.10. Fundamental mode transmission for an 8x1 flared MMI as a function of the variance of the surface roughness.

V. Discussion and Summary

To underscore the generality of the analysis, a specific example was considered: combining eight 980-nm pump diodes using a 1x8 MMI GaAs waveguide. Using the appropriate base index of 3.52, the optimized length of the device scales ~28mm (~3.5x smaller than the original optimized device length calculated in Fig. 3.3) producing the same ultra-high transmission found in the generalized analysis presented in Fig 3. Such simulations validate the scaling laws presented in Section II.

One of the principal problems with MMI couplers in general is their long length and the difficulties associated with fabricating and handling structures of large length-to-width ratio. The increasing length-to-width ratio of the device as it scales will
make it fragile. Additionally, imaging a mask of such a long structure across a substrate is difficult to achieve accurately. It has been shown that an MMI coupler with a narrower MMI region will have a shorter length compared to wider MMI couplers [15]. In the case modeled here, making a narrower MMI region will require a reduction in the pitch between the ports on the multi-port end, but will also result in a shorter optimized device; however, care must be taken to avoid coupling between the input ports prior to entering the MMI section. One possible solution to the problem of length may lie in the use of total internal reflection to fold the MMI section into an S-like curve, thereby reducing its physical aspect ratio [16]. This solution will likely reduce the efficiency of the device, because light that would normally interact with the side-walls in the region of the fold will be lost.

In principle, the modeling presented here indicates that this tapered MMI concept is scalable to a larger number of input ports. However self-organizing diode laser systems have to date been restricted to approximately 10 elements due to the inability of the laser system to obtain and maintain the proper phase relation between the ports [5]. Even with this limitation, the combination of eight, commercially available, 0.75-watt, single-mode laser diodes could be combined via the tapered MMI to make a 6-watt, single-mode semiconductor laser.

In summary, a 1xN, tapered, MMI coupler was numerically studied for use in a self-organizing semiconductor laser-array system. The MMI structure is linearly tapered in a way such that the single-port side is wider than the N-port side. The single-port waveguide is N times wider than the other ports to maintain intensity similar to that in
each of the N-port waveguides. Using such a device, the N-ports of a semiconductor laser array can be coherently combined in a self-organizing architecture. This modified MMI design increases the output power threshold for catastrophic optical damage while maintaining only single mode excitation of a wide single port output. The device is non-adiabatic with a single-pass power transmission of 98%. A power imbalance up to 40% in a single port reduces the device efficiency by less than 1%, while a waveguide roughness as large as 70 nm rms detracts only 3% from the device efficiency. When designed to work at 1 μm wavelength, the structure has a full-width half-maximum pass-band of 10 nm, which can provide wavelength selectability when used in a self-organized semiconductor laser-array system.

REFERENCES


Chapter 4: Impact of Cavity Confinement on Broad-Area Laser Beam Quality

I. Introduction

The most widespread use of BALs is in pumping high-power dual-clad fiber lasers, which do not require diffraction-limited beam quality from the BALs. A dual-clad fiber (DCF) has three optical layers in the radial direction. The core is nominally single-mode for the desired lasing wavelength and doped as a gain medium for use as a fiber laser or amplifier, while the pump light is confined to the inner cladding region of the fiber by the outer-cladding [1]. The light of the pump laser, now in the multi-mode region of the DCF, is required to be absorbed by the gain medium to be useful to the intended fiber laser or amplifier. However, since the gain cross-sectional area is much smaller than the pumped area, the absorption of the pump light occurs over longer distances compared to the lower-power core-pumped configuration. Higher brightness BALs would allow smaller inner claddings for shorter absorption lengths or higher powers via higher pumping density. The motivation for this work is therefore to improve but not perfect the beam quality of BALs using a simple technique that does not require new equipment or fabrication processes to implement.

In this chapter, the notion of evanescent spatial filtering is defined, and numerical models are applied to explore the enhancement of evanescent spatial filtering via waveguide and cavity design. Specifically, BAL brightness enhancement is studied by exploiting the loss resulting from the modal evanescent tails propagating in the lossy
cladding as a function of the index step that defines the optical waveguide and the reflectivity of the output facet. In Section II, losses in the evanescent field are compared at totally internally reflecting (TIR) angles. In Section III, numerical simulations are used to study the effects of these losses. In Section IV, practical issues involved with the beam quality improvement technique are presented. Section V contains a discussion of the results and concluding remarks.

II. Spatial Filtering via Evanescent Field Loss

Filamentation in BALs creates an optical field profile within the laser cavity that contains high spatial frequencies. The desirable fundamental mode of the BAL waveguide, which allows tight focusing and coupling into single-mode-fiber, consists of low spatial frequencies. Therefore, by designing a laser cavity with increased loss at high spatial frequencies, it is reasonable to suggest that the beam quality can be improved.

In a laser cavity, fine lateral spatial structure is indicative of coherent light traveling at large angles with respect to the nominal propagation axis, i.e. high spatial frequencies. It is well known that light impinging on a dielectric interface at an angle exceeding the critical angle “samples” the medium on the other side of the waveguide even though no net power propagates beyond the interface due to total internal reflection [2]. In waveguide terminology, this is the evanescent tail of the mode that exists outside the boundary of the waveguide but propagates parallel to its surface. In the context of filamentation, high spatial frequencies propagating in the laser cavity will “sample” more of the material outside the waveguide than lower spatial frequencies. Since this region is
un-pumped and therefore lossy in the semiconductor materials of interest, this evanescent loss acts as a weak spatial filter against high spatial frequencies.

From the ray perspective, the Goos–Hänchen shift describes the apparent axial dislocation of a beam upon total internally reflection (TIR) from the interface as [2]:

\[
\Delta z_{GH} = \left( \frac{2}{k_1} \right) \frac{\tan \theta_c}{(\sin^2 \theta - \sin^2 \theta_c)^{1/2}}
\]  

where \( \Delta z_{GH} \) is the shift down the wall of the interface, \( \theta_c \) is the TIR critical angle as measured from the perpendicular with the interface, \( \theta \) is the angle of incidence of the beam of interest, and \( k_1=2\pi n_1/\lambda \) where \( \lambda \) is the optical wavelength and \( n_1 \) is the refractive index of the waveguide core. This distance \( \Delta z_{GH} \) is used to describe the interaction length of the optical field with the absorbing cladding material upon each reflection. The ratio of \( 2\Delta z_{GH} \) to the total axial distance traveled in a single lateral round trip reflection creates an effective absorption for spatial frequencies corresponding to a range of angles of reflection. The axial distance traveled per sidewall reflection depends geometrically on the angle of incidence and the width of the waveguide, \( w \). This relation can be used with \( \Delta z_{GH} \) and the absorption of the un-pumped material beyond the interface to create an effective absorption due to lossy material outside the waveguide:

\[
\alpha_{eff} = \alpha \left( \frac{\Delta z_{GH}}{w \tan \theta + \Delta z_{GH}} \right)
\]  

(4.2)
Fig. 4.1 shows effective absorption for TIR light in a 100-μm-wide cavity as a function of sidewall incident angle. Since the modes of the cavity have different amounts of power beyond the waveguide, this picture is not complete. However, this figure does illustrate the vast relative difference in absorption between the fundamental mode containing the waveguide's low spatial frequencies and that of higher spatial frequencies characteristic of filamentation; a filamenting beam will experience 10-30x more loss than the fundamental mode. Including a weighting factor for the modal power in the cladding will only exacerbate this picture, as the higher-order modes have increasingly more power propagating in the cladding. Since the properties of this loss are dependent on the refractive properties of the incident light with the sidewall, this difference in effective modal loss will be referred to as evanescent spatial filtering.

Since this filtering mechanism provides loss while the beam is propagating, extending propagation in the cavity naturally leads to a higher level of spatial filtering. The effective extension of propagation in the cavity can easily be accomplished by increasing the output coupling reflectivity. Increasing the cavity lifetime and thus increasing the filtering distance allows for additional attenuation of high spatial frequencies and thus better beam quality of the laser output. Moreover, the index step at the waveguide interface provides an additional degree of freedom through the TIR angle in Eqn. 4.1.
**III. Simulations of Evanescent Spatial Filtering**

This concept was explored numerically using a Fox-Li beam propagation method (BPM) simulation of a BAL cavity [3], as described in Chapter 2. The parameters used in the BPM, shown in Table 4.1, were chosen to mimic typical high-efficiency commercial BALs [4], with resulting simulated performance (power, efficiency, threshold, beam quality) that closely match their commercial products [5]. Once these parameters were matched, simulations were performed on a typical 2mm-long laser with a 100-µm lateral waveguide stripe. A high-reflectivity coating (95%) was used at the rear.
facet, while the front (output) facet reflectivity was varied to study the effect of effective cavity length on the output beam characteristics.

**Table 4.1**
**Parameters Used in Numerical Simulation**

<table>
<thead>
<tr>
<th>Physical Quantity</th>
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<tr>
<td>Diffusion constant</td>
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</tr>
<tr>
<td>Transparency carrier density</td>
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<tr>
<td>Non-radiative lifetime</td>
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</tr>
<tr>
<td>Spontaneous emission coefficient</td>
<td>$1.4 \times 10^{-10}$ cm³/s</td>
</tr>
</tbody>
</table>

The first evidence of spatial filtering comes from examining the field inside the laser cavity. Once transients were damped out in the simulation, the forward propagating half of the intra-cavity field was captured and Fourier transformed to reveal the spatial frequency content of the light re-circulating in the cavity. Fig. 4.2 displays the Fourier amplitude of these fields for various output facet reflectivities. As the output facet reflectivity increases, the width of the spatial frequency spectrum decreases, implying
lower beam divergence and therefore better beam quality. The reduced Fourier spectral width indicates that there is less fine structure on the beam, which is verified with the snapshots of the electric field amplitude outputs shown in Fig. 4.3. Fig. 4.3 also reveals that for low output facet reflectivity, a significant amount of light resides outside the pumped/wave-guided region of the laser that is bounded by dashed (red) lines. This is related to the fine structure in Fig. 4.2 and is also indicative of light being scattered beyond the critical angle of the waveguide. Figures 4.2 and 4.3 clearly demonstrate that increasing the number of effective round trips in the cavity via increased cavity reflectivity results in increased evanescent spatial filtering.

Nominally, spatial characteristics of laser fields can be quantified by analyzing the amplitude of their spatial Fourier transforms. However, the chaotic nature of the filamentation in BALs makes it necessary to average these quantities over time, represented by cavity round trips in the BPM simulation, in order to obtain “typical” (as opposed to instantaneous) characteristics. The results of this analysis under varying condition of output coupler reflectivity (1% to 50%) are shown in Fig. 4.4. These plots show a clear narrowing of the divergence of the laser with increasing output coupler reflectivities. Qualitatively, this far-field narrowing should result in a direct improvement in beam quality since the emission aperture is identical for all cases.
Intracavity Single-Pass Fourier Components for Varying Cavity Reflectivity

Fig. 4.2. Simulated, normalized Fourier-transform amplitude of a laser beam as it passes through a laser cavity for various cavity reflectivities. The propagation direction is from the high-reflectivity surface at the bottom of each sub-figure to the low-reflectivity surface at the top of each sub-figure. The lateral dimension describes spatial frequency components.
Fig. 4.3. Simulated snapshot of the lateral electric field amplitude of a laser beam exiting the cavity for various facet reflectivities. Dashed (red) lines indicate the waveguide boundary.
Fig. 4.4. Simulated average far-field amplitudes of the output laser field for various facet reflectivities.
Fig. 4.5. Angular width of the time-averaged far-field amplitude as a function of output facet reflectivity. The curve is drawn to guide the eye.

The $2\sigma$ divergence angle of the far-field distribution, shown in Fig. 4.5, clearly depicts this expected far-field narrowing. By replacing conventional low-reflectivity coatings (~2-4\%) with higher reflectivity coatings, the far-field distribution can be narrowed by a factor of two. Of course, with higher reflectivity coatings, it is reasonable to expect a reduction in laser output since more light is re-circulated within in the cavity instead of emitting from the cavity. Fig. 4.6 shows the device slope efficiency as a function of output facet reflectivity, while Fig. 4.7 shows the beam quality as a function of reflectivity. The beam quality in Fig. 4.7. is represented by the commonly accepted measure given by the parameter $M^2$, which is defined as the ratio of the divergence of a given beam compared to the divergence of a Gaussian beam of the same $2\sigma$ beam width.
[6]. Figure 4.6 shows that the efficiency decreases linearly with increasing reflectivity, as would be expected by letting less light escape from the laser cavity. However, Fig. 4.7 shows that $M^2$ drops much more rapidly resulting in a net increase in beam brightness, coarsely defined as the output power divided by the product of the emission aperture area and the emitted beam divergence. In fact, by comparing typical low-reflectivity coatings (2-4%) to a simple uncoated output facet (~30%), the beam quality can be improved by a factor of two while only sacrificing 10% in device efficiency.

**Output Coupler Effect on Slope Efficiency**

![Plot showing simulated slope efficiency (W/A) as a function of output facet reflectivity.](image)

Fig. 4.6. Simulated slope efficiency (W/A) as a function of output facet reflectivity.
Fig. 4.7. $M^2$ as a function of output facet reflectivity for various waveguide index steps: $\Delta n=0.01$ (black triangles), $\Delta n=0.001$ (red squares), and $\Delta n=0$ (blue diamonds). The lines are merely guides for the eye.

It was previously noted that the magnitude of the index step can play a role since it determines the TIR critical angle and thus the spatial extent of the modes in the cladding. Fig. 4.8 shows $M^2$ as a function of index step for output facet reflectivities of 0.3 and 0.05. The index step in fact plays a critical role in determining the beam quality via evanescent spatial filtering. For large index steps, the modes are all highly confined, resulting in very weak evanescent spatial filtering. For small index steps, the modes are weakly confined, resulting in high loss for all modes and therefore reduced relative modal filtering. Fig. 4.8 also shows that there is an optimum index step for providing evanescent filtering. For traditional low reflectivity output couplers, optimizing the index step can result in more than a factor of 2 improvement in beam quality without sacrificing laser efficiency. A further 60% beam quality improvement can be obtained by
simultaneously optimizing the facet reflectivity. Regardless of the facet reflectivity chosen, the optimal index step is near 0.001. This value will be used for the remainder of the simulations.

![Plot of simulated $M^2$ vs. broad-width index step at 30% (triangle) and 5% (square) output facet reflectivity.]

Fig. 4.8. Plot of simulated $M^2$ vs. broad-width index step at 30% (triangle) and 5% (square) output facet reflectivity.

Fig. 4.7 shows $M^2$ as a function of the output facet reflectivity for three cases of index step: strongly guided ($\Delta n=0.01$), moderately guided ($\Delta n=0.001$), and gain-guided ($\Delta n=0$). As discussed previously, the strongly guided case leaves little mode power in the cladding, resulting in virtually no evanescent spatial filtering, as evidenced by the nearly constant $M^2$. In contrast, the gain-guided case allows the modes to spread well beyond the waveguide boundaries, resulting in relatively high loss for all modes. Nevertheless, evanescent spatial filtering can still be effective in reducing the $M^2$ down to
the level of the strongly guided case. The moderately guided case allows for full exploitation of refractive spatial filtering, with a ~2x reduction in M$^2$ compared to the conventional low reflectivity case (a few %). Moreover, the beam quality for the uncoated facet is 3x better than the strongly guided case, which is a typical configuration for high efficiency diode lasers.

**IV. Practical Considerations**

As was indicated previously, high power laser configurations nominally have low reflectivity coatings on the output facet in order to allow the highest efficiency laser emission. By increasing the facet reflectivity to enhance the effects of refractive spatial filtering, more of the light is retained in the laser cavity, resulting in reduced laser emission. Fig. 4.6 shows the simulated electrical-to-optical slope efficiency as a function of output facet reflectivity. Although the efficiency linearly decreases with increasing facet reflectivity, the beam quality (Fig. 4.7) improves more rapidly, resulting in a net improvement in laser brightness. More importantly, the commercially practical change, from a low reflectivity coating to an uncoated facet, reduces the efficiency by only 10% while offering a beam quality improvement of a factor of 2.

This point is further underscored in Fig. 4.9, which shows the slope efficiency as a function of the 2σ beam width for 5% and 27% output facet reflectivities. For waveguides that can support more than a few spatial modes, the efficiency is nearly constant regardless of the waveguide width. This can largely be explained in terms of the filamentation dynamics. Since the nominal filament spacing is a result of the interplay
between carrier-induced self-focusing and diffraction, the filamentation spacing should be constant at a given pump level provided the waveguide is sufficiently large to support many waveguide modes [7].

**Slope Efficiency as a Function of Beam Waist**

![Slope Efficiency vs Beam Waist Plot]

Fig. 4.9. Simulated slope efficiency as a function of $2\sigma$ beam waist for lasers with output facet reflectivities of 0.05 (square) and 0.27 (triangle). This plot contains slope efficiencies at a range of pumping levels.

**V. Discussion and Summary**

Free-carrier induced filamentation is a continuously seeded process, making lumped spatial filtering ineffective when high operating power causes the filamentation length to be shorter than the round trip of a cavity. A continuous filtering method is therefore required to combat filamentation in a power-scalable manner. This chapter has
shown that the sidewalls of a BAL provide a weak spatial filter that can be enhanced by optimizing the lateral waveguide index step and increasing the cavity lifetime via the output facet reflectivity. Instantaneous analysis of the electric field within the cavity demonstrates that increased filtering occurs despite the increased power stored in the cavity with high output facet reflectivities. A broad-range of optimum index step exists to provide high loss only to the higher order modes and thus provide low-loss spatial filtering. Higher confinement reduces the desirable effects by reducing the amount of light outside the waveguide, while lower confinement allows even relatively low spatial frequencies to see similar losses as high spatial frequencies. Potentially, evanescent spatial filtering can be improved by using a more strongly absorbing media in the un-pumped cladding regions of the lateral laser waveguide.

In summary, spatial filtration of the intra-cavity semiconductor laser beam has been numerically demonstrated by optimizing the output facet reflectivity and the lateral waveguide index step. The evanescent tail of waveguide modes experience absorptive loss, which becomes increasingly higher for higher-order modes, equivalently creating a weak spatial filter. Increasing the effective laser cavity length in a broad-area laser enhances the effect of the filter by extending propagation in the cavity, leading to improved output beam quality. Simulations predicted a factor of two increase in beam brightness with only a 10% efficiency penalty.

REFERENCES

Chapter 5: Filamentation-Free Diode Laser Design

I. Filamentation Suppression

As stated in the previous chapter, obtaining good beam quality in a BAL requires spatial filtration in the laser cavity. Continuous filtering has desirable scaling properties because the high spatial-frequency modulation that leads to filamentation is continuously discarded. This is in stark contrast to the case for devices with discrete spatial filters, such as tapered/flared resonators, which can allow filamentation to occur within a single round-trip of the cavity due to the high gain inherent to semiconductor lasers. Some examples of a continuously filtered laser are the angled-grating laser [1] and the slab-coupled optical waveguide laser [2], both described in Chapter 1.

It has been reported that a linearly ramped lateral gain profile can result in good-beam-quality output from multimode broad-area lasers at low powers before filamentation dominates [3]. The off-axis nature of the modes generated by such a gain profile tends to cluster their far-field distributions into a narrow angular bandwidth. Additionally, the modes resulting from a linearly ramped gain profile [4] do not contain high-spatial-frequency content that seeds filamentation, resulting in an increased filamentation threshold. However, filamentation eventually occurred at power levels comparable to single-mode diode lasers [3]. There are two conditions that may have caused this failure. One is that the thermally induced refractive-index became large enough to allow conventional index-guided modes that lack the crucial null-less feature and therefore become high-frequency spatial seeds for filamentation. The second
possible cause is a spatially confined lasing action involving the remaining unsaturated gain, which will be expanded upon later in this work.

Nevertheless, the modes resulting from this linearly ramped lateral gain profile have highly desirable spatial properties [4]. All of the modes resemble deformed Gaussians (with no nulls) that emit off the longitudinal axis of the device due to the gain-induced phase tilt (with a different tilt for each mode). These similarly shaped modes all nominally share the same space and saturate the gain similarly. Moreover, the null-less mode shapes also ensure that there are no natural (mode-induced) high-spatial-frequency perturbations to saturate the gain and cause filamentation via free-carrier induced refractive-index changes.

The basic results of the original tailored-gain experiments were described analytically via linearly ramped lateral gain profile, although the device was fabricated with a linearly ramped lateral current profile. Also, as with similar mode calculations for gain-guided diode lasers, the prior analytical work did not include the saturation dynamics of carrier-based refractive-index changes, which are particularly significant near the gain peak. Ensuring such a precise linearly ramped gain profile in practice would require dynamic lateral control of the free carriers, which is not currently feasible. However, the concept of utilizing a generalized class of null-less modes to minimize filamentation seeding can be extrapolated to realistic (i.e., fabricable) devices.

In this work, a 97X nm laser that exploits the beneficial nature of tailored-gain-guided modes is proposed. The model numerically predicts that with the inclusion of intrinsic but engineered spatial filtering, a significant fraction of power in the remaining
modes can be coupled into SMF-28 fiber (4.1 µm radius core, 1.4670 index core 1.4665 index cladding) at multi-Watt power levels. Specifically, exploitation of the combined effects of lateral injection-current and refractive-index tailoring is used to design a filamentation-free 980-nm BAL for high-power core-pumping of erbium-doped fiber amplifiers (EDFAs). In Section II, the devices design is described and simulated to reveal the complex physics of this device and the similarity to the prior analytic gain-guided modes. High-power, high-brightness performance is shown with a design enabling high-power coupling to SMF-28 fiber. In Section III, practical aspects of the device are considered, such as the tolerance of the profiles, robustness to injection-current and refractive-index inhomogeneities, and thermal effects. Section IV provides a discussion, including fabrication options, as well as concluding remarks.

II. Device Physics

The combined effects of lateral injection-current and refractive-index tailoring have been explored numerically using conventional Fourier beam propagation method (BPM) simulations, which include diffraction, local carrier-dependent linear gain, local carrier-dependent refractive-index changes, and carrier diffusion [5], [6], [7] as described in Chapter 2. This split-step Fourier BPM simulation provides coupling of forward and backward traveling diffractive waves through the gain and refractive index determined by the injected free carriers, which are in turn modified by the optical fields and diffusion. In this model, convergence of a stable near field means that the device is operating free of filamentation [5].
To emulate starting from spontaneous emission, simulations were started from a low intensity field with random phase distribution, and a random, sub-transparency carrier distribution. From this point, injection-current was increased to develop the laser's operating profile. Though current spreading is not included in this model, this work shows the design to be robust against current shape and perturbation. The parameters used in the simulations can be found in Table 5.1. These simulations were calibrated by using published parameters for commercial, high-efficiency, single-quantum-well BALs and matching their stated performance [8, 9]. The longitudinal length of the device under study was two millimeters with 95/29% facet reflectivities to approximate a high reflector and a cleaved facet. This high output-coupler reflectivity is required for sufficient feedback-enhanced evanescent spatial filtering [10] to maintain good beam quality and for balancing longitudinal gain saturation.
While either symmetric or asymmetric refractive index profiled waveguides support modes of only flat, axially directed wavefronts, it is well known that in the absence of a strong index guide, gain causes semiconductor laser modes to have

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<td>Spontaneous-emission coefficient</td>
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</table>
wavefronts that are not flat [11]. Although such a wavefront would typically exhibit curvature over the optical beam, preliminary simulations with right-triangle-shaped current injection revealed that as the optical power in the laser is increased, an electric field with an exceptionally flat but tilted wavefront will be produced. Such a tilted wavefront describes optical power propagating at a lateral angle in the cavity that is absorbed in the semiconductor outside the gain stripe, inducing transparency in that region. This leads to a rapid widening of the laser beam accompanied by degraded beam quality since the far-field width does not improve at an inversely proportional rate. To remedy this problem, a sloped lateral index profile was placed across the cavity to (a) contain the beam, and (b) increase the slope efficiency by reducing the region of optically induced transparency.

The need for this controlled addition is evident in earlier work with the linearly gradient gain structure, where the experiment showed heavily modulated near field (NF) [3], in spite of the very smooth NF predicted from theory [5]. Since the measured NF was also narrower than predicted, these observations may be attributed to a thermally induced refractive-index change toward the tapered-current side of the device. Any index change is critical in the onset of filamentation because it can eventually dominate over the gain guide and support modes that have significant nulls, unlike the desirable gain-guided modes discussed in [5]. Such nulls modulate the index via gain saturation, leading to filamentation as described previously. In the case of the linearly gradient gain structure, all sources of lateral index-guiding (native, thermal, and gain-induced) should be engineered such that they do not dominate gain-guidance yet provide enough
confinement to limit the beam broadening created by the filtering-induced transparency. The methodology for achieving this will be detailed later in this work.

**Designed Refractive-Index and Pump-Current Profiles**

![Graph showing tailored index difference profile and current profile](image)

Fig. 5.1. Tailored index difference profile (black, dashed), and tailored current profile (red, solid).

To maximize lasing performance, the lateral profiles of built-in refractive index and current injection were tailored to optimize the beam quality with respect to filamentation minimization and beam spreading due to induced transparency. Using the refractive-index and injection-current profiles shown in Fig. 5.1, the model predicts up to 7.7 W of stable continuous-wave output power with 0.72 W/A slope efficiency. This efficiency is close to but less than commercially available BALs, as would be expected from any semiconductor laser utilizing a spatial loss-filtering process.
Fig. 5.2. Output facet values for the (Top) net gain profile, with the shaded region representing positive net gain, (Bottom) total (designed + carrier-induced) index-difference profile (black, dashed), normalized output-intensity profile (7.7 W) (red, solid), and for the phase profile (red, dash-dotted) normalized to $80\pi$ radians.

The resulting total NF intensity and the total refractive-index change profile, including free-carrier-induced changes, are displayed in Fig. 5.2. Optimization of refractive-index slope results in a controlled but significant spreading of the beam into the un-pumped region. However, the simulated NF reveals very limited lateral beam
modulation in spite of multimode operation and a large beam, indicating that the filamentation tendencies are very weak. The total (gain-induced) phase profile is also shown in Fig. 5.2, which is remarkably flat and inclined at an angle that corresponds to non-axial emission and increases with increasing injected current.

### Tailored and Conventional BAL Far-Fields

![Graph showing far-field intensity profiles](image)

**Fig. 5.3.** Power-normalized far-field intensity profiles for simulated lateral current- and index-tailored diode operating at 7.7 W output power (black, solid), and conventional BAL (200 round-trip average) operating at 7.3 W output power (red, dashed). The labels (a)-(d) refer to the wavelet transform regions in Fig. 5.4.

The tilted phase profile shown in Fig. 5.2 is also reflected in the far-field (FF) intensity, shown in Fig. 5.3, which contains a distinct and desirably narrow off-axis peak. The full width of the stable main FF lobe of the tailored laser is ~8x narrower than that of the conventional filamenting BAL, which is also shown in Fig. 5.3. The FF is most revealing about the internal mode structure of the laser under study. The peaks to the
right of the main peak are not the tailored-gain-guided modes from prior work [5], but are instead due to the waveguide formed by the tailored index profile. Such modes are allowed by the induced transparency and are weak because they are filtered by lossy propagation, as evident in the net gain profile at the top of Fig. 5.2. A second family of modes, indicated by very weak peaks to the left of the main peak, is comprised of asymmetric modes similar to the type produced by the linear gain profile [5]. These modes are effectively gain filtered [12] due to lower overlap with the gain; higher order modes, represented by wide FF angles, are slightly wider and further from the right-hand edge of the gain profile. There are no modes centered near the gain peak due to severe free-carrier induced negative refractive-index changes and a refractive-index discontinuity in the unsaturated gain.
Modified Discrete Wavelet Transforms

Fig. 5.4. Normalized electric field magnitude of the modified wavelet transform of four regions of the BAL FF along with the whole NF. The whole NF is shown in (a) (black) (7.7 W), main lobe is shown in (a) (red) (5.1 W), the second region is shown in (b) (green) (2.1 W), the third region is shown in (c) (brown) (0.22 W), and the least paraxial 4th region is shown in (d) (blue) (0.13 W).
Using a modified wavelet transform, one can study where features in the FF have contributions from the NF [13]. In this work, four windowed regions of the FF, corresponding to each of the primary peaks indicated as (a)-(d) in Fig. 5.3, are Fourier transformed to determine spatial the contributions of the NF and are shown in Fig. 5.4. The contribution to the main lobe of the FF, shown in Fig. 5.4(a), largely overlaps the tailored current stripe, implying that it is the dominant saturating and shaping force for the shaded region of free carriers in Fig. 5.2. The two more paraxial lobes of the FF transform to NF structures with significant power increasingly far from the current stripe, shown in Fig. 5.4(b) and (c). Though not as easily interpretable as the main lobe’s transform due to what is possibly multiple unresolved modes in each of these FF wavelet regions, these two transform regions seem to have inflection points indicative of conventional higher-order index-guided modes. The fourth transform, shown in Fig. 5.4(d), is taken from just outside the main lobe of the FF. While at first glance this FF region seems to be of insignificantly small power, its transform is revealing about the physics of the device. Having a smooth NF farther from the gain than the primary mode combined with a FF that is also at a higher angle than the primary mode indicates that this mode is of the same family of gain-guided modes as the primary mode. It also leads to the conclusions that (a) the primary mode is the fundamental gain-guided mode, (b) higher-order gain-guided modes are eliminated by gain filtering and evanescent spatial filtering, and (c) this would effectively be a single-spatial-mode laser if the index ramp were not required to confine the beam spreading.
Although it seems intuitive that a widened beam as shown in Fig. 5.2 will have a proportionally narrower FF, this is not the case for a filamenting BAL, whose FF width is governed by the spatial frequencies of the filamentation. Moreover, similar M² values in highly multimode BALs do not directly translate into similar fiber coupling efficiencies, particularly for few-moded fibers. Nevertheless, the narrow, stable, far-field distribution shown in Fig. 5.3 suggests that a significant fraction of the light from this tailored BAL can be coupled into conventional single-mode fiber.

**Overlap between Focused Output and Fiber-Core**

![Fig. 5.5. BAL output intensity re-imaged for fiber coupling into (a) the LP₀₁ mode (5 W), and (b) the combined LP₀₁ and LP₁₁ modes of SMF-28 fiber (5.5 W). The BAL wide (lateral) axis is horizontal, and the fiber core is depicted as a dashed circle. Though spatial overlap is shown the complex overlap is used to determine coupling.](image-url)
Under appropriate imaging conditions, the BAL output can therefore be re-focused to produce a spot that can be efficiently launched into SMF-28 fiber, which supports several modes at the 980-nm erbium-pumping wavelength of interest. Two such launch conditions are shown in Fig. 5.5, corresponding to optimized coupling to the LP_{01} fiber mode (top) and the combined LP_{01} and LP_{11} fiber modes (bottom). Optimizing for coupling into the additional anti-symmetric LP_{11} mode yields higher coupling because the laser output can be focused asymmetrically on the core, using more of the electric field to overlap the available modes. The existence of several fiber modes therefore allows for 70% coupling efficiency of the optimized BAL into SMF-28 (determined by complex-valued mode-overlap integrals), resulting in up to 5.5 W guided by the fiber core. This is a substantial increase (7x) over the nominal 0.75 W that is currently commercially available for core pumping of erbium-doped fiber amplifiers.

In order to ensure that coupling optics can physically realize the predicted coupling, a first-order, triplet thick-lens system was modeled. A design comprising two plano-convex cylindrical lenses on either side of a radially symmetric bi-convex lens with an overall diode-to-fiber length of 1.05 mm resulted in a 69% coupling efficiency into the core of SMF-28 fiber at the maximum power presented in this work. It should be noted that the design includes an off-axis shift and tilt in order to accommodate the off-axis shift and tilt in order to accommodate the off-axis emission.

### III. Practical Considerations
Although the predictions for operation at maximum power show highly desirable performance, construction and operation of the device will be subject to a number of real world complications. This section addresses the variation of device performance with power as well as tolerance to non-ideal index profiles. Furthermore, inclusions (defects) and statistical variations (inhomogeneities) to refractive index and injection-current are studied, as well as means of mitigating potential detrimental effects. Finally, the difficulties and potential benefits of thermally induced refractive-index changes are presented.

Current conventional BALs operate at a range of power levels with a reasonably stationary center axis of propagation. However, the same is not true for the gain-guided design presented here due to the induced wavefront tilt. While the proposed device will operate at a continuous range of power levels up to its maximum, the nature of the gain-guided modes induces a shift in the FF emission angle with current. Fig. 5.6 shows the off-axis progression of the FF emission as power is increased due to increased asymmetrical gain, which modifies the phase profiles of the emitting modes. Though the near-field is only spreading and scaling, a fixed fiber coupler designed for the maximum operating point will show significant decrease in coupling efficiency when used to either side of its designed power specification. The change is sufficiently slow such that operation at a stated output power should result in negligible power drift compared to the nominal long-term drift of such lasers (~1-2%). On the other hand, this feature may be exploited for applications requiring for electronically controllable beam steering, such as laser-based printing.
Fig. 5.6. Intensity of the Far-field (Top) and Near-field (Bottom) operating at drive currents 9.2 A (red) (7.7 W), 7.3 A (blue) (6.1 W), 5.1 A (green) (4.2 W), and 2.4 A (brown) (1.8 W).
In order to test the robustness of the device design, several additional index shapes were simulated. Fig. 5.7 shows the near-field intensity of the BAL where the linearly sloped index is replaced by either a cosine or a Gaussian. In this figure all plots are normalized to compare each profile's NF to that of the original (linear index ramp) design. The resultant NFs, all taken at 8.4 A operating current, are nearly identical to the original design, showing that the precise nature of the index slope is not important, only that it provide a gradual confinement of the beam spreading. Moreover, even though the alternative profiles have increased current spreading at low powers due to decreased slope at the peak of the current stripe, the output powers are nearly identical (6.13 W, 6.18 W, and 6.26 W for the cosine, Gaussian, and linear profiles, respectively).

As this work deals with free-carrier refractive-index changes, which are known to cause severe instability in semiconductor lasers, it is important to understand what effect fabrication inhomogeneities might have on the performance of the BAL. A set of 11, 1x2 µm perturbations of ±30% in both current and index profiles were hand placed in locations near important boundaries, such as near cavity reflections and along the index step at the peak of the gain. These simulations shows that in spite of the enormous defects these represent, they had negligible effect on the device performance in terms of output power, NF profile, FF profile, or efficiency.

A second set of fabrication inhomogeneities was also implemented in simulation of the laser via statistically distributed imperfections based on current manufacturing tolerances [14-17]. Though there is a significant lack of detailed information about perturbations in molecular beam epitaxy, likely due to variations from machine to
machine and operator to operator, it is generally considered that a layer can be targeted to within 1% composition and there is often ~1% change in a layers composition from center to the edge of a wafer [14]. Despite claims that there is no lateral composition variation [15], completeness requires that a set of statistical inhomogeneities be explored.

**Near-Field Intensities for Various Index Profiles**

![Near-field intensity output for half-Gaussian (red, solid) (6.18 W) and quarter-cosine (black, dashed) (6.13 W) index profiled BALs operating at 8.4 A compared to constant sloped index profile at 8.4 A (dash-dotted, blue) (6.26 W).](image)

Fig. 5.7. Near-field intensity output for half-Gaussian (red, solid) (6.18 W) and quarter-cosine (black, dashed) (6.13 W) index profiled BALs operating at 8.4 A compared to constant sloped index profile at 8.4 A (dash-dotted, blue) (6.26 W).

There are two parameters that govern such Gaussian statistical processes: the correlation length and the RMS amplitude. Although no published data exists on either of these values, a 10-µm correlation length can be implied from [16]. The amplitude of the refractive index variation was assumed to be reasonable at 1% of the variation
traditionally found across the wafer. Finally, the RMS variation of injection-current was selected to be 10%. Using these parameters to generate a two-dimensional perturbation profile for refractive index and injection-current, the proposed design was re-simulated to include these perturbative effects. Nominally, the random perturbations induced lateral reflections that, when combined with the intentional index slope, caused net reflections sufficient to induce beam modulation that could seed filamentation. To minimize this compounded effect, the refractive-index slope in these simulations was simply reduced by half in these simulations. Fig. 5.8 shows the resultant NF, which shows increased modulation due to the perturbations. However, the FF is still reasonably stable, resulting in $\sim 3.6$ W coupled to SMF-28 fiber while operating at 6.6 Amps. This performance is valid regardless of the particular realization of the randomly generated inhomogeneity map. It should also be noted that the inhomogeneity levels used in these simulations was based on crude estimates since no values could be found in the literature. In a practical design, the inhomogeneity statistics (correlation length, RMS amplitude) of a particular fabrication process should be used as input to the simulations in order to optimize the degree of refractive index slope required for maximum fiber coupling.
Near- and Far-Field Intensities for a Tailored BAL with Manufacturing Imperfections

Fig. 5.8. Intensity of the far-field (top) and near-field (bottom) of a tailored BAL (half refractive-index slope) perturbed by a random refractive index with 10 um correlation length and RMS amplitude of 1% of the bulk index variation and 10% current inhomogeneities operating at 6.6 Amps (5.2 W).
Thermal variations to the refractive index are also important to BALs in general, but also for the proposed BAL specifically due to the requirement of the refractive-index profile. A simplified two-dimensional model was used for first-order derivation of the thermal properties [18] of the laser, including the geometry of the submount. This model incorporates thermal diffusion of ohmic losses in a single-volume semiconductor layer and free-carrier-generated heat via non-radiative decay of excited carriers in the optically active region of the proposed device under power. Convective boundary conditions were used for semiconductor- and metal-to-air interfaces above the submount, while conductive boundary conditions were held at semiconductor/metal and metal/metal interfaces. The submount/simulation boundary was held to ambient. This model was solved using a finite difference time dependent scheme with eight micron resolution run to steady state for each ramp in operating power level. 50% electrical-to-optical power efficiency was assumed.

Recent work has shown that carefully prescribed submount contacts can significantly and beneficially modify thermal profiles [19,20]. Applying this concept to the proposed device design, an approximation of the desired refractive index can be generated using a thermal index profile rather than a complex semiconductor fabrication process, particularly since Fig. 5.7 shows that the shape of the profile is not important. In applying this concept, the submount is designed using an undercut that leaves an air gap under one side of the unpumped region of the semiconductor, with a conducting contact pedestal, as shown in Fig. 5.9. The semiconductor is 152 um thick, while the metal and air gap layers are 16 microns thick. The injected current region is undercut by eight
microns and the pedestal is eight microns wide. The pedestal is separated from the main contact by 272 microns. The submount is 840 microns thick. The resultant thermal profile is also shown in Fig. 5.9, along with the resulting NF. This NF shows the same qualitative features as the original device design, albeit with more spatial structure that is indicative of operating on the edge of filamentation instability. Using this first-order (i.e., non-optimized) submount design and foregoing any other fabricated refractive-index profile, the device using the thermally produced index predicts 6.9 W maximum (low-filamenting) operating power with ~3 W into conventional telecom fiber. In this simulation the thermal index has, to some degree, replaced the need for a manufactured refractive-index step, though a more elaborate insulating gap design could help generate a more desirable profile near the pumped region. Alternatively, the submount design can be made to flatten the thermal profile and remove it from the problem [20] and instituting a fabricated refractive-index profile instead.

IV. Discussion and Summary

As previously mentioned, prior work with this gain-tailored design failed at powers approaching conventional single-mode diode limitations with two likely explanations. First, the thermally induced index profile likely formed conventional modes, which led to unfilterable perturbations in the gain and thus refractive index. As described previously, such thermal gradients can be mediated (or even beneficial) with proper submount design. Perhaps more significantly, the location of the modes with respect to the gain creates a sharp free-carrier peak shown in the gain curve in top of
Fig. 5.2. Such high yet narrow gain should approximate a single-mode gain-guided laser that can lase independently. The simulations revealed that the interplay of such a narrow gain-guided mode with the other tailored-gain-modes results in an unstable modulation of the total lateral optical field and leads to filamentation. In the tailored design, the presence of a refractive-index step in this narrow gain region rapidly couples light out of any developing mode, making the lasing threshold for modes in this region extremely high and significantly elevating the filamentation threshold.

The concept presented in this chapter uses refractive-index tailoring to balance the spreading and filtering of light in a uniform quantum well in a configuration that may seem complex. However, the required current profile was demonstrated decades ago via selective current contacting [4]. Although the desired refractive-index profile could be generated via multi-step etching or implantation processes, these processes could disturb the quantum well. Alternatively, recent work in micro-channel coolers and contact tailored sub-mounts demonstrates that the thermal refractive-index profile changes can possibly be mitigated to within the required boundaries and, more importantly, suggests that the desired refractive-index profile may be created entirely thermally [19-22]. Such an approach would reduce the complexity of the proposed semiconductor manufacturing in favor of simpler sub-mount engineering.
Fig. 5.9. Top: Undercut submount design used in simulation to provide required thermally indices refractive-index profile. Middle: Normalized output electric field intensity (red, solid) and thermal profile above ambient (black, dashed) for a tailored BAL with a thick contact sitting on pedestal and shelf operating at 8.4 A (7.0 W) compared to linear profiled BAL without thermal (black, solid) at 8.4 A (6.9 W). Bottom: Respective far-field profiles.
An alternative to using refractive index (thermal or otherwise) to restrict beam broadening in the cavity would be to increase spontaneous decay in the regions outside the pumped area, for example by disordering the quantum well outside the pumped region [23].

In summary, broad-area laser simulations predict suppression of free-carrier-induced self-focusing using tailored refractive-index and injection-current profiles. An engineered combination of distributed gain- and loss-filtering mechanisms lead to 7.7 W of spatially stable (non-filamenting) output power enables high-efficiency (70%) coupling into SMF-28, resulting in 5.5 W of fiber-coupled power for EDFA pumping. The resulting design is found to be robust against the profile shape, current and refractive-index inhomogeneities, and thermal lensing.

REFERENCES


Chapter 6: Spectral and Spatial Filtering
via Fiber-Coupled Far-Field

I. External Feedback

Broad-area lasers (BALs) have both spectrally and spatially erratic emission caused by multi-mode operation, thermally induced refractive index changes [1], and refractive index changes induced by non-uniform gain [2]. These effects lead to 9xx-band BALs having spectral widths from 2-6 nm at peak operating power and spectra that drift 0.3-0.4 nm per degree Kelvin [3]. These characteristics can become problematic when strong interactions with a material’s narrow absorption peak are desired (e.g., pumping ytterbium-doped fiber lasers).

Selective laser feedback is well known to be able to modify the spectral behavior of a laser. In broad-area laser diodes, two such prominent techniques are the inclusion of a distributed Bragg reflector on the diode [3] or using a volume Bragg reflector in an external cavity configuration [4-5]. While a distributed Bragg reflector that is monolithically integrated with the diode does not require physical alignment to narrow a BALs spectral output, such devices still suffer from wavelength variability due to temperature and, therefore, operating power. Alternatively, volume Bragg gratings are more robust to temperature changes, but must be carefully aligned and tend to have scattering losses that reduce the overall output power efficiency.

This chapter presents experimental results for the use of a single-mode (SM) fiber Bragg grating (FBG) to narrow and stabilize the emission wavelength of a commercial
BAL. This technique is also shown to enhance the output power, unlike the volume Bragg grating (VBG) approach, and to modify the far-field (FF) emission pattern with the potential to improve the slow-axis beam quality. Based on these findings, a novel pump delivery fiber geometry is proposed for integration of this concept into conventional packaged systems.

In this experiment, an off-axis portion of a BAL's slow-axis doubled-lobed FF emission was selectively fed back into the BAL. Though off-axis feedback has been demonstrated numerous times using free-space, hard-aperture reflectors [6, 7], feedback from a single-mode fiber containing an FBG acts as a narrow spectral and spatial filter whose nearly Gaussian apodization (provided by the fiber mode shape) serves to reduce the excitation of undesired spatial modes.

II. Experimental Setup

Figure 6.1, on the following page, shows the experimental configuration used to achieve sub-aperture FF feedback from a SM FBG. The FBG (O/E-Land) was measured to have 98% reflectivity, 1.0 nm full-width half-max (FWHM) reflectivity, and peak reflectivity at 974 nm. The BAL used in the experiment (Axcel Photonics CM-975-3000-150) operates at 977 nm at full power (~3 W), but was cooled to more closely match the FBG. Due to low reflectivity coatings on commercial BALs, only a small amount of external feedback is needed to drastically change the lasing behavior. A modest 3.2% of the BAL output power was coupled to SM fiber (SMF) prior to enabling feedback via the FBG. The spectral widths were measured as the FWHM.
Fig. 6.1. Schematic of FBG sub-aperture far-field feedback experiment. FA Cylin. is a cylindrical lens system in the fast-axis of the diode. Pol. Cont. is a fiber polarization controller to align the feedback polarization into the BAL. The diagnostic suite consists of a power detector and an optical spectrum analyzer.

III. Spectral Narrowing

Figure 6.2 shows the spectral impact of this sub-aperture FF FBG feedback. Operating at 3.0 A, the BAL emission spectrum had a spectral width of 0.26 nm with feedback, a factor of 10.6 times narrower than the 2.8 nm width of the isolated emission. In the optimum feedback configuration, the spectrum peak was not observed to shift from 974.4 nm or significantly broaden for a range of operating powers and temperatures ranging from 14.2 °C to 20.8 °C, despite shifts in the free-running laser wavelength over this range. This high level of spectral narrowing and stability is similar to what is achieved with FBG stabilized narrow-stripe diode lasers, which have become the workhorse for reliable pumping of lower power (sub-Watt) level fiber amplifiers.
Fig. 6.2. BAL spectrum with narrowband, SM, FBG feedback (black) compared to a free-running BAL (red) operating at 3.0 A.

Of particular interest for this pumping application is the spectral density of the emission. The fraction of the output spectra emitting into specific spectral bins (centered on the emission peak) was calculated for the BAL emission with and without feedback. Figure 6.3 shows the results for both cases as a function of the spectral bin width. Using practical metric for containing most of the emission as 95%, the spectral width of the BAL with feedback is less than half that of the free-running BAL. Given the very narrow FWHM but wide pedestal of the feedback spectrum shown in Fig. 6.2, it is expected that greater feedback would eliminate the pedestal, further narrowing the total spectrum, allowing for greater utility in narrow absorption bands and significant benefits over the conventional (non-feedback) case.
One of the key aspects to a practical laser architecture is the sensitivity to the particular configuration. Figure 6.4, on the following page, shows the ratio of the FWHM of conventional BAL to that of the compound cavity device with feedback provided from a range of positions in the FF. Position 1 is located near the central axis of the emission and increasing positional indexes correspond to increasingly off-axis feedback. Position 14 is near the edge of the FF, meaning that the range of FF position indexed covers nearly the entire span of the nominal laser (half) FF. Optimal spectral narrowing was observed near the peak of FF emission, likely due to increased coupling and feedback to preferentially lasing filamentation patterns [8]. More importantly, the range of coupling covers a large fraction (~25%) of the nominal FF emission, indicating
that commercial application of this technique will be robust against fabrication and alignment tolerances.

![Graph of Ratio of Spectral Improvement as a Function of Angular Step]

**Fig. 6.4.** Ratio of the spectral FWHM of the free-running BAL to the compound cavity BAL over a range of FF feedback positions.

Figure 6.5 shows the ratio of the FWHM of the conventional BAL to that of the compound cavity BAL as a function of heat-sink temperature ranging from 14.2 °C to 20.4 °C. Over the temperature range of the measurements, the spectral peak of the BAL with FBG feedback remained fixed to 974.4 nm even though the free-running BAL shifted in wavelength by ~4nm. The experimental coupling system exhibited some variability with temperature, noted most prominently by the factor of 18.8x improvement at 15.3 °C, with more reproducible results obtained around 10x improvement. These results indicate that: (a) a packaged system would yield more reproducible results than those obtained on an optical table, (b) further work on thermal stability of the system
mechanics would aide in coupling and allow for increased performance and thermal wavelength stability; and (c) although 10x spectral narrowing was routinely and stably observed, the spectrum may be able to be narrowed by perhaps another factor of two.

Fig. 6.5. Ratio of the spectral FWHM of the free-running BAL to the compound cavity BAL over a span of heat-sink temperatures.

**IV. Power and Spatial Changes**

In addition to the spectral impact of this FBG feedback, favorable changes to the emitted power were measured, as were changes in the FF slow-axis emission pattern. Figure 6.6 shows the increase in output power of the external-feedback BAL over the free-running BAL. Increases in emitted power from 7-13% were measured in the 1.4-3.0 A regime, with 13% measured at 3 A (maximum rated) current. This relative power increase exhibits variation because the emission pattern of the BAL, and therefore the relative impact of the feedback, changes with current since the fiber was fixed at one
location in the far field for this measurement. As the output power changes, high intensity FF features can move across the SMF, causing variation in feedback to the BAL. At these moderate-to-high power levels, the relative amount of coupling stays reasonably high with varied power, indicating that positional tuning is unnecessary for the primary benefits of this configuration. However, the location of the fiber in the FF plane should be optimized for each BAL design. It must be noted that due to the experimental configuration (shown in Fig. 1), this power measurement was taken from half of the diode's FF emission, thus potentially only shows a change in the symmetry of the output. However, the chaotic nature of gain-index coupling in BALs implies that the output should be spatially distributed primarily by the gain pattern of the device and not directly by feedback [2], as indicated in Fig. 6.7.

![Enhanced Emitted Power](image)

Fig. 6.6. Percent increase in BAL output power with FF FBG feedback over free-running BAL as a function of drive current.
Perturbation to the internal spatial behavior of the BAL due to feedback from the SMF FBG is indicated by the half-FF profiles recorded in Figure 6.7. This figure shows that the feedback causes an enhanced peak at the location of the FF feedback. It must be noted that the nature of the change in the FF profile is dependent on the segment of the FF that is fed back to the BAL. In addition, the FF feedback location was selected to maximize the performance, which is nominally accomplished by enhancing the existing dominant spatial profile in the laser [8]. Although only a slight change in the FF profile is shown, increased feedback can potentially simultaneously improve the sharpness of the FF lobes as well as power and efficiency. The result could be a significantly higher brightness BAL with improved spectral purity.

Fig. 6.7. Intensity profile for half of the BAL FF profile with feedback (solid, black) and while Free-running (dashed, red).
IV. Discussion and Summary

Though this experiment was conducted by accessing the slow-axis FF of the BAL via free-space propagation for experimental purposes, the slow-axis FF would be accessed in the Fourier plane of a cylindrical lens in a practical system. Such a system, in combination with conventional fast-axis optics, would focus the desired slow-axis FF for coupling into a high-power delivery fiber. However, to enable the beneficial spectral-narrowing effects of the proposed technique, this multi-mode delivery fiber would have an embedded off-axis SM core with an FBG, as depicted in Figure 6.8 on the following page, much like a conventional dual-clad fiber. This system would then replicate the experiment while capturing all emitted light from the BAL for its intended purposes such as optical pumping or machining. In other words, in spite of the feedback configuration, the dual-clad-fiber-like implementation of the concept captures all of the light emitting from the diode laser. This is in stark contrast to many feedback techniques by which only half of the light may be used, or where filtering techniques cause large intra-cavity loss [9]. The technique proposed here should have a lower amount of scattered light compared to using a VBG, which nominally results in reduced output power relative to the FR laser [5]. In addition, any residual scattering in the present configuration is likely to still be captured by the multi-mode delivery fiber.

The literature also describes greatly enhanced spatial and spectral properties from double-armed feedback [9]. While such a system would nominally severely limit the extractable power due to the geometry of having feedback from both sides of the emission, the concept presented here would capture all of the emission on the delivery
fiber concept. Double-armed feedback could be readily accomplished with a second FBG core mirrored about the central axis of the multi-mode fiber.

With the potential to modify beam quality, this technique could also allow the use of smaller diameter for the multi-mode fiber, enhancing brightness of the overall fiber-coupled diode laser system. For spatially tiling multiple BALs typical in higher-power systems [10], multiple such FBG cores could be included for each laser using standard multi-core fiber fabrication techniques [11]. In all of the cases presented above, the common theme is to exploit the existing large-core pump delivery fiber for high-power BALs with extremely narrow spectral bandwidths.

**Off-Axis FBG Fiber Depiction**

Fig. 6.8. Depiction of a delivery fiber with an off-axis embedded core FBG configured for sub-aperture FF FBG feedback.

The work presented in this chapter has shown that the lasing behavior of BALs can be drastically changed by utilizing a highly reflective FBG and angularly selective
feedback from the far field. The spectral content of a 3.0 A commercial BAL was narrowed by a factor of 10.6 down to 0.26 nm. This technique, like conventional low-power FBG-stabilized SM diodes, is independent of the laser diode temperature. The method introduced here includes a spatially and spectrally selective reflector in the FF, which also enhances the emitted power (without increasing emission angle) and thus increases spatial brightness of the BAL by up to 13% at its intended operating power. This filter also causes a change in FF profile shape, indicating that additional beam quality improvement may be derived from further optimization. Novel pump delivery fiber configurations were presented that enable this technology to be rapidly integrated into the current manufacturing environments and significantly enhance the benefits attained by this technique for commercial high-power diode pump laser systems.

REFERENCES


Chapter 7: Spatial Coherence Collapse and Recovery in Broad-Area Lasers

I. Introduction

Recently it has been shown that, at low powers, a spatially resolved self-heterodyne detection scheme can be used to measure the lateral modes of a broad-area laser [1]. This scheme is based on the premise outlined as follows. Each lateral mode of the resonator will have a distinct optical frequency based on its 2D eigenvalue: the lateral modal effective index coupled with the longitudinal resonator condition. Therefore, any two lasing modes impinging on a detector will beat together at an RF frequency corresponding to their separation in optical frequency. If measured with sufficiently high spatial resolution (i.e., sub-sampling the emission), the beat frequencies can be used to reconstruct spatial patterns that exist at each beat frequency.

This technique has practical implications in that it may be able to be used to track the progression of slowly growing defects in the laser and thus predict the failure of a BAL [2]. From a physics perspective, knowledge of mode behavior is important to the quest for brightness improvements in BALs particularly with regards to filamentation. In this vein, it is interesting to note that the prior experimental demonstration [1] had some interesting anomalies. First, the data was published only at relatively low optical powers. Second, this low-power data revealed only simple Box Model modes, with no indication of the spatio-temporal chaos indicative of the filamentation that is prevalent in these devices [3, 4].
In this chapter, the evolution of models and filamentation in BALs is measured over all power levels. An alternative setup for BAL self-heterodyne measurements is demonstrated incorporating an optical fiber as a sub-aperture sampling mechanism. The measured results indicate that while the mode description of the optical field is sufficient at relatively low powers, the modes seem to vanish at higher powers, indicating collapse of spatial coherence. At even higher powers, spatial coherence partially recovers, indicating an interplay between filamentation and the mode structure of the laser resonator.

II. Experimental Setup

In the experiment, diagramed in Fig. 7.1, the use of a Discovery Semiconductor DSC-20H detector nominally allowed the detection of beat frequencies up to 30 GHz. However, the two radio-frequency (RF) amplifiers used in the experiment limited the measurements to 19 GHz. The magnified image of the BAL near-field was sampled with an optical fiber. This configuration allows a decoupling of detector size requirements from the method previously demonstrated [1], which enables the freedom to select a detector based solely on more important experimental parameters such as responsivity and bandwidth. Removing the detector from the direct beam also eliminated the problem of overfilling the detector. Such overfilling leads to generation of charges outside of the active region, which migrate to the active region via diffusion rather than drift, thereby slowing down the response of the detector.
Using anamorphic coupling optics to independently focus the fast-axis (or transverse mode) of the NF, the optical fiber could be used for sampling a BAL near-field image down to 2-6 micron resolution in the image. Although multiple NF magnifications were investigated, a 3.5x magnification and 1.9 micron object-space (NF) resolution was determined to give sufficient spatial resolution without imposing challenging limits on data acquisition time. Each spatial location was measured across the bandwidth of the RF amplifier in use (0-10 GHz and 6-19 GHz) and time averaged, resulting in ~1.5 minutes per location. The stage was then laterally shifted for the next spatial location. This was repeated ~72 times per amplifier to span the emission profile within the 10% emission boundaries. This process required nearly 4 hours for a single mode measurement, which was repeated at different pump currents and at various other operating conditions.

The BAL investigated in this experiment was a C-mounted Axcel Photonics CM-975-3000-150 laser diode driven with continuous current. The laser was temperature controlled via mounting to a cold plate kept to 16.3±0.2 degrees Celsius by a thermoelectric cooler.
Fig. 7.1. Schematic of an experiment for self-heterodyne measurement of lateral modes of a BAL using a scanning single-mode optical fiber to sample the optical near field.

This measurement system allows one to sample the image of the BAL. Each sample point is the result of the emission of all lasing modes of the BAL. Upon detection, the rapidly varying optical frequency differences between these modes manifests as an RF signal which can be analyzed in the frequency domain using an RF spectrum analyzer. By arranging the samples as they are collected, a spatio-spectral map can be made that is representative of the spatio-spectral mode structure of the lasing diode. In particular, the spectral axis represents the difference between the effective indices of the modes, while the spatial axis represents the spatial intensity overlap between the modes.

Figure 7.2 shows two such maps taken at a 3 A operating current using 1 MHz spectral resolution integrated over 1.5 minutes per spatial-sampling point. This time
integration is long compared to any dynamics in the laser system and will serve to average out any time varying aspects of the signal. As expected, the detected maps are nearly identical, even though these to particular maps were taken several days apart. Although not shown in Fig. 7.2, several properties of the system cause the quality of the data to degrade at higher frequencies, particularly beyond ~8 GHz. Both the detector responsivity and the RF amplifier gain decline with , and the RF spectrum analyzer itself has a noise floor that increases with frequency.

**BAL Mode Map Stability**

Fig. 7.2. Two measurements of the BAL under test operating at 3 A pump current taken days apart.
III. Box Model Analysis

The previous measurement and analysis [1] discounted the beating of neighboring longitudinal modes and their associated lateral modes. However, the existence of these longitudinal modes reveals itself in the data and must be included in order to properly interpret the observed data. Specifically, this higher-order mode beating causes patterns emerging at RF frequencies that encroach on the fundamental modes that are the course of the study. To include multiple longitudinal modes in the model presented by Stelmakh and Vasilyev, one first requires relation between the neighboring longitudinal modes, which beat at a separation frequency described by the equation

\[ \Delta \nu_{FP} = \frac{c}{2n_{eff,g}L} \quad (7.1) \]

where \( \Delta \nu_{FP} \) is the separation/beat frequency determined by the Fabry-Perot (FP) cavity, \( c \) is the speed of light in vacuum, \( n_{eff,g} \) is the effective group refractive index of the modes, and \( L \) is the length of the cavity. Lateral modes from additional longitudinal modes will beat with the lateral modes from all other longitudinal modes. Although nominally this interplay will result in beat frequencies outside of our measurement band, there is one set of frequencies in particular that will come into play.

Consider a single longitudinal mode at frequency \( \nu_i \) and the next higher-frequency longitudinal mode at frequency \( \nu_{i+1} \). Each of these nominal longitudinal cavity modes will have corresponding lateral modes at frequencies \( \nu_{i,m} \) and \( \nu_{i+1,m} \), respectively. This is schematically shown in the top of Fig. 7.2. In the case of a single longitudinal mode, the
mode at frequency $v_{i,0}$ and will beat with the mode at frequency $v_{i,1}$, resulting in an RF beat frequency

$$\Delta v_{i,0-1} = v_{i,0} - v_{i,1} \quad (7.2)$$

Note that since the change in lateral mode spacing is nearly zero with change in longitudinal mode, this beat frequency occurs independently at each longitudinal mode. With the additional of the next higher-frequency longitudinal mode, the beat frequency between the fundamental lateral modes at each of these longitudinal modes results in a beat frequency

$$\Delta v_{i-i+1,0} = v_{i,0} - v_{i+1,0} = \Delta v_{i,0-1} = \Delta v_{FP} \quad (7.3)$$

where $\Delta v_{FP}$ is given by Eqn. (7.1). Again, as is typical in any Fabry-Perot resonator, this frequency occurs for every pair of longitudinal modes. Now consider the next lateral mode of the lower-frequency longitudinal mode beating with the fundamental mode of the higher-frequency longitudinal mode. This interaction will result in a beat frequency

$$\Delta v_{(i,1)-(i+1,0)} = v_{i,1} - v_{i+1,0} = \Delta v_{i,0-1} = \Delta v_{FP} - \Delta v_{i,0-1} \quad (7.4)$$

where the right-hand side of Eqn. (7.4) was derived by simply exploiting Eqns. (7.2) and (7.3). The analysis above can, in fact, be completed for any set of lateral modes between neighboring longitudinal modes, resulting in the general relation

$$\Delta v_{(i,m+1)-(i+1,m)} = v_{i,m+1} - v_{i+1,m} = \Delta v_{FP} - \Delta v_{i,m-m+1} \quad (7.5)$$

Equation 7.5 shows that in the typical case of multiple longitudinal modes, every lateral mode beat frequency will be represented twice in the RF domain – once at the expected beat frequency and once at the FP frequency minus the expected beat frequency. The beating of increasingly higher-order modes will have a corresponding mirrored
progression coming down from the RF frequency of the FP spacing, as represented in the lower plot of Fig. 7.3. The implications of this effect and the insights that can be gained will be discussed below.

**Mode Beating Relationships**

![Mode Beating Relationships Diagram]

Fig. 7.3. Pictorial representation of the generation of the descending beat frequency $v_{(i,m+1)-(i+1,m)}$. The first index represents a longitudinal mode with a comma separating the second index that labels the order of the lateral mode. Interaction between lateral modes 1 and 2 and beating beyond the FP frequency are not shown to maintain pictographic simplicity.
Self-Heterodyne Measurement and Box Model

Fig. 7.4. (a) RF Self-heterodyne measurement of a BAL at 0.6 A, and (b) the a Box Model prediction of the measurement with seven lateral modes and two longitudinal modes. The dashed line shows the symmetry point in each case.

For the 2mm diode used in this experiment, the beat frequency related to the full longitudinal mode spacing of ~20 GHz falls outside the presently measurable range (19 GHz). Nonetheless, this experiment still measures mode beating between neighboring longitudinal mode sets shown in Figure 7.4 (a). Since the beat frequencies caused by the inclusion of higher-order lateral modes mirror those of intra-longitudinal mode beat frequencies, a symmetric point can be observed at half the longitudinal mode spacing. Examples of this effect arise in both experiment and model, as shown in Figures 7.4 (a) and 7.4 (b) respectively. The differences between Figures 7.4 (a) and 7.4 (b) are
presumed to come from an asymmetrical, lateral, refractive-index profile. Since waveguide modes are analogous to quantum well energy levels [5], an asymmetrical perturbation to the waveguide distorts the Box modes and splits their degenerate eigenvalues. Similar to Stark splitting in a quantum system, an asymmetrical perturbation to the step index profile, caused for example by thermal mounting asymmetry, causes the diode behavior to deviate from the simple Box model at low powers. Anti-symmetric split modes increase the number of detected beat frequencies and demonstrate symmetrical power densities.

**Symmetry Refractive Index Analysis**

![Graph](image)

Fig. 7.5. RF spectral measurement at the middle of a BAL operating at 1.1A. Symmetry is marked by a dashed line corresponding to an effective group refractive index of 3.875.

Knowing that the symmetric point occurs at half of the longitudinal mode spacing, one can use this frequency and knowledge of the diode length to determine the
effective refractive index. This deduction can be accomplished by experimentally finding this symmetric point and solving Equation (7.1) for $n_{\text{eff},g}$ using the symmetric frequency so that $\Delta \nu_{FP} = 2\nu_{\text{symm}}$. From Figure 7.5, the effective index can be determined to be 3.875, which likely corresponds to a strained InGaAs laser with high dispersion near an absorption peak [6]. Additionally, thermal refractive index changes due to thermal refractive index changes will increase the refractive index [7,8].

Though use for inter-longitudinal mode beating has been demonstrated, the plethora of beat frequencies encountered as increased drive currents are used begin to defy measurement and analysis. Figure 7.6 (a) shows that, for this diode, the measured RF structures become markedly less distinct at 1.2 A of pump current when compared to 7.4 (a), though some of the previously evaluated symmetry can still be observed. There are two striking features of Fig. 7.6 (a). First, there is a remarkable lack of spatial structure throughout most of the spatio-spectral map. Second, there is also a remarkable lack of structure in the spectral domain. In effect, the entire spatio-spectral map seems washed out compared to the clear and distinct mode beating patterns shown in Fig. 7.4(a).
High-Power Analysis

Fig. 7.6. RF Self-heterodyne measurement of the BAL operating at (a) 1.2 A and (b) 1.6 A. (c) Laterally summed frequency map of the BAL operating at 0.6 A (dashed, black), 1.2 A (solid, green), and 3 A (dash-dotted, red).
There are two conclusions that could be drawn from this observation. First, the lack of RF structure indicates that the beating does not come from distinct spatial modes that have distinct eigen-frequencies (effective indices). Second, the relative lack of spatial structure in the RF map indicates that there may be no predominant spatial patterns in the lasing itself (i.e., no modes). It is important to note that both of these conclusions can only be true in the time-averaged sense. It may be possible, for example, that the mode patterns and effective indices are changing on timescales much faster than the ability to measure them in this experimental set up. On the other hand, it may be possible that spatio-temporally chaotic filamentation has completely dominated the behavior if the device, indicated by the significant broadband noise shown in Fig. 7.6(a).

Determining which physical phenomenon is in fact occurring would take a more sophisticated experiment, for example a very long time-scale streak camera. Regardless, the lack of modal cohesion over measurable timescales indicated a complete breakdown of spatial order, i.e., spatial coherence collapse.

This spatial coherence collapse, however, does not continue as the output power of the device is increased. As the current is increased further, the mode-beating patterns eventually reappear, albeit on top of a broadband background. This yields spatially integrated spectra similar to the red dash-dotted line in Fig. 7.6(c). The presence of mode beating without suppressing the broadband background indicates partial recovery of spatial coherence in the device. Figure 7.6 (b) also shows the development of a sharp, high-contrast, RF spectral feature at 1.6 A that does not exhibit the aforementioned spectral symmetry described in Fig. 7.4. Particularly, the sharp peak located at 838 MHz
does not have a distinguishable high frequency counterpart, which should occur around 18.5 GHz. Although this experiment and analysis was originally designed to examine the RF beating between lateral modes, it fundamentally will measure any spatial pattern occurring at a specific RF frequency. Since the sharp bright line shown in Fig. 7.6(b) has no mirrored RF frequency, it is possible that this line is a direct measurement of quasi-stabilized filamentation, which exhibits dominant spatial and oscillatory (RF) features [8]. In this case, there would be no symmetry line since the filamentation is not a mode-beating phenomenon and would therefore not exhibit the RF spectral symmetry shown in Fig. 7.4. Moreover, the measured RF frequency of this sharp line is in the GHz range, as predicted and measured previously [9, 10].

As the current is increased even further, a combination of all of these effects is generally observed at all times: some mode-beating patterns, with high broadband noise, and often a spectrally sharp non-mirrored RF pattern. The red dash-dotted line in Fig. 7.6(c) reveals the two primary behaviors without the sharp spectral peak.

The observed behavior on this laser, from coherent modal lasing, to coherence collapse, to partial coherence recovery, can be attributed to refractive index changes occurring in the device, both dynamically and statically as a function of current. There are four pertinent refractive index mechanisms occurring in the broad-area laser. The first is a designed refractive index step fabricating via etching. While this would create a lateral waveguide, it is unknown whether this particular device includes this index step since broad-area lasers often operate in the gain-guiding regime to save fabrication costs at the expense of device efficiency. The second is a thermal index profile due to ohmic
heating in the device. This mechanism will create an increasingly positive refractive index step as the current is increased. Unfortunately, the lateral distribution of the induced index profile cannot be known since it is highly dependent on the specifics of how the laser is mounted, the submount design, and many other fabrication parameters. The third mechanism is the free-carrier-induced index step governed by the linewidth enhancement factor. Once above lasing threshold, this mechanism should nominally produce a negative index step approximately shaped as the current distribution, leading to a negative lateral waveguide that can combat the thermally induced waveguide, possibly leading the observed coherence collapse. In addition, this same physics also leads to the fourth mechanism, a severe and dynamic disruption to the refractive index pattern through spatial hole burning and subsequent filamentation: high-intensity light, even as simple mode peaks, saturate the local gain resulting in a positive change in refractive index. The stability of the nominal mode profiles will ultimately be determined by the magnitudes of these effects with respect to each other.

Our speculation is that these free-carrier index changes can be sufficiently strong to impact the modal properties of the laser on a dynamic scale, leading to spatial coherence collapse. It is critical to understand that the free-carrier induced index changes do not need to be strong enough to completely mitigate the other waveguiding mechanisms. They only need to be sufficiently strong to ensure that the spatial and effective indices of the modes change sufficiently that from one moment to the next, such that the time-averaged measurement shows light occupying all space over the whole RF domain.
Continuing this hypothesis, the partial coherence recovery could then be explained by the increasing thermal refractive index step. As the thermal index step becomes larger, the relative size of the free-carrier-induced index step becomes smaller. As such, these dynamic changes have a smaller impact on determining the spatial shape and eigenvalue of the modes, which would effectively partially stabilize the mode patterns. Finally, the sharp peak may be explained complete via quasi-stable filamentation, which exhibits a characteristic feature size, or it may be a more complex interaction wherein the self-focusing is coupled to existing high-order lateral modes of the dynamically changing waveguide.

IV. Discussion and Summary

Self-heterodyne measurements of BALs allows for spatial discrimination of BAL lateral mode beat frequencies with megahertz resolution. The literature has shown the results to match well with the simple Box Model for BALs at low optical powers [1]. Extension of detection to 19 GHz shows that the limitation of the literature's analysis to sub-longitudinal mode spacing is not sufficient to ignore the presence of multiple longitudinal modes. Due to all of the inter-mode beat frequencies that occur, cross-longitudinal mode beat frequencies appear in a measurement window descending from high frequency. This interaction develops an RF symmetry about a frequency half that of the longitudinal mode spacing (and at every integer multiple) that allows for the measurement of the effective refractive index of the device using low-cost RF components.
More importantly, the use of this technique has identified three distinct regimes of operation in a commercial BAL. The first is a low-power regime where individual lateral mode beat frequency pairs are distinguishable operating as a conventional linear waveguide. The second is a mid-power regime where distinguishing mode beating becomes impossible, mimicking free-space or chaotic-type behavior, i.e. spatial coherence collapse. Then at high-power, characteristic frequencies once again become resolvable over a broadband RF noise floor, indicating partial recovery of spatial coherence, with the additional introduction of filamentation-like behavior that lacks the RF symmetry (mirroring) properties given by the distinct mode-beating patterns.

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1.3μm InGaAs, AlGaInAs and GaInNAs semiconductor lasers under high hydrostatic pressure,” Electronics Letters, vol. 38, pp. 325-327, 2002.


Chapter 8: Conclusions and Future Work

I. Conclusions for High-Brightness Laser Diodes

This thesis aims to improve the development of diode laser usefulness at high powers. Although electrically pumped semiconductor lasers have highly desirable properties in terms of wall-plug efficiency, wavelength selection, size, and robustness, areal power density limits the maximum output power of these devices through the mechanism of catastrophic optical damage. While this can be avoided by increasing the lateral dimension of the diode laser beyond the single-mode waveguide limit, such a broad-area laser diode will have reduced beam-quality and brightness since it will be a multi-mode device.

The traditional solution to multi-mode operation, i.e. an inter-cavity spatial filter, fails to produce satisfactory single-mode results in BALs due to free-carrier induced refractive-index changes that can significantly alter an optical field distribution on length scales shorter than the cavity length. More advanced techniques have been attempted to achieve high-power, high-beam-quality emission from diode lasers such as coherent beam combination, tapered lasers, tapered master-oscillator power amplifiers, low-confinement SCOWLs, angled distributed Bragg reflectors, and single mode external feedback. None of these techniques have been met with success in scaling to higher powers with good beam-quality, and few have been proven to be worth the effort. This lack of success has left fields such as laser display, laser marking and welding, and fiber-optic pump lasers wanting for advancement in the development and understanding of high-power, high-brightness BALs.
In Chapter 3 of this work, a tapered waveguide multi-mode interference coupler was designed for passive coherent beam combination of a number of single mode diode sources. This device is intended to maintain maximum areal power densities equivalent to that of a single-mode diode laser while supporting N-to-N feedback between single-mode gain elements for self-organized coherent beam combination. The result is a design for a low-loss, fixed-intensity coupler that preferentially supports lasing of a desired wavelength in a self-organized coherent beam combination system.

In Chapter 4, the effects of carrier-induced refractive-index changes were numerically studied in convention BALs, with a particular emphasis on the relations between these effects, waveguide cavity confinement, and beam quality. The results indicate that care should be taken to include beam-quality in calculations of optimum facet reflectivity. Additionally, a BAL should be designed so that, prior to accounting for free-carrier induced refractive-index changes, a slight positive lateral waveguide exists so that the effect of free-carrier induced changes nearly eliminates the lateral waveguide. Proper and robust design was predicted to lead to a 2x improvement in output beam quality over a poorly designed device with no costly changes to manufacturing processes.

In Chapter 5, the simulations of Chapter 4 were expanded with the goal of tailoring pump-current and refractive-index profiles of a BAL to suppress filamentation and improve lateral beam-quality. Prior art had discovered that a specific tailored current profile could result in improved beam-quality at low operating powers. Simulations in this work suggested that the limitations derived from thermal refractive index profiles...
which limited the continuous filtering generated by the tailored gain. Further simulations predicted that with a right-triangle-shaped current profile and refractive index control, it is feasible to reach laser power out of \( \sim 7.7 \) W with sufficiently good beam-quality to couple 5.5 W into a single-mode EDFA core. Statistical noise was added to refractive-index and pump current to show that the device did not suffer significantly from manufacturing imperfections. Since lithographic control of lateral refractive index profiles is technologically challenging, an alternative method of controlling refractive index through the thermal properties (that ironically caused the historical failure of the tailored BAL) was proposed. A tailored thermal submount was simulated and developed that approximates the desired refractive-index profile when the device is subjected to full pump current. Though not ideal, this method predicts high-beam-quality operation at power 3.6x greater than commercial devices.

In Chapter 6, enhancements to a BAL were experimentally investigated using off-axis external cavity feedback. Specifically, a single-mode FBG was placed in the BAL in the far-field to act as a spatial filter while providing spectrally selective feedback. The spectral FWHM of the BAL emission was narrowed by \( \sim 10x \), with the spectrum fixed relative to the grating despite thermal variations in the free-running BAL over a large range of pump current. A 10% efficiency improvement was also observed due to this feedback. Modification to the far-field emission profile implied that this cavity design could also provide spatial brightness improvements to the BAL. A novel pump delivery fiber with an embedded, off-axis, single-mode core containing an FBG was proposed for employing this method for a manufacturable system to narrow and stabilize
emission wavelength, improves brightness, and capture all light, e.g. for pumping a dual-clad fiber laser.

In Chapter 7, the lateral mode behavior of a BAL was studied through the use of a spatially resolved RF self-heterodyne measurement, nominally to observe the beating between various lateral modes. This experiment was improved over the literature through the use of optical fiber, broader spectrum RF amplifiers, and a faster detector. It was also determined that the disregard for multiple longitudinal modes in prior work was incorrect due to cross longitudinal-mode beat frequencies. This phenomenon was found to be useful for measurement of the effective index at frequencies within common SMA-based amplifier bandwidths, and for analysis of higher order physics revealed in the experiment. Three distinct regimes of operation were observed: (1) full spatial coherence, characterized by pure mode beating; (2) spatial coherence collapse, characterized by the dissolution of spatial structure and broadband RF noise; and (3) partial spatial coherence recovery, characterized by some mode beating and filamentation with significant broadband RF noise.

II. Future Work

Graduate student studies should inevitably end, while the search for knowledge does not. Additionally, doctors of philosophy should understand their specialties and be able to look ahead to direct the course of research, be it their own or research left to future students. In this section, expansions to topics presented in this dissertation will be proposed as targets for future work.
Chapters 3-5 of this dissertation cover numerical design of high-brightness diode-laser systems. The obvious extensions to these works are to extend them to physicality via experimental validation. A number of ways could be attempted for the work in Chapter 3. Monolithic integration of gain sources with the MMI structure is beneficial in terms of the ability to efficiently couple gain waveguides to the MMI coupler. However, the MMI is required to be passive or else the detrimental effects of free-carrier refractive-index changes will ruin its purpose. Even when un-pumped electrically, if the same quantum well structure is in the MMI as is in the gain branches, then the device will have tremendous losses and suffer from free-carrier effects. It may be desirable to manufacture the MMI separate from the gain array and mount them together after lithographic manufacture. This separation would allow for conventional diode quantum-well boundaries while allowing for same material coupling. Due to the length of the MMI, same-material manufacturing may be deemed cost prohibitive. In this case, coupling to a silica-on-silicon waveguide could be an option, though care must be taken to achieve adequate coupling efficiencies. In either case, sub-wavelength control of the path lengths of the gain element arms will likely be critical in achieving self-organized coherent beam combination. In the non-monolithic cases, diode arrays with different path length configurations may be able to be swapped while using a single MMI coupler. As a smaller project, the device could be simulated in entirety with gain elements using the current BPM code.

The first step in the physical realization of the concept in Chapter 4 is simple in that BAL diodes are currently made commercially and their facet coatings are normal in
the manufacturing process. The difficulties arise in the ability to obtain either uncoated BALs or BALs coated to specification. If the coating is done at the university level, testing of the coating properties would be important for any scientific correspondences, but this would likely need to be done to transition to experimentally demonstrating the waveguide step parameter. It is unlikely that a commercial partner would be willing to alter their lithographic processes so much as to change the waveguide over a number of runs, so this device would likely have to be grown at a university or in conjunction with another research institution.

Chapter 5 describes the design for a filament free broad-area laser. Unlike the laser in Chapter 4, the laser from Chapter 5 could be constructed from a laser diode wafer prior to electrical contacts being formed. This could significantly reduce the time and expertise required to develop a lasing structure from scratch. Continuation of the work in Chapter 5 would have the additional challenges of cleaving and careful mounting of the BAL on a carefully and likely micro-lithographically defined sub-mount. Further numerical design with regard to the thermal impact on the refractive index is also of interest. The thermal design presented in this dissertation was made at 8 micron resolution. Higher resolution design could develop a sub-mount pattern that more carefully controls the thermal profile. A clamping mount with N-side contact could also be designed with the objective of shifting the thermal peak to more closely coincide with the current peak, thereby increasing the performance of the device.

The experiment of Chapter 6 can be expanded in a number of ways. Dual-arm feedback could be attempted in separate fibers, but this would sacrifice a great deal of
measurable information unless an intra-cavity beam sampler were included, which would itself degrade performance. To significantly progress the experiment into the realm of commercial viability, the proposed pump delivery fiber with embedded FBGs should be made, along with a custom designed and fabricated micro lens for properly scaled coupling of the slow-axis far-field to the fiber in a compact manner. This experiment would require a relay system and an intra-cavity sampler to obtain any information about the change in beam-quality. It would also be interesting to inspect the half-far-field of the original experiment using the technique of Chapter 7 to study how the lateral mode structure changes with the inclusion of off-axis feedback.

The experiment of Chapter 7 could be attempted with other BALs to develop broader reaching conclusions about the evolution of mode structure with lasing power. The experiment could also be attempted without the use of coupling optics. An optical fiber could be tapered down to achieve a smaller sampling point and then positioned, under microscope, very close to the facet of the BAL. This removes any impact of poor lens alignment on the system. Additional higher-level physics can be obtained more complex experimental configurations to extract temporal details about the spatial mode structure. Examples include streak cameras, which measure time and space but over only short windows of time, or transient digitizers, which can measure long time traces with high resolution but only at a single point. Ultimately, understanding the physics details of the coherence collapse region would benefit from either of these methods, or preferably both.