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The Effects of Optical Feedback on Polarization
of Vertical Cavity Surface Emitting Lasers

THESIS

Gregory J. Vansuch, Captain, USAF

AFIT/GAP/ENP/93D-09

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**The Effects of Optical Feedback on Polarization
of Vertical Cavity Surface Emitting Lasers**

THESIS

**Presented to the Faculty of the Graduate School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Engineering Physics**

**Gregory J. Vansuch, B.S., M.A.
Captain**

December 1993

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Preface

The goal of this effort was to investigate the effects of optical feedback on the polarization of Vertical Cavity Surface Emitting Lasers (VCSELs). Motivation for the research began because VCSELs are likely candidates for many photonics applications, including optical communication and computing, in which polarization of the laser is important. Since VCSELs, like edge-emitting semiconductor lasers, have been shown to be quite sensitive to optical feedback, it made sense to investigate feedback effects on VCSEL polarization.

This research succeeded with the help of many people. My advisor, Captain Jeff Grantham, provided the initial motivation for the research and kept me interested even when progress was slow. His expertise in the laboratory and thorough knowledge of VCSELs were essential to solving the many problems encountered along the way. Many thanks to Captain Richard Bagnell, who donated many hours of patient tutoring to help me get the experiments running. I am indebted also to Captain Scott Brown, my colleague in VCSEL research. Besides providing a daily exchange of ideas, he directly solved at least two major experimental problems that had me stumped. I also appreciate the support provided by Mr. Rick Patton, whose knowledge of the laboratory proved invaluable.

Without the VCSELs, there would be no research. My thanks go to the University of Arizona and the University of Virginia for providing the samples for experiments. Major Paul Ostdiek provided an essential link to the researchers at University of Virginia and polished the substrate of the VCSEL to allow back-side feedback.

Without my wife, Diana, I would be lost. She endured my absence from the "real world" for three months. More importantly, having experienced the trials of scientific laboratory research herself, she provided constant reassurance of a light at the end of the tunnel. How right you were, Diana.

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Abstract

Vertical Cavity Surface Emitting Lasers (VCSELs) are a type of semiconductor laser with a cavity oriented orthogonally to the planes of material growth. These lasers differ from conventional edge emitting lasers in several important ways. They have symmetric output beams and they are easily built into two dimensional arrays, making them very attractive as photonic components. The characteristic of interest in this thesis is polarization. While the asymmetric cavities of edge emitters exhibit a clear preference for light polarized in a particular direction, the cylindrically symmetric cavity of a VCSEL has no clear preference. Therefore, it should be relatively easy to change the polarization of a VCSEL. This thesis examines the polarization switching effects of optical feedback from an external reflector. By feeding back various amounts of cross-polarized light, the switching susceptibility of the VCSEL can be determined. Measurements confirmed that the polarization of a VCSEL can be switched through polarized optical feedback, with the degree of switching depending on the strength of feedback. This switching was a relatively rare behavior, indicating that most VCSELs had some type of preferential polarization. This preference could be due to the VCSEL structure itself or the manner in which it was excited.

I. Introduction

This thesis is an investigation of the effects of optical feedback on the polarization of Vertical Cavity Surface Emitting Lasers (VCSELs). These lasers are of growing interest in the photonics field because of their symmetric beam shape, low thresholds, single mode operation, and the ease with which they can be made into arrays. The beam shape, low threshold, and single mode make a VCSEL very appealing as a light source for optical fiber communication. The fabrication of arrays is a critical step for efficient optical computing or the creation of a high power optically steered laser beam. In all these applications, and in reading/writing to magneto-optic disks, polarization of the light is a critical parameter, motivating the study of polarization in VCSELs. Compared to most semiconductor lasers, VCSEL cavities are highly isotropic, so the preference for a particular polarization is very weak. This makes the VCSEL highly susceptible to an external polarized stimulus, such as optical feedback of polarized light. Since optical feedback in the form of reflections is a fact of life in many applications (VCSELs do not exist in splendid isolation from other components), it is very important to understand the effects the feedback will have on the VCSEL's polarization.

Polarization changes also have beneficial uses. Polarization can be used as a method of signal modulation, the signal changing between orthogonal polarization states based on an input of some type. (Liu, 1985; Chen, 1984) The appeal of polarization modulation is that it can be done with very constant output power, offering great stability in system design. (Sapia, 1987) In polarization modulation, switching speed is a critical parameter, and optical feedback in the form of retroreflections may slow or speed the switching. Finally, optical feedback offers the possibility of bistability in polarization state. This has been shown for other lasers that are highly isotropic. (May, 1989;

Stéphan, 1985; Xiong, 1991) If bistability can be found in VCSELs, the number of uses in optical switching and optical computing could be enormous.

Background

VCSELs, like all lasers, need three main components: a source of excitation (pump), a gain medium to excite, and mirrors. In a VCSEL, the gain medium and mirrors are grown from semiconductor material using either Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Deposition (MOCVD), resulting in an integrated structure of layered material. The pump source for VCSELs is typically electrical, with contacts on both sides of the device. In this research, the pump source was optical. This was done because there were no electrically-pumped VCSELs available and optical pumping introduces less asymmetry than the etching process that created electrically pumped VCSEL cavities. Figure 1 shows a typical VCSEL of the type used in this research.

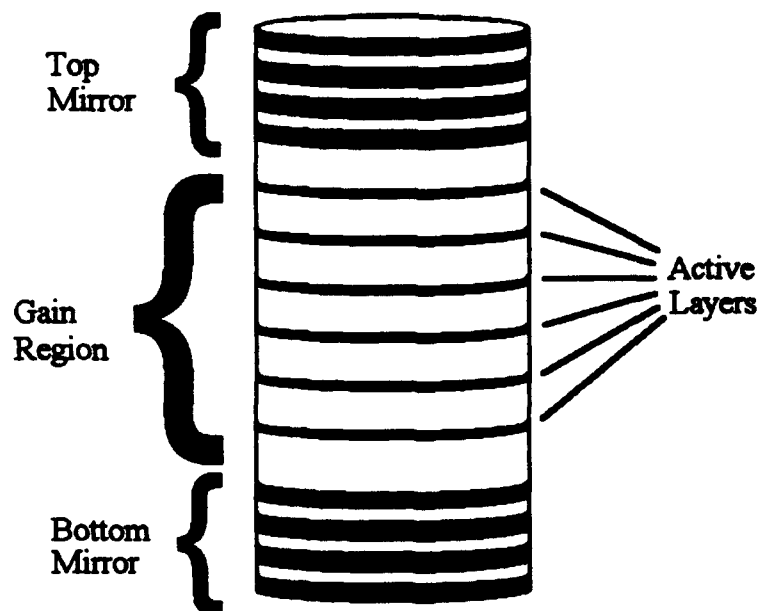


Figure 1. Typical VCSEL Geometry

The VCSELs used in this research had gain regions made from III-V compounds such as Gallium Arsenide (GaAs) or Indium Gallium Arsenide (InGaAs), which have band gaps in the near-infrared region with wavelengths between 800 nm and 1000 nm. Although the gain region could be 100% active material, it is more efficient to put the active material only where the electromagnetic field intensity will be at a maximum. Figure 1 shows the geometry of the active region in a case where the cavity length equals three wavelengths of the light. Note that this is not an issue for most other lasers; it is the extremely short cavity lengths of VCSELs (on the order of microns) and the fact that one can control layer composition along the cavity that allow this periodic gain structure. As a further option, the active regions can be bulk material or quantum wells. Both bulk and quantum well active regions were used in this study.

The mirrors were also made from III-V compounds, but were alternating layers of high and low index materials, resulting in a Distributed Bragg Reflector (DBR). The two indices and the layer thickness were all optimized to reflect light at the wavelength for which the laser is designed. For more details, see Bagnell, 1992. A typical VCSEL reflectivity as a function of wavelength is shown in Figure 2.

The pump source in this effort was another laser at a higher frequency (lower wavelength). A tunable laser was used to choose a wavelength that corresponded to the first low reflectivity dip in the mirror (see Figure 2). This allows the highest coupling of pump energy into the medium at a wavelength close enough to the lasing wavelength that little energy is released as heat. The lasing will occur at the Fabry-Perot dip, as shown in Figure 2.

One of the key features of VCSELs is they are easily designed to operate in a single longitudinal mode. The longitudinal mode spacing is given by

$$\Delta\nu = \frac{c}{2nd} \quad (1)$$

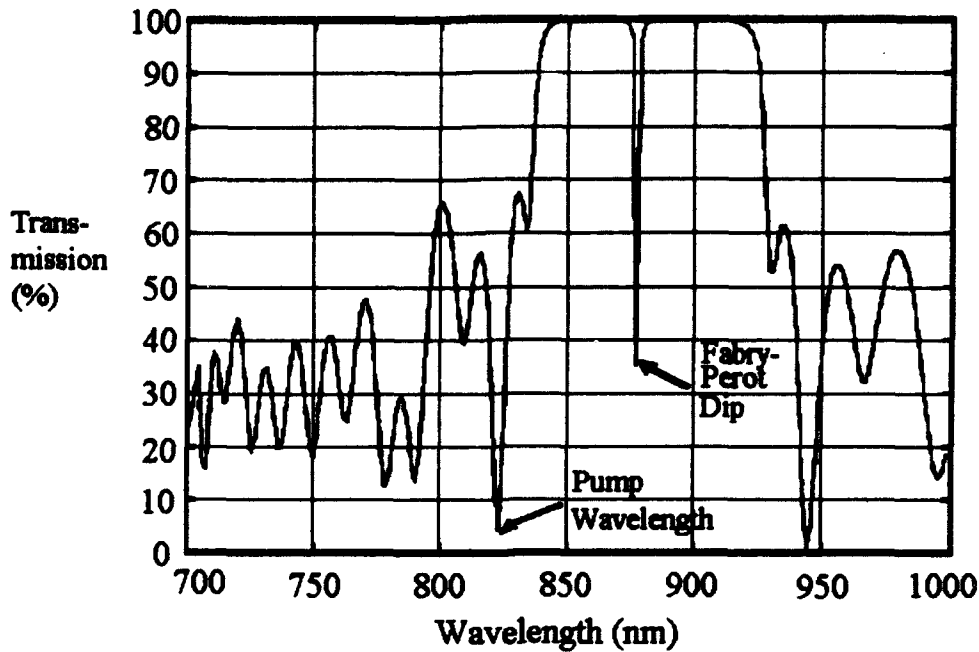


Figure 2. Typical VCSEL Reflectivity (Bagnell, 1992: 1-5)

where c is the speed of light, n is the index of refraction, and d is the cavity length. With cavity length on the order of microns, mode spacing is large enough to put adjacent modes outside the high reflectivity zone of the DBR mirrors. However, multiple transverse modes can still exist, and will be examined for polarization effects.

Polarization of VCSELs is the main characteristic of interest in this thesis. Light from lasers is polarized because the process of stimulated emission creates duplicate photons with the same frequency, phase, and polarization as the stimulating photon. The particular polarization created in a laser is due either to a preferred polarization in the active medium, or by some preferential loss in other intracavity components. An example of the first type is the quantum well, which if put under strain, will favor polarizations in one plane over another, depending on the direction of strain. (Corzine, 1991) An example of the second type is the Brewster window common on larger lasers, which partially reflects one polarization out of the cavity, while transmitting the cross-polarization. Both

phenomena can be analyzed simply by examining the difference between the gain and loss coefficients for a laser cavity, and finding the polarization dependence. In the case of VCSELs with a cylindrical cavity, flat DBR mirrors, and a planar gain region, there is no clear polarization preference in the gain or loss coefficients. This leads to the classification of a VCSEL as a "quasi-isotropic," where any anisotropy is small, unintentional, and often random.

The process of optical feedback is simple to state but hard to analyze. In this thesis, optical feedback refers to reflection of some emitted laser light back into the laser cavity. This can be done intentionally (with a mirror) or unintentionally (reflections off the front face of a detector). Any time optical feedback is present in a nonlinear optical system, there may be bistability. (Saleh, 1991: 846) Bistability is the existence of two values of output for a single value of input; the output value at any time is determined by the past history of the system (hysteresis). Bistability is the fundamental characteristic of logic circuits, making the possibility of a bistable VCSEL very interesting for optical computing.

The optical feedback process is difficult to analyze because there are many variables. The process depends on feedback signal characteristics (amplitude, coherence, time delay, and phase); the design of the cavity (mirror reflectivities and gain coefficient); and the residual anisotropy of the cavity, which for VCSELs is completely unknown.

Scope of Problem

The theory for this problem has not been completely developed. Because this thesis was intended to be primarily experimental, no new theoretical work has been done. The approach, then, is to piece together the best predictions existing theory has to offer and check them against experimental data. Because of the time available, only a few

experiments could be accomplished. The experiments were designed to address the more important parts of the theoretical predictions, namely:

- Determine the "natural" polarization of at least two different VCSELs. One is a conventional VCSEL, grown in a $\langle 100 \rangle$ direction. The other is grown in a $\langle 110 \rangle$ direction. Effects on direction and degree of polarization will be noted.

- Determine the effect of feedback on the polarization of both VCSELs. Characterize the dependence on feedback amplitude and VCSEL parameters.

- Demonstrate the difference between coherent and non-coherent feedback and determine the effects of phase for coherent feedback.

Method of Presentation

The body of theory on this subject will be presented in Chapter II, concluding with a summary of anticipated predictions. The experimental design will be described in Chapter III. Results and comparison with predictions will be presented in Chapter IV, followed by a chapter of conclusions and recommendations.

II. Theory

There is no well developed theory in place to predict effects of optical feedback on polarization of a VCSEL. Pieces of the process have been described by theory. Each of these pieces will be examined in turn.

Polarization in VCSELs

Most analyses of VCSEL polarization have been of VCSELs grown in a $\langle 100 \rangle$ crystal direction. That is, one of the principal axes is in the direction the layers are grown. With III-V compounds being zincblende structures, the other two axes are in the plane of growth and orthogonal to each other. This is an important assumption to note, because VCSELs are also being grown in $\langle 110 \rangle$ directions to investigate the effects on polarization.

Sources of Polarization.

The central equation for semiconductor lasers is the relationship between cavity loss and gain. The condition for lasing is that the gain coefficient exceed the loss coefficient.

Using the terminology of Saleh and Teich (Saleh, 1991: 621), one can write the relationship for threshold gain as:

$$\gamma = \frac{1}{\Gamma} \left(\alpha_s + \frac{1}{2d} \ln \frac{1}{\mathfrak{R}_1 \mathfrak{R}_2} \right) \quad (2)$$

where:

- \mathfrak{R}_1 : reflectivity of mirror 1
- \mathfrak{R}_2 : reflectivity of mirror 2
- Γ : confinement factor
- γ : gain of the cavity
- α_s : distributed cavity losses
- d : length of gain medium

The first term on the right side of Equation (2) accounts for losses like absorption in the materials making up the laser or reflection from surfaces other than the mirrors. The second term explicitly accounts for losses due to mirrors, which are "good" losses, but nevertheless count as loss for threshold calculations. The next few paragraphs explain the polarization dependence of the various factors in the equation.

The confinement factor (Γ) describes the fraction of the electromagnetic intensity contained within the gain region. Within the VCSEL, the wave can be described by wave guide mathematics as a sinusoid of some order within the gain region and a decaying exponential outside the gain region. The confinement factor is calculated by integrating the square of the space-dependent field amplitude $E(r)$ within the gain region and over all space and taking the ratio.

$$\Gamma = \frac{\int_{\text{gain}} |E(\vec{r})|^2 d\vec{r}}{\int_{\text{space}} |E(\vec{r})|^2 d\vec{r}} \quad (3)$$

In the case of a one dimensional cross section of a TEM_{02} Gaussian beam, the field being integrated is easily seen in Figure 3.

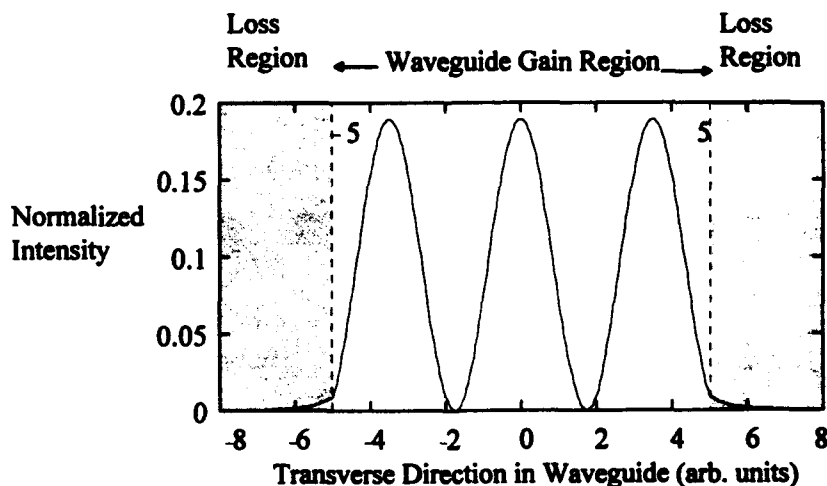


Figure 3. Amplitude vs. Transverse Location for TEM_{02} Mode in Wave Guide

For a wave traveling in the z direction, if a gain region is wider in the x direction than the y direction, the confinement factor will be different in the x and y directions. The result is a different confinement factor for x-polarized and y-polarized waves and a different equation for threshold gain. Thus, non-circular cavities are expected to have a polarization preference. This is the basis for work at Sandia National Laboratories, where various cavity cross-section shapes have been shown to have strong polarization preference. (Choquette, 1993a & 1993b) Conversely, a cavity which is perfectly circular should have no confinement factor asymmetry.

The gain factor (γ) is a description of the active material's propensity to produce stimulated emission. It is usually expressed in the following way.

$$\gamma(\nu) = \frac{\lambda^2}{8\pi\tau_r} \rho(\nu) f_g(\nu) \quad (4)$$

where

- λ : wavelength of light
- τ_r : electron-hole recombination lifetime
- $\rho(\nu)$: optical joint density of states (frequency dependent)
- $f_g(\nu)$: Fermi inversion factor (frequency dependent)

This equation is deceptively simple. Embedded within the expressions for ρ and f_g is all the complexity of three dimensional bandgap diagrams. For a chunk of III-V material, both ρ and f_g are relatively easy to calculate, if only the major effects of the crystal are considered. The result is a gain curve that looks like Figure 4.

A common modification to this type of gain material is the quantum well. Quantum wells are layers so thin that one can analyze the electron as a "particle in a box" in the direction normal to the layer, while treating the electron with normal solid state techniques in the plane of the layer. The result is a density of states (ρ) with abrupt

changes as the quantum state changes, but constant otherwise. This stair step function modifies the gain coefficient as shown in Figure 5.

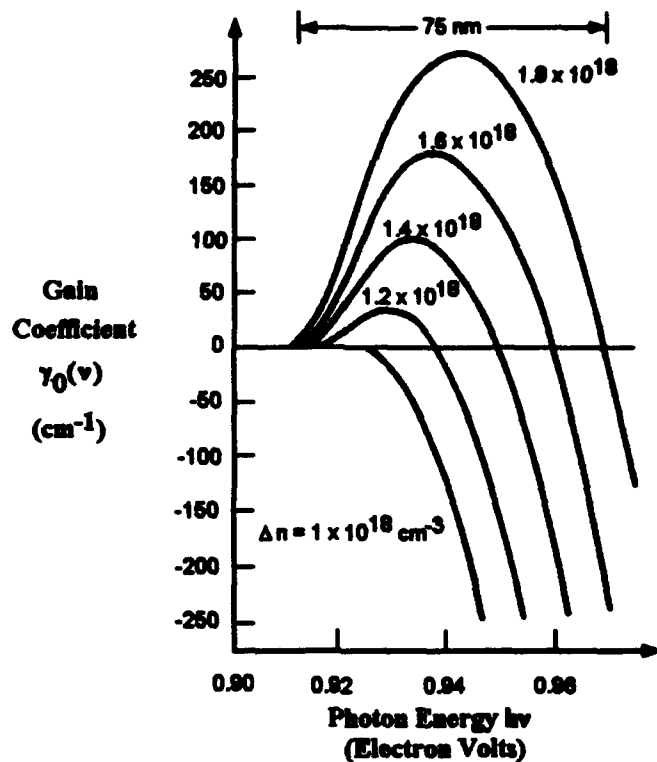


Figure 4. Typical Gain Curve for GaAs (from Saleh, 1991: 641)

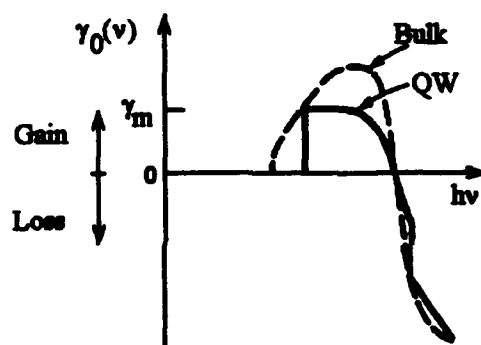


Figure 5. Quantum Well Gain Coefficient (Saleh, 1991: 635)

Polarization dependence of gain occurs when some anisotropic stress is in the gain region. Stress can be due to lattice mismatch, differing thermal expansion coefficients, or residual defects. Lattice mismatch effects can be seen in quantum wells, where the active layers are so thin the atoms line up with the same spacing as the surrounding layers, rather than the natural spacing of the active material. (Corzine, 1991) The result is atoms spaced closer (or farther) than normal in the growth plane and farther (or closer) in the perpendicular direction. The result is a non-cubic structure with different gain in the plane and perpendicular to the plane. Since VCSEL polarizations are all in the plane, this strain effect doesn't seem to apply. But engineered stress can produce a polarization preference.

By applying different amounts of strain in the x and y directions, one can achieve different levels of gain in the two directions. Researchers at the Tokyo Institute of Technology (TIT) have shown that an elliptical etched hole above the VCSEL introduces different amounts of stress and bending along the major and minor axes. (Mukaihara 1992a, 1992b, 1993) The result is a clear polarization preference along one of the two directions. (The favored direction depends on the material.) The few VCSELs that do not have the desired polarization can be switched by application of additional external stress in the proper direction, as done in (Patel, 1973). Clearly stress can affect the gain coefficient in different polarization directions.

Another factor in the threshold equation is the distributed loss factor (α_p). This includes all of the unaccounted losses like absorption and scattering. While theory to predict this factor is not developed, one could imagine some polarization dependence. An example is a linear defect running across the laser. Clearly atoms near the defect line would absorb light differently with polarization along the fault than perpendicular to the fault.

Mirror reflectivities (\mathcal{R}_1 and \mathcal{R}_2) can also have polarization dependence, although the simple description of a VCSEL in earlier chapters does not allow for it. In fact, most DBR mirrors are polarization independent. But one can take steps to introduce a difference. The researchers at TIT have done this by growing a square DBR mirror with one pair of vertical sides coated with high index material and the one pair of sides uncoated. (Shimizu, 1991) See Figure 6 for a drawing.

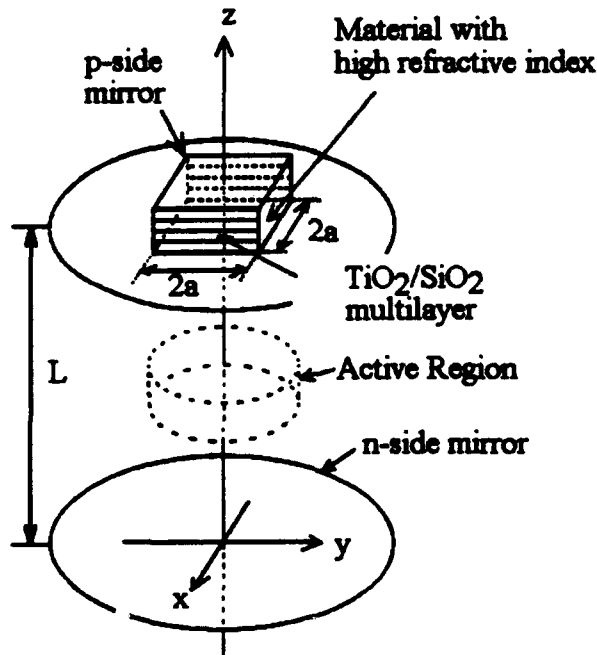


Figure 6. Anisotropic Mirror (Shimizu, 1991: L1015). The anisotropic mirror is the p-side mirror.

The result is a different reflectivity for x-polarized and y-polarized light. The calculation of this reflectivity is done via unspecified matrix methods. (Shimizu, 1991) The results of the calculations are shown in Figure 7. The effect on polarization is expressed by the authors as a differential loss.

$$\Delta\alpha = \frac{1}{2L}(\ln R_x - \ln R_y) \quad (5)$$

where

$\Delta\alpha$: differential loss due to reflectivity difference

L : cavity length

R_x : reflectivity for x polarization

R_y : reflectivity for y polarization

If this differential loss is larger than any unintentional polarization differential loss, the polarization can be controlled through careful design of this mirror. The mirror is not a trivial thing to grow, since it involves coating the side of a mesa with material. But it demonstrates the theory of differential reflectivity very well.

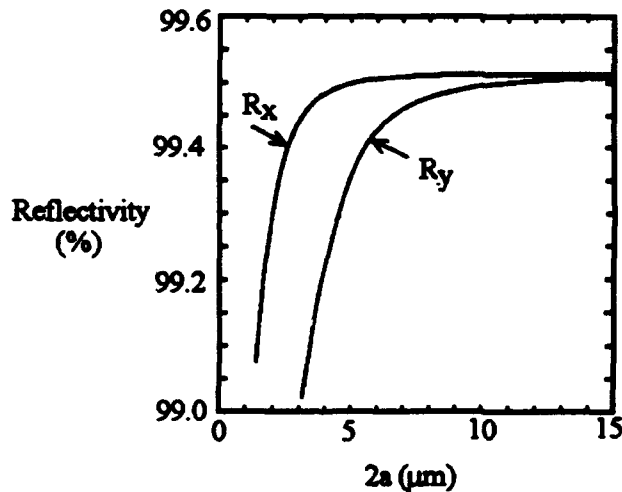


Figure 7. Polarization Dependent Mirror Reflectivity (Shimizu, 1991: L1016)

Every term in equation (2) has been examined for polarization dependence. In principle, all polarization effects can be accounted for in one of these terms, plugged in to the gain equation, and examined for its effect. Unfortunately, one striking polarization feature of VCSELs has not been completely explained by theory. It will be the focus of the next paragraphs.

The question is whether some "natural" polarization direction exists in a zincblende VCSEL structure. The experimental results are mixed. One group of researchers claims that for circular cross section VCSELs grown in the (100) direction, light tends to be polarized along the (011) or (0 $\bar{1}1$) crystal direction. (Choquette, 1993; Shimizu, 1988; Shimizu, 1991) Others in the field report linear polarization, but with random orientation relative to the crystal. (Jewell, 1989; Mori, 1992; Chang-Hasnain, 1991a/b) The groups use different VCSELs. Some have cavities created by etching away surrounding material. Others have cavities created by ion implantation. It is possible that some of the processes (etching) create more anisotropy than others (ion implantation). But with no sound theory and lack of information on microscopic anisotropy, there is no conclusive reason to expect a "natural" polarization preference.

On the other hand, VCSELs grown in a $\langle 110 \rangle$ direction have a natural anisotropy in the crystal. In a GaAs structure, if one looks through the crystal in a direction normal to the (100) plane, each atom sees essentially the same thing in the two orthogonal directions within the plane. However, looking normal to the (110) plane, each atom sees different atoms in different spacing in the two orthogonal directions. See Figure 8 for a drawing of these views. This simple approach indicates the possibility of different gain for light polarized in these two directions.

Polarization and Transverse Modes in Cylindrical Wave Guides

The terms often used to describe polarization direction and transverse modes in VCSELs ("TEM₀₀ mode", for example) are borrowed from polarization analysis in rectangular wave guides of edge-emitting lasers. For cylindrical VCSELs, one should solve Maxwell's equations in cylindrical coordinates for a dielectric material. Most texts on optical fibers present a solution (Cheo, 1990: 41-72). The solutions are named HE_{lm} for modes when the longitudinal electric fields dominate, and EH_{lm} when the longitudinal magnetic fields dominate. Pure transverse electric (TE_{lm}) and transverse magnetic

(TM_{lm}) modes exist, but they are different than the modes with the same name in rectangular coordinates. Figure 9 shows the lowest order modes that are likely to propagate in a cylindrical dielectric wave guide, along with the polarization.

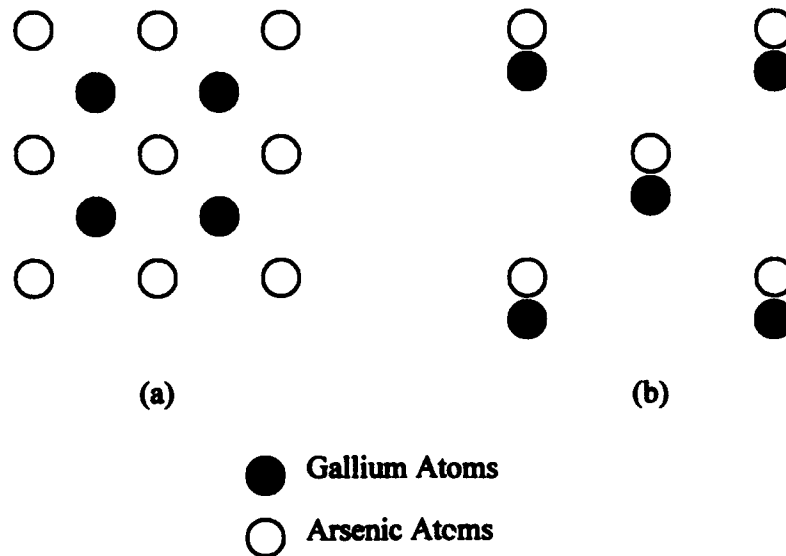


Figure 8. Crystal Planes in GaAs Structure. Part (a) shows view looking normal to the (100) plane, while (b) shows view looking normal to the (110) plane. Pictured atoms are not coplanar.

Note that for case (a), two orthogonal linear polarizations are shown. The choice of direction was arbitrary. In case (b), the polarizations are circularly symmetric, so no arbitrary choice was made. For case (c) linear polarizations are shown, but they are not arbitrary in direction. The polarization must either be parallel or orthogonal to the null line.

The particular cylindrical mode that oscillates in a cylindrical VCSEL cavity is determined by which mode matches the high gain regions of the cavity best. See (Chong, 1993) for a description and a model of how the mode is selected.

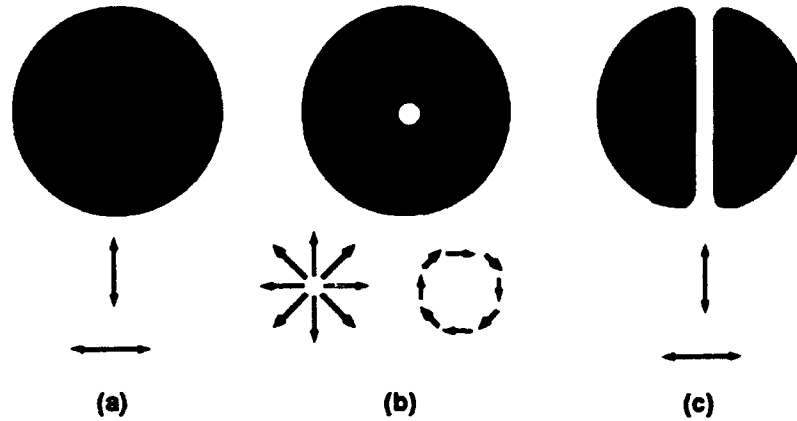


Figure 9. Spatial Distributions of Low Order Cylindrical Modes. a) is the lowest order HE_{11} mode; b) is any of the TE_{01} , TM_{01} , or HE_{21} modes, all of which are second order; c) is a combination of HE_{21} with either TE_{01} or TM_{01} . Possible polarizations are also indicated. (Cheo, 1990: 50)

Optical Feedback in VCSELs

Feedback in laser systems has been studied extensively, since retroreflections are always present in real applications for lasers. In semiconductor lasers, the feedback effects of greatest interest in the literature are the spectral effects. Polarization effects have not been reported.

The first issue to be addressed is the sensitivity of a laser to feedback. A commonly used measure of sensitivity is the optical feedback parameter κ , which is defined as follows. (Chung, 1991)

$$\kappa = \frac{1}{\tau_s} \frac{T_s}{\sqrt{R_s}} \sqrt{\eta} \sqrt{1 + \alpha^2} \quad (6)$$

where

- τ_s : photon round trip time in laser cavity
- T_s : output mirror transmission
- R_s : reflectivity of output mirror
- η : feedback power ratio, including coupling loss
- α : line width enhancement factor

From this equation, one would expect VCSELs, with low mirror transmission (T_s) and high mirror reflectivity (R_s), to have a smaller feedback parameter (κ) and therefore be less susceptible to feedback than an edge-emitting laser. But the VCSEL cavity length is so short that photon round trip time (τ_s) is small enough to make up for the high reflectivity. Experiments confirm VCSELs and edge-emitters display similar susceptibility to feedback. (Chung, 1991)

The optical feedback behavior most studied in semiconductor lasers is spectral change. The behavior has been described by Tkach and Chraplyvy in different "regimes," depending on the amplitude of the feedback. Table 1 describes these regimes and the feedback levels at which they were observed by Chung and Lee for a VCSEL. Note that regime 5 has not been observed in VCSELs.

Table 1. Feedback Regimes for Semiconductor Lasers (Tkach, 1986 and Chung, 1991)

Regime	Feedback Level in VCSEL	Spectral Characteristics
1	< -65 dB ($< 3 \times 10^{-7}$)	Narrowing or broadening of laser line, depending on phase of feedback.
2	-65 dB (3×10^{-7}) to -40 dB (10^{-4})	Splitting of line into two modes, which are adjacent "external cavity" modes. Mode hopping occurs. Magnitude of split depends on mirror distance and feedback amplitude.
3	-40 dB (10^{-4}) to -35 dB (0.003)	Narrowing of single laser line, independent of phase or distance of feedback source.
4	-35 dB (0.003) to ??	Coherence collapse. Significant broadening of laser line, independent of phase or distance of feedback source.
5	??	Complete external cavity operation. Not observed in VCSELs due to high reflectivity mirrors.

These regimes have been successfully explained by simultaneously solving the rate equations for photon density, electric field phase, and carrier density. Numerous people have done this for edge-emitting lasers. (Henry, 1986; Lang, 1980; Lenstra,

1984a, 1984b, 1985; Schunk, 1988; Tkach, 1986) H. M. Chen applies this same kind of analysis to VCSELs, and shows excellent agreement between theory and experiment, particularly for regime 4. (Chen, 1993)

While this approach has been successful in describing the spectral effects of optical feedback, it has limitations. The solutions of the three rate equations assumes a laser with a single mode and single polarization. While this is good for edge emitters with rectangular wave guides and strong polarization preference, it is not clear that it is valid for cylindrical VCSEL cavities. H. M. Chen notes the problem when he mentions "a difficulty in the experiment is to control the polarization of the feedback field." (Chen, 1993: 19) The implication is that a change in polarization negates his analysis. He chooses to describe the effect of cross polarized feedback as simply a type of non-coherent feedback. Non-coherent feedback usually means the feedback delay time is greater than the coherence time of the light. Non-coherent feedback can be analyzed using the rate equations, as done by Lenstra in his three articles.

This would still be inadequate for VCSELs. The problem is that the VCSEL cavity can usually support both polarizations equally well, unless some intentional asymmetry is introduced. Therefore both polarizations, regardless of which one is the original cavity mode and which one is the feedback, need to be treated on an equal footing. The assumption of a single mode with known polarization made by all the authors on optical feedback in edge-emitting semiconductor lasers is simply not true for quasi-isotropic VCSELs. To find an adequate treatment of polarization, one needs to turn elsewhere.

Optical Feedback and Polarization Switching

There is a body of experimental and theoretical work on the subject of optical feedback and polarization switching. Unfortunately for this thesis, the work is based on a

helium-neon laser operating at 3.39 μm , not a VCSEL. Even so, the theory has been carefully developed to apply to "quasi-isotropic lasers," a general category that includes the He-Ne and other gas lasers, as well as VCSELs. (May, 1989; Stéphan, 1985; Xiong, 1991) A quasi-isotropic laser (defined earlier) is simply a laser with no strong polarization preference.

The theoretical approach begins with Lamb's original laser theory (Lamb, 1964), and generalizes it from one dimensional scalar fields to two dimensions. (May, 1989: 2356) For this reason, it is often called vector laser theory. A complete recount of the theory is not possible in this thesis. It is important just to realize that the model is very fundamental, and it treats polarized feedback as a small complex anisotropic reflectance on the output mirror. If one follows through to find solutions to the vector rate equations, one finds the stability of the solutions depends on a quantity called the Liapunov exponent (Xiong, 1991: 1237). Each of the two polarization modes (called mode A and mode B) has a Liapunov exponent. The convention used is that mode B is polarized in the direction of the polarized feedback, while mode A is polarized orthogonally.

$$\begin{aligned}\lambda_A &= \left\{ 2[\epsilon_r + \epsilon \cos\phi_f] \right\} + \left\{ \sqrt{S_r^2 - 4(\epsilon_i + \epsilon \sin\phi_f)^2 + 4(\epsilon_i + \epsilon \sin\phi_f)S_i - S_r} \right\} \\ \lambda_B &= \left\{ -2[\epsilon_r + \epsilon \cos\phi_f] \right\} + \left\{ \sqrt{S_r^2 - 4(\epsilon_i + \epsilon \sin\phi_f)^2 - 4(\epsilon_i + \epsilon \sin\phi_f)S_i - S_r} \right\}\end{aligned}\quad (7)$$

where

- $\lambda_{A,B}$: Liapunov exponent for modes A and B. Sign determines stability.
- S : Complex differential saturation parameter. Includes self-saturation of the mode and cross-saturation between modes. Includes real (S_r) and imaginary (S_i) parts.
- ϵ_r : Internal amplitude anisotropy of bare cavity, assumed to favor mode B.
- ϵ_i : Internal phase anisotropy of bare cavity.
- ϵ : Amplitude of apparent anisotropy caused by feedback, which favors mode B.
- ϕ_f : Phase of apparent anisotropy caused by feedback.

Stability is described by the sign of the real part of $\lambda_{A,B}$. If it is negative for mode A or mode B, the mode is stable; if it is positive, the mode is unstable. This allows four combinations of signs, as shown in Table 2.

Table 2. Polarized Mode Stability

Real Part of λ_A	Real Part of λ_B	Stability
-	+	Only mode A will oscillate.
+	-	Only mode B will oscillate.
-	-	Modes A and B are bistable. Mode depends on laser's history.
+	+	Not possible.

In their experiments, Xiong and his colleagues were interested in the effects of feedback as the laser was scanned in frequency by moving one of the two cavity mirrors. Figure 10 shows the real part of the two Liapunov exponents (λ_A and λ_B) as a function of the mirror position/laser length. Since scanning the mirror affects both the saturation parameter (S) and the phase of the feedback (ϕ_f) in Equation (7), the behavior of the exponents is quite complicated.

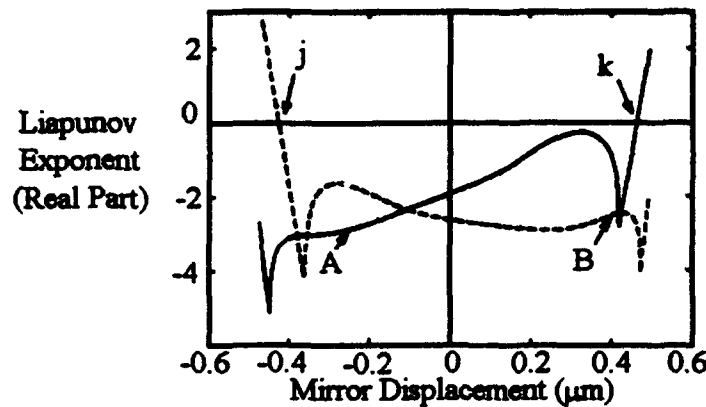


Figure 10. Real Part of Liapunov Exponents for Modes A and B vs. Length of the Laser. (From Xiong, 1991)

Note that to the left of point *j* and the right of point *k*, the laser operates in a clearly defined polarization, mode A and mode B, respectively. Between these points both modes are stable, so the mode that oscillates depends on where one came from, the left or the right. This is the region of bistability, where hysteresis is important.

Similar diagrams could be drawn showing the exponents as a function of other parameters, including feedback amplitude and phase. Figure 11 shows the Liapunov exponents as a function of feedback phase (ϕ_f) for two different values of the cavity amplitude anisotropy (ϵ_r). The numbers used were from the He-Ne laser experiment in (Xiong, 1991). Note that for zero anisotropy, the laser oscillates equally between polarizations A and B as the phase of the feedback goes through a complete cycle. When the bare cavity anisotropy (ϵ_r) is 0.001, which is closer to the feedback amplitude (ϵ) of 0.0016, the laser stays longer in mode B than mode A and the crossing points shift. Note the absence of hysteresis here; the feedback phase changes do not affect any of the complex internal parameters of the laser, so the behavior is simple. This is due to the small feedback approximation made by Xiong (Xiong, 1991: 2357). At larger feedback levels, one would expect a coupled-cavity effect like that seen in edge-emitting lasers.

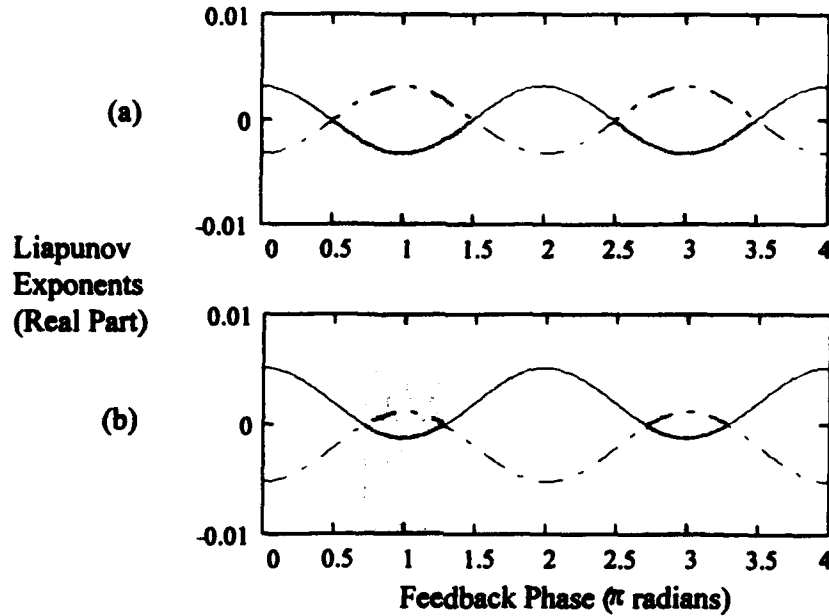


Figure 11. Calculated Liapunov Exponents versus Feedback Phase. Plot a) is for zero internal anisotropy, plot b) is for anisotropy of 0.001 (per pass) favoring mode B. Feedback level is 0.0016 favoring mode B. Solid lines are polarization mode A, dashed lines are mode B. Shaded regions indicate mode A lives, unshaded regions indicate mode B lives.

The effect of varying feedback amplitude (ϵ) is even simpler. It changes the magnitude of the Liapunov exponents, but does not affect the cross-over points or the time spent in mode A or mode B.

The vector laser theory does not explicitly address the issue of incoherent feedback. One could adapt it to incoherent feedback. Using the rate equations for the two polarizations, one could consider the incoherent polarized feedback as a kind of stimulated emission term that is stronger in one polarization than the other. This effort is beyond the scope of this thesis.

The vector laser theory should apply, as is, to semiconductor VCSELs; the major difference would be in the value of some parameters. In particular, one would expect the complex differential saturation parameter (S) to be rather different for a VCSEL than a gas laser. Since semiconductor gain is much broader than an atomic gas, and the material

is more dispersive than a gas, both the real and imaginary parts of S should be very different for VCSELs.

Summary of Predictions

Piecing together the bits of theory that apply to this problem, one can list a set of general expectations. Quantitative prediction would require adaptation of the He-Ne vector theory to the VCSEL, a project that awaits future work.

The VCSELs should be linearly polarized, at least at low values of gain. At higher gain, expect higher order transverse modes with polarization 90° rotated from the original mode, as seen and reported in (Char Hasnain, 1991). Theory does not predict a particular direction for the polarization, but it will be interesting to note if the spots are consistently in the same direction. This may indicate the purported $\langle 011 \rangle$ polarization preference, or some kind of asymmetry in the dimensions of the pumped region (Choquette, 1993; Shimizu, 1988)

The effects of non-coherent feedback polarized orthogonally to the VCSEL polarization are not addressed explicitly by theory. Previous experiments (Grantham, 1991) indicate that at high enough levels of feedback (20%), some switching should occur.

Coherent feedback should switch the laser's polarization, depending on the phase of the feedback. If feedback dominates any internal anisotropy, the laser polarization should spend equal time in the two polarized states. If the internal anisotropy is large enough, the laser should spend noticeably more time in one polarization than the other.

III. Experimental Approach

The experimental approach was designed to investigate as much as possible about the polarization effects of optical feedback, and still prove workable in a three month effort. Thus, the experiment had two parts. The first part was to investigate the effects of non-coherent feedback on gallium arsenide (GaAs) VCSELs fabricated at the University of Arizona. The second was to investigate coherent and non-coherent feedback on a VCSEL made of indium gallium arsenide (InGaAs) grown in a $\langle 110 \rangle$ direction at the University of Virginia. Part 1 was designed to be fairly easy, since the experimental apparatus was similar to that used in previous experiments. (Bagnell, 1992; Grantham, 1991) Part 2 offered the more interesting investigation. It involved a VCSEL grown in an unusual crystal direction, and because of the material used, it offered the opportunity to produce coherent feedback.

Configuration(s)

Figure 12 is the equipment configuration used in Part 1 of the experiment. The argon ion laser pumps a tunable CW Titanium:Sapphire laser. The Ti:Sapphire laser enters the VCSEL through the top mirror, being focused by a lens to achieve maximum power density in the wafer.

Assuming the VCSEL lases, the output from the top side of the VCSEL travels back along the same path until hitting the dichroic beam splitter (DBS). The DBS reflects the majority of the light at the VCSEL wavelength (and passes most of the pump wavelength). A normal beamsplitter creates two parallel paths: one contains VCSEL light and residual pump light (which dominates the VCSEL light), and the other is filtered to retain only VCSEL light. Both paths are directed to the diagnostic equipment: video camera, power meter, and spectrometer.

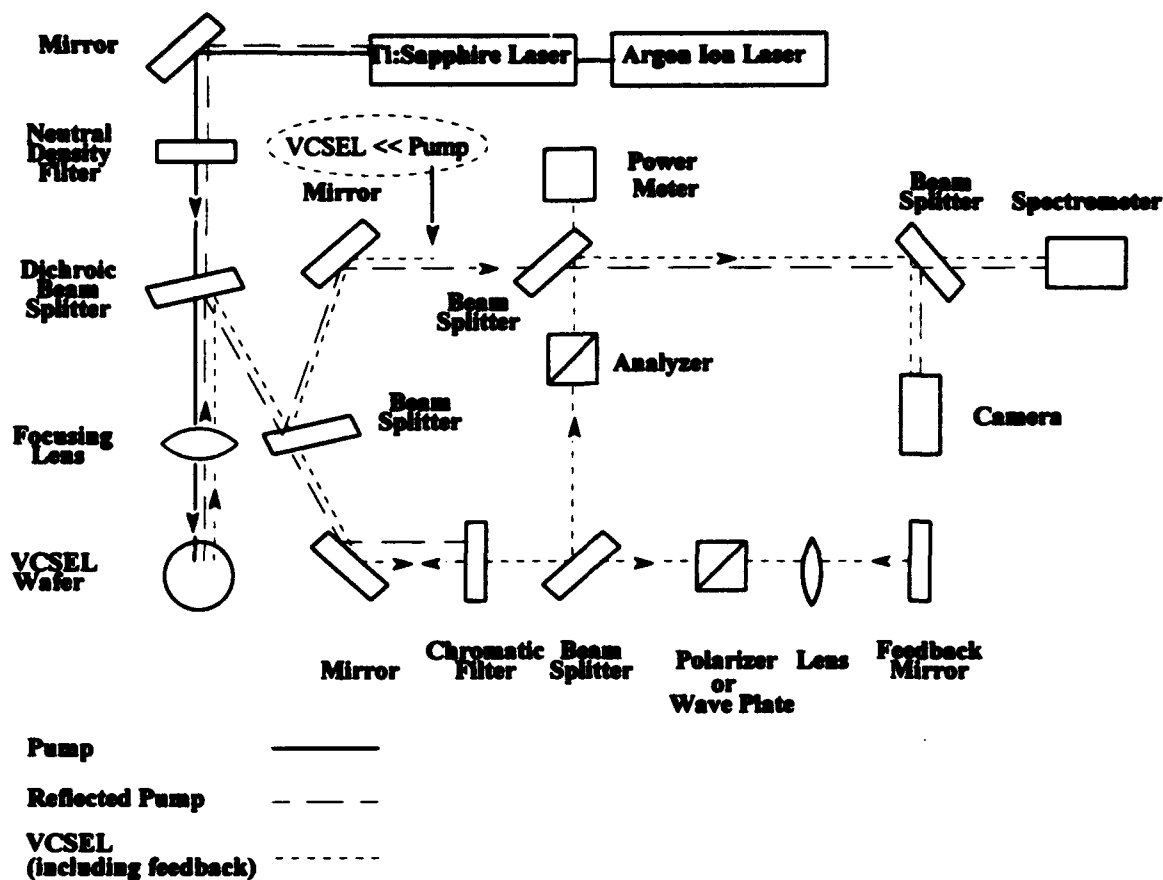


Figure 12. Equipment Configuration for Part 1 Experiments

The VCSEL path is further split to provide a feedback path. This path includes a linear polarizer to select the polarization of the feedback (or a wave plate to rotate the polarization) and a mirror to provide the reflection. Occasionally an additional lens was required to collimate the feedback for coupling back into the VCSEL.

The polarization analyzer is placed in the VCSEL path before any measurement devices. It consists of a rotatable linear polarizer plus a quarter wave plate for analyzing circular polarization. The analyzer is removed or adjusted to provide power measurements for various polarization states. A more detailed description of the experimental components follows.

In the interest of any future work in this area, Table 3 documents the exact equipment specifications used. Key characteristics are included as well.

Table 3. Equipment Specifications and Characteristics

Argon Ion Laser	Model	Spectra-Physics 2020-03
	Wavelength	514.5 nm
	Output Power	6 Watts
Ti:Sapphire Laser	Model	Spectra-Physics 3900S
	Wavelength	700-980 nm
	Output Power	~750 mW (at 790 nm)
	Beam Divergence	1 mrad
	Beam Mode	TEM₀₀
Dichroic Beam Splitters (2)	Manufacturer	CVI
	Maximum Reflectance	875 nm, 950 nm
	Maximum Transmission	830 nm, 910 nm
	Design Angle	5 degrees
Beam Splitters	Manufacturer	Melles Griot
	Reflectance/Transmittance	~50/50
Filters (2)	Manufacturer	Ealing
	Center Wavelength	880 nm, 940 nm
	Spectral Width	10 nm, 10 nm
Spectrometer	Model	EG&G PARC OMA
	Wavelength Range	500 - 1000 nm
	Resolution	0.06 nm
Focusing Lenses (Diode Lenses)	Manufacturer	Melles-Griot
	Focal Lengths	8, 14.5, 25.6, 48 mm
Focusing Lenses (Microscope Objectives)	Manufacturer	Edmund Scientific Corp.
	Magnification	10x, 20x, 40x
	Focal Lengths	16.6, 8.78, 4.5 mm
Power Meter	Model	Coherent Fieldmaster
	Detector	LM-2 Silicon Detector

Polarizers (Cubes)	Manufacturer Extinction Ratio	Newport Research Corp. 100:1
Wave Plates (3)	Manufacturer Order Wavelength Rotation	CVI Zero (0) 875 nm, 875 nm, 950 nm $\lambda/4$, $\lambda/2$, $\lambda/2$

Part 2 of the experiment used a very similar configuration, the only difference being the VCSEL mounting. A special mount was built with a hole over which the VCSEL was centered. This special mount was designed so the VCSEL beam coming from the bottom mirror (through the GaAs substrate) could be used for feedback. Because the bottom side was free of all the optics used on the pump side, the feedback mirror could be placed very close to the VCSEL, hopefully within the coherence length. This configuration looks like Figure 12 with the feedback section moved down to the bottom side of the VCSEL. Clearly this approach only works if the substrate below the bottom mirror is transparent to the VCSEL light; the sample from the University of Virginia met this condition.

Three VCSEL wafer samples were used in this experiment: two GaAs wafers in Part 1 and a single InGaAs wafer in Part 2. The key characteristics of these three samples are listed in Table 4.

Experimental Procedure

For Part 1 experiments, the sample was scanned until a number of spots were identified as lasing spots. Measurements of the coherence length were performed by constructing a Michaelson interferometer at the beamsplitter leading to the feedback path, with fringe visibility monitored from the camera. Polarization measurements were made by changing the analyzer and recording the intensity transmitted. Feedback was achieved

Table 4. Characteristics of VCSEL Samples

Characteristic	Sample #1	Sample #2	Sample #3
Producer	U. of Arizona	U. of Arizona	U. of Virginia
Gain Region	Bulk GaAs	Bulk GaAs	Quantum Well InGaAs
Substrate	GaAs	GaAs	GaAs
Wavelength	860-880 nm	870-880 nm	~930 nm
Top Mirror Layers	34	44	32
Bottom Mirror Layers	45	51	39
High Index	AlGaAs	AlGaAs	GaAs
Low Index	AlAs	AlAs	AlAs
Active Region Thickness	726 nm (3λ)	726 nm (3λ)	~270 nm (1λ)
Pump Wavelength	~840 nm	~840 nm	~850 nm

by aligning the feedback lens (if used) and mirror until the feedback spot was visibly matched with the VCSEL spot on the camera. The feedback was polarized with a polarizer cube, if the VCSEL beam was not already extremely polarized. In cases where the VCSEL was strongly polarized and cross-polarized feedback was desired, a quarter wave plate (two passes) or half wave plate (single pass) was used to rotate the polarization of the feedback.

In Part 2, the procedure was conceptually very similar. The feedback alignment procedure required that the VCSEL light be monitored from the back side of the VCSEL, but all the other procedures were the same.

IV. Results and Discussion

Results from the experiments are presented for each sample individually. Polarization information is described by the four Stokes parameters, which completely define the polarization state. The parameter S_0 represents the total intensity, is usually normalized to 1, and is therefore not reported. The other three parameters range from -1 to +1 (normalized relative to S_0), with ± 1 representing complete polarization and 0 representing no polarization in that state. The overall degree of polarization (V) is given by Equation (8), where $0 \leq V \leq 1$.

$$V = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \quad (8)$$

The polarization directions associated with each parameter are given in Table 5. Note that S_0 and V are always positive, by definition. For more information on the definition and calculation of the Stokes parameters, see (Kliger, 1990).

Table 5. Definition of Stokes Parameters

Stokes Parameter	Positive Values	Negative Values
S_0	Normalized to 1	N/A
S_1	Horizontal Linear	Vertical Linear
S_2	+45° Linear	-45° Linear
S_3	Right Circular	Left Circular
V	Degree of Polarization	N/A

The reported Stokes parameters will usually be reported with a statistical uncertainty, derived from fluctuations in the measurements. There may be a degree of systematic bias in the measurements as well. Polarization bias of the optical elements

between the VCSEL and the polarization analyzer was measured and used to correct the Stokes parameters. However, in some cases where the VCSEL polarization was known *a priori*, the corrected Stokes parameters were still in error. Fortunately, whatever bias exists is probably constant. Since this thesis is about changes in polarization, the data are still of value, despite the systematic error.

The systematic error could have a number of sources. The calibration data could have been at a different wavelength than the polarization measurement data; wavelength was only measured infrequently. The alignment could be slightly different in the calibration step than in the data acquisition. The intervening optics could be slightly birefringent, due to anisotropic stress, which would explain some of the errors.

Finally, the choice of direction for S_1 is arbitrary, but the choice determines the other directions. Since the optical biases mentioned earlier apply to polarizations horizontal and vertical to the table, these were the directions chosen for S_1 . Throughout this section horizontal (H) and vertical (V) refer to table orientation. A drawing showing each VCSEL's orientation relative to these directions will be given.

Sample 1: GaAs Bulk

This sample had GaAs bulk gain and, since the substrate was also GaAs, was not suitable for using light from the bottom. Since the coherence length was less than 1 cm, experiments were restricted to incoherent feedback. The sample was oriented as shown in Figure 13, indicating the direction of H and V polarization.

Polarization Preference

This sample displayed a wide variety of polarizations. The degree of polarization (V) ranged from a maximum of 0.919 ± 0.079 to a minimum of 0.212 ± 0.014 . Likewise, the type of polarization varied from spot to spot, usually dominated by a linear component, but often with a strong circular component.

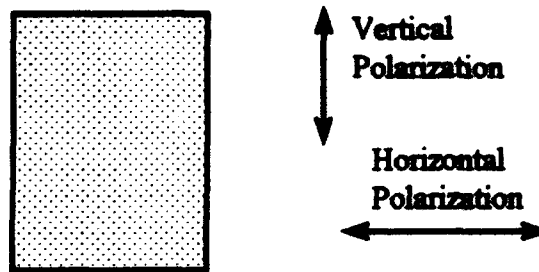


Figure 13. Sample #1 Orientation with H and V Polarizations

One would think that the degree of polarization for a laser should be 1. After all, laser light is stimulated emission, so all the photons should have the same polarization. A number of things could reduce the value of V . First, if the laser is operating with two different modes with orthogonal polarizations (say H and V) with no fixed phase relationship between the two, the beam would appear unpolarized ($V=0$). For this sample, there is no evidence of multiple, orthogonal modes.

Second, "unpolarized" light is simply light whose polarization state switches quickly relative to the time scale of the measurement. The coherence length of this VCSEL was measured as less than 1 cm, corresponding to a coherence time less than 30 picoseconds. On average, every 30 ps the phase of the E field changes randomly; at the same time, the polarization may be free to switch, too. Since the power meter's detection time is no less than milliseconds, the polarization could be switching 10^9 times per detection interval! If it does switch this often, the laser would appear completely unpolarized. Since some spots have a high degree of polarization, there are clearly factors that reduce the randomization of the polarization.

Beyond the degree of polarization, the type of polarization also fluctuates from point to point. Figure 14 shows the Stokes parameters for 12 different spots on this VCSEL.

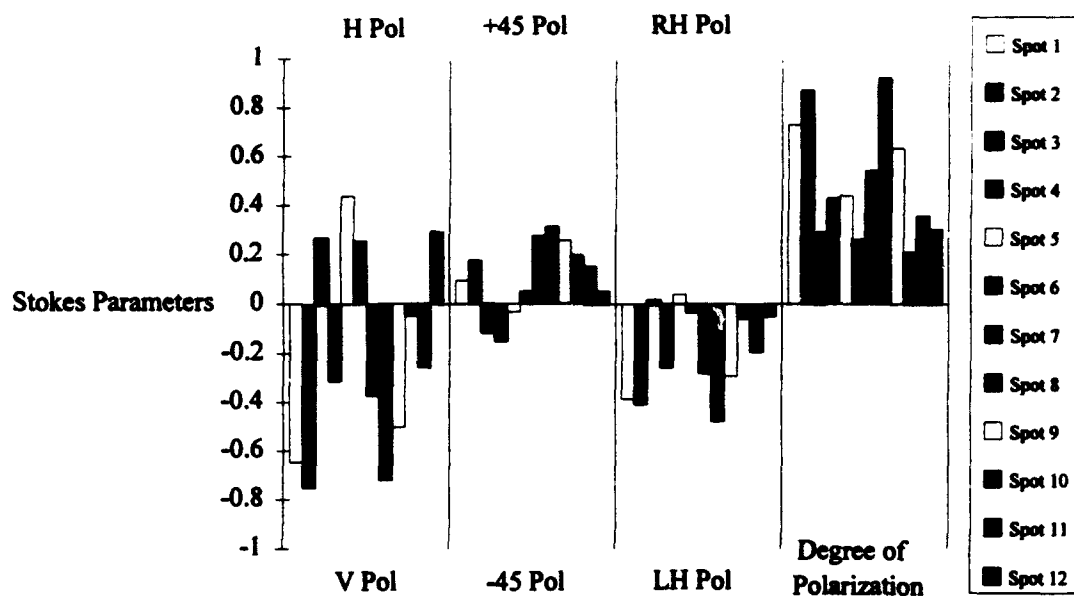


Figure 14. Stokes Parameters for 12 Locations on Sample #1

Clearly the strongest polarization states tend to be H or V linear polarization. Since H and V directions appear to align with a cleavage plane for the crystal, as shown in Figure 13, the crystal may have a slight preference for this direction. However, the number of measurements is too small to make any conclusions. Some spots (spot #10) are clearly polarized along a 45° angle, also. The most puzzling item is the size of the circular components. There is no theoretical reason or experimental precedent for circular polarized light from a VCSEL. One possible explanation is the bias in the experimental setup mentioned earlier. In some tests of the bias correction, VCSEL light which was linearly polarized by placing a polarizer earlier in the path was measured as having a circular component of 0.2 - 0.3. However, over the 12 points measured, the circular component varies considerably, which cannot be explained by any systematic bias. It is possible that the circular component is real, caused by birefringence in some element between the VCSEL cavity and the analyzer. In fact the VCSEL crystal itself,

particularly the mirrors (which are relatively thick), could be locally anisotropic, due to localized imperfections causing an anisotropic stress. This could create birefringence and add ellipticity to the linearly polarized VCSEL light.

Incoherent Feedback

This sample did not display complete polarization switching at any sample point. The percentage of VCSEL light applied as feedback was limited to about 30%, due to losses from all the intervening optics. It is possible that larger feedback fractions would produce switching.

Feedback did have some effect. In most cases it affected the magnitude of the Stokes parameters to some degree. For example, in Figure 15 the Stokes parameter S_1 changes from 0.273 (slightly H) to 0.595 (moderate H) when H feedback is applied. When V feedback is applied, S_1 changes to 0.179 (barely H). If true switching had occurred, the sign of S_1 would have switched when V feedback was applied. Instead, cross-polarized (V) feedback only lessened the degree of H polarization.

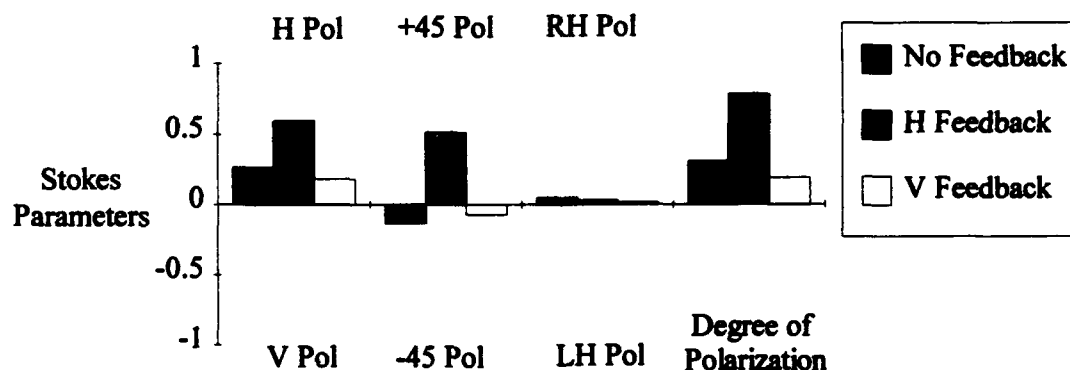


Figure 15. Effects of Feedback on Stokes Parameters for Spot 3

Interestingly, the H feedback produced a significant change in S_2 , the 45 degree polarization parameter. Not shown on the figure is the amount of uncertainty in the data.

The large S_2 value with H feedback is 0.513 ± 0.7 . The huge uncertainty is due to two factors. The measurements themselves were small and highly fluctuating. Second, the Stokes parameter calculation involves subtraction of two similar magnitude numbers, making the propagated relative error large. The same caveat applies to the large value of V with H feedback; the uncertainty is larger than the value.

No other spots showed more significant feedback effects than this one. Figure 16 shows the effects of feedback on three other, typical spots on this sample. The feedback often, but not always, moved the polarization in the direction of the feedback.

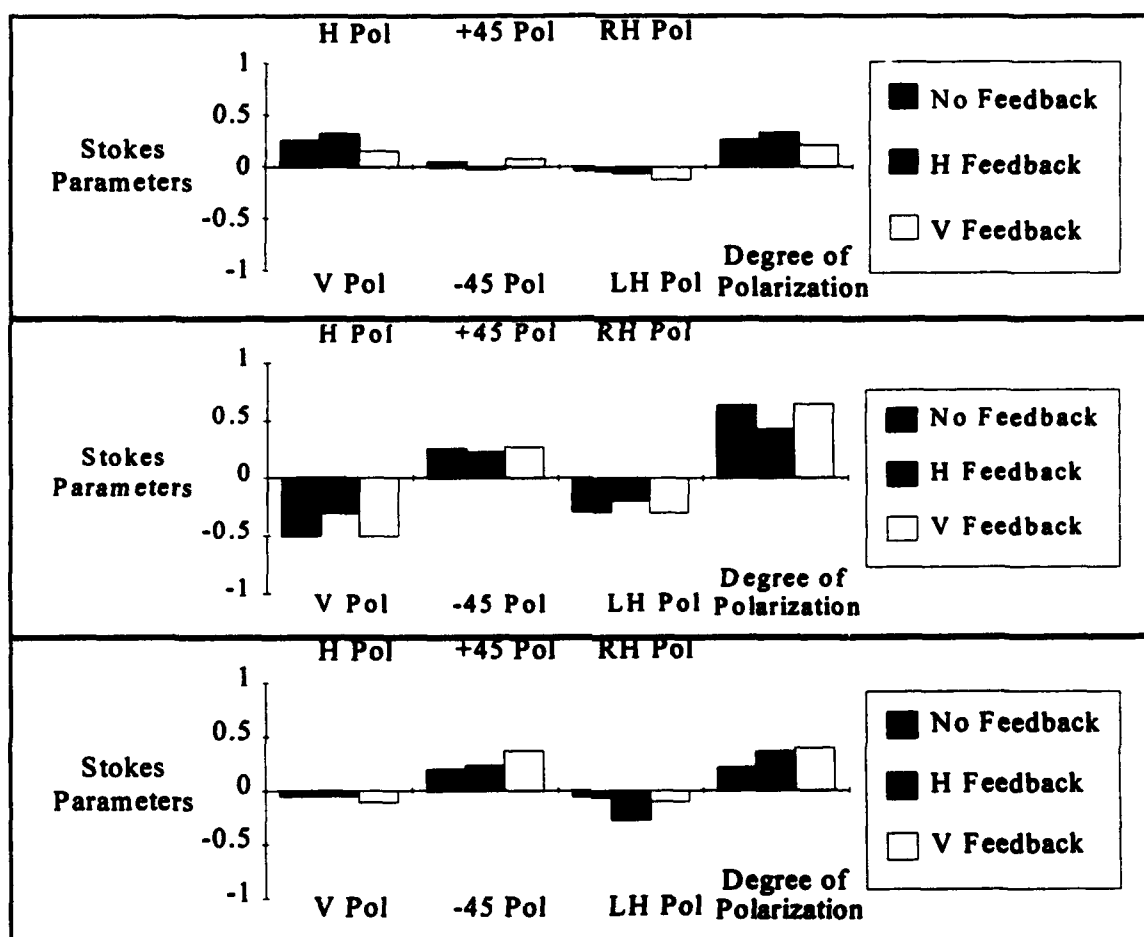


Figure 16. Effects of Feedback on Three Different VCSEL Spots from Sample #1. Data are from spots 6, 9, and 10. Stokes parameters given for no feedback, feedback of dominant linear polarization, and feedback of "weak" polarization.

Sample 2: GaAs Bulk

This sample was very similar to the first sample, but with more layers in the mirrors. Because it was grown on GaAs substrate which absorbs the lasing radiation at 880 nm, the back side was not available, so experiments were limited to incoherent feedback. Figure 17 shows the orientation of the sample relative to the V and H directions.

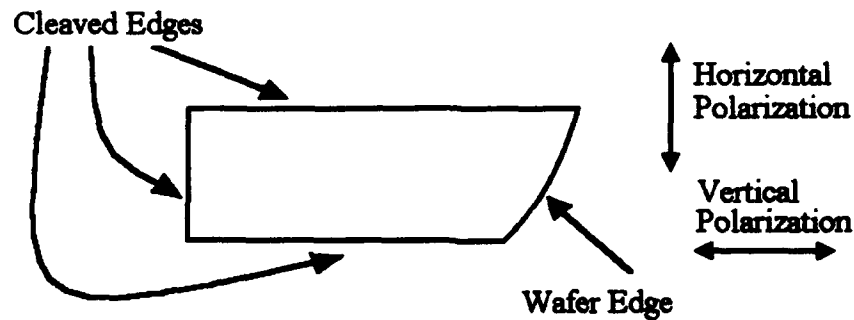


Figure 17. Sample #2, GaAs Wafer Chip

Polarization Preference

This sample showed even stronger polarization preference than sample #1. Figure 18 shows the Stokes parameters for seven different spots. Note spots 4 and 7 were measured at two different times, resulting in 4a and 7a. The degree of polarization (V) varies considerably, but the polarization is always dominated by the S_1 term. The one spot (#7) that has a significant S_2 parameter also has a very large uncertainty ($S_2 = 0.148 \pm 0.261$) for the usual reasons.

As in sample #1, the polarization preferences lie along a cleavage direction for the crystal. This sample had considerably fewer spots that would lase, so the factors that created a few lasing spots may also have created a preferential polarization along the V direction. It is worth noting that spots 1-3 were so close to each other as to be

indistinguishable on the translation stage. The different spots were achieved simply by bumping the VCSEL apparatus! The fact that spots 1 and 3 were polarized V and spot 2 was polarized H shows the forces affecting polarization can be extremely localized. These two observations, though contradictory, demonstrate the extreme difficulty in analyzing anisotropies at the micron level.

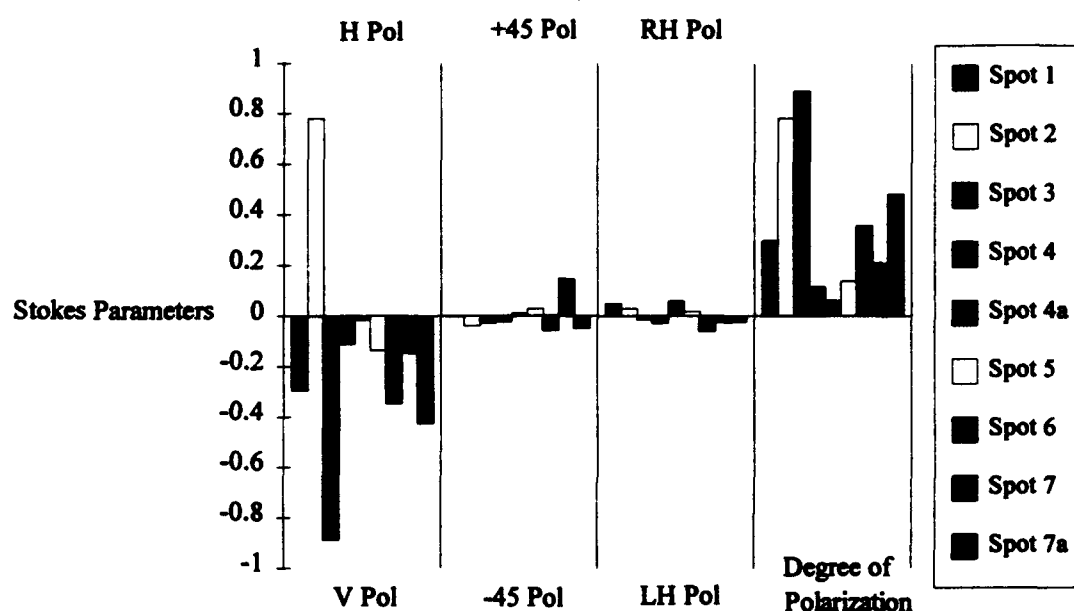


Figure 18. Stokes Parameters for Various Spots on Sample #2

Incoherent Feedback Effects

Polarization switching due to optical feedback was observed in this sample. Most of the seven spots demonstrated switching to one degree or another. Table 6 summarizes the switching behavior observed in these spots. The switching figure cited in the table is simply the absolute value of the difference between S_1 before and after the feedback was applied. In all cases, the feedback was polarized opposite the dominant linear

polarization using a polarizing cube. Spot 7 was measured with low pumping (dim) and high pumping (bright).

Table 6. Polarization Switching of Sample #2

Spot	S_1 Without Feedback	S_1 With Feedback	Switching Figure (ΔS_1)
1	-0.294 ± 0.134	0.563 ± 0.04	0.857 ± 0.140
2	0.779 ± 0.086	-0.313 ± 0.037	1.092 ± 0.093
3	-0.887 ± 0.067	0.524 ± 0.12	1.411 ± 0.137
5	-0.135 ± 0.037	0.117 ± 0.087	0.252 ± 0.095
6	-0.346 ± 0.041	0.36 ± 0.061	0.706 ± 0.073
7 (dim)	-0.145 ± 0.236	0.309 ± 0.245	0.454 ± 0.340
7 (bright)	-0.424 ± 0.072	0.263 ± 0.046	0.687 ± 0.085

By the measure of the switching figure (ΔS_1), spots 2 and 3 displayed the greatest amount of polarization switching. These two spots were investigated further, by varying the amount of feedback applied and noting the degree of switching. Figure 19 shows the value of S_1 as the percentage of VCSEL feedback is varied for spot #2. The switching point is where the line crosses the $S_1=0$ axis, with a feedback fraction around 0.13. Figure 20 shows the same relation for Spot #3, which switched even more. The switch point this time is with a feedback fraction of 0.24. With both spots it is quite likely that a greater feedback fraction would have produced greater switching, since the behavior was very smooth and consistent as feedback fraction varied.

The reasons for the ready switching of this sample, particularly at spots #2 and #3, are not clear. These were also the spots with the greatest degree of initial polarization (V), which seems counter-intuitive. The explanation is that spots with a high degree of polarization are also more coherent than spots with low polarization. Therefore, the

feedback is more coherent and more likely to affect the VCSEL than the less coherent (low I) spots.

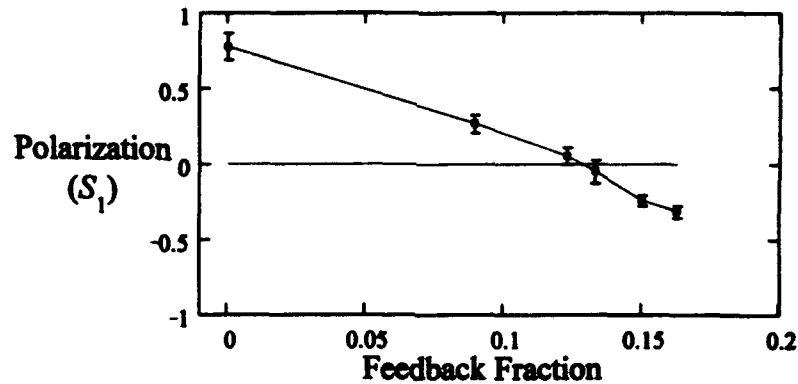


Figure 19. Polarization (S_1) vs. Feedback Fraction for Sample #2, Spot #2.

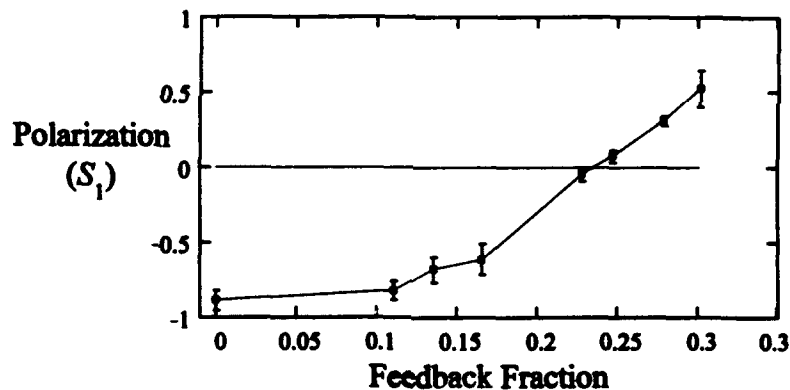


Figure 20. Polarization (S_1) vs. Feedback Fraction for Sample #2, Spot #3.

Other Observations

The spatial mode of the VCSEL varied from spot to spot and with different focusing lenses. With the 10x and 20x focusing lenses, the spatial mode was always the fundamental mode, HE_{11} . But with the higher power 40x lens, higher order modes were observed as often as the HE_{11} mode. Figure 21 shows images of the VCSEL beam taken by the camera, demonstrating the two higher order modes discussed earlier in Figure 9b,c.

In these images, the upper left spot is the pump laser, while the lower right spot is the VCSEL. The optics between the camera and the VCSEL consist of a single lens and a series of reflectors. The images, therefore, are of the beam cross-section at the focus of the lens, which is roughly at the VCSEL's top surface.

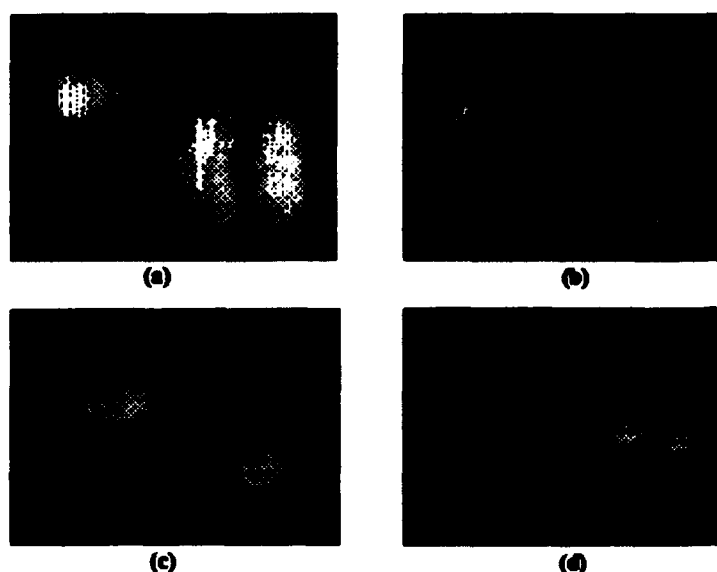


Figure 21. Transverse Modes of VCSEL

A likely reason for these higher modes is the decrease of gain in the central core of the cavity. The modes only appeared with the higher power lens, which concentrated the pump intensity very high in the center of VCSEL cavity. This led to a localized temperature increase high enough to reduce the gain in the core, as described in (Scott, 1993). The surrounding region, at lower temperature, still had enough gain and so the VCSEL lased in a mode with maxima in the surrounding regions, not the center.

Spectral analysis of the VCSEL and feedback effects was performed only rarely, due to the unavailability of the spectrometer. In all cases observed, only one single transverse mode existed, even at very high pumping rates. It varied from 878 nm to 881

nm, depending on the pump intensity and the location on the VCSEL wafer. Spectral width was approximately 0.5 nm. The cross-polarized higher transverse modes reported by others (Chang-Hasnain, 1991a) were never observed. The only spectral effect of feedback was to shift the VCSEL wavelength up by about 0.25 nm.

Sample 3: InGaAs Quantum Wells

This sample was very different from the other two. It was grown on GaAs substrate and designed to lase above 900 nm, which is outside the absorption band of the substrate. Therefore, access to the back side of the laser was possible, and the modified mount was used, in hopes of investigating coherent feedback effects. Unfortunately, the coherence length of this VCSEL was measured at 0.4 mm, which was far too short to allow room for a polarizer and mirror. The short coherence length was probably caused by a number of factors.

Intensity fluctuations in the Ti:Sapphire pump laser, leading to fluctuations in carrier number, diminished the coherence. The carrier fluctuations caused wavelength fluctuations in the VCSEL due to a variety of nonlinear mechanisms outlined in (Brown, 1993). Experimental evidence for this comes from Sample #2, which was pumped with the Ti:Sapphire and then a much steadier diode laser. While coherence length with the Ti:Sapphire pump was 1 cm, with the diode laser pump it was 10 cm.

Some other factors caused rapid, large fluctuations in VCSEL intensity, leading to coherence loss. The most likely culprit is temperature. Since the pump intensity at the VCSEL surface was about 400 mW, while the VCSEL output was never greater than 2 mW, there was a lot of excess energy. Presumably, it went into heating the VCSEL, where the higher temperature increased fluctuations.

Polarization Preference

Because of the unusual crystalline growth direction and the interest in its effect on polarization, this sample was more thoroughly investigated for polarization preference. The experimental setup was varied from the standard setup in order to eliminate any systematic error in the Stokes parameter measurements. The results of these excursions were enlightening.

The first discovery of interest was the effect of pump geometry on polarization. The pump beam was oriented so that it was not perfectly orthogonal to the VCSEL's surface. The resulting focused pump spot was therefore slightly elliptical, not perfectly circular. The VCSEL polarization was consistently polarized in the vertical (V) direction, which was orthogonal to the direction in which the spot was spread. When the pump was carefully realigned to be orthogonal to the VCSEL, a much wider variety of polarizations were measured, none of them strongly polarized in the V direction.

Further confirmation of the effect was obtained while the pump beam was still skewed. The VCSEL wafer was rotated around the axis normal to its surface. The polarization remained in the direction of the skewed pump spot, and did not rotate with the VCSEL wafer. Clearly the asymmetry in the pump spot, leading to an asymmetric gain region, was more influential than any natural crystalline forces in the $\langle 110 \rangle$ plane in determining the VCSEL's polarization. This effect had not been previously reported for optically pumped VCSELs.

The second discovery was that the VCSEL light is definitely polarized elliptically, with a fairly significant circular component. While the first two samples had circular components ($S_3 \neq 0$) also, the circular components measured on this sample were much larger. To make sure there was no error, all the optical components between the VCSEL and the polarization analyzer, except for the DBS, were removed for measurement of the Stokes parameters. The results showed the same large circular component. The

conclusion is that either the DBS is birefringent, or the VCSEL itself is creating elliptically polarized light. The most likely answer is that the VCSEL itself is birefringent, due to some anisotropic strain in the crystal. This would transform the linearly polarized light into elliptically polarized light.

The Stokes parameters for a variety of spots on this sample are presented in Figure 22. A few clear patterns in the data stand out. First, the degree of polarization (V) is very high compared to the other two samples. With the exception of spot #5, all the spots have $V > 0.8$. Second, it is clear that there are two types of spots. Spots 1-3 and 8-13 have a similar pattern in the sign of their three Stokes parameters (+, +, -), while spots 4-7 have the opposite sign for all parameters (-, -, +). In other words, the VCSEL appears to be polarized in one of two states, which are roughly orthogonal to each other.

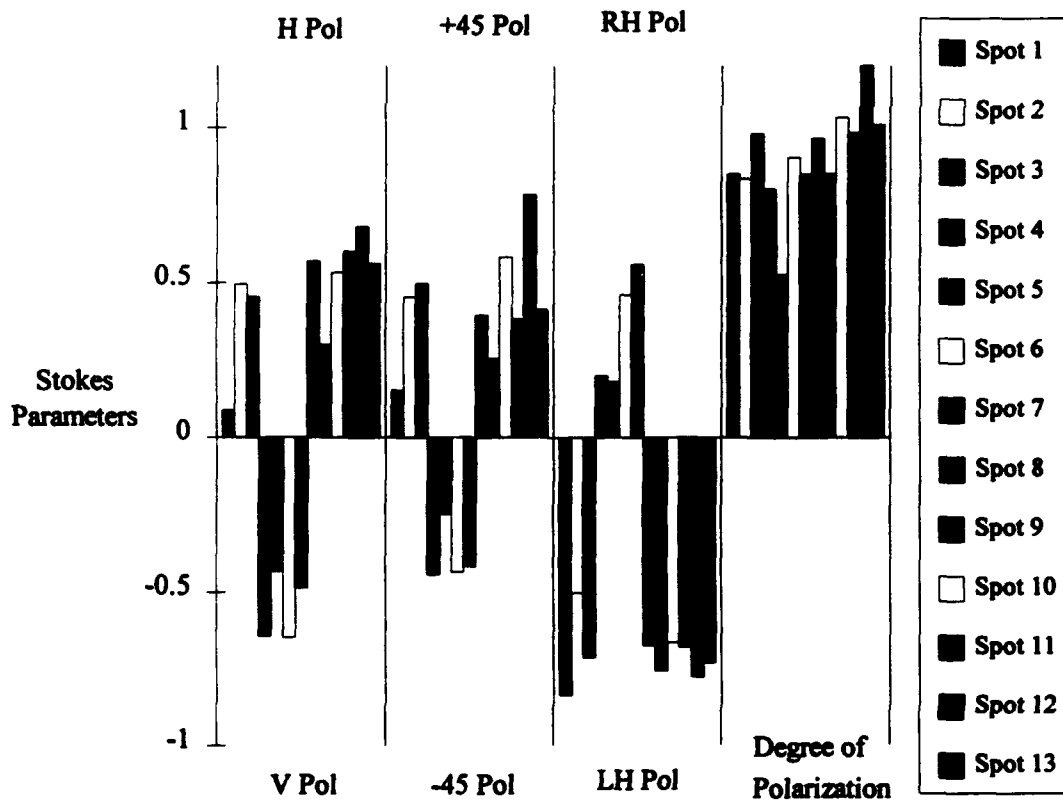


Figure 22. Stokes Parameters for 13 Locations on Sample #3.

The orientation used for this VCSEL is shown in Figure 23. Shown with it are depictions of the elliptical polarizations for two spots: one of the first type (spot #3) and one of the second type (spot #6).

These results indicate that growth of $\langle 110 \rangle$ layers seems to establish a preferred polarization direction. But it is not a very strong preference, since the pump spot geometry can override it. Even with a symmetric pump spot, the polarization direction seems to be in one of two orthogonal directions, much like the results reported by some groups for etched VCSEL cavities.

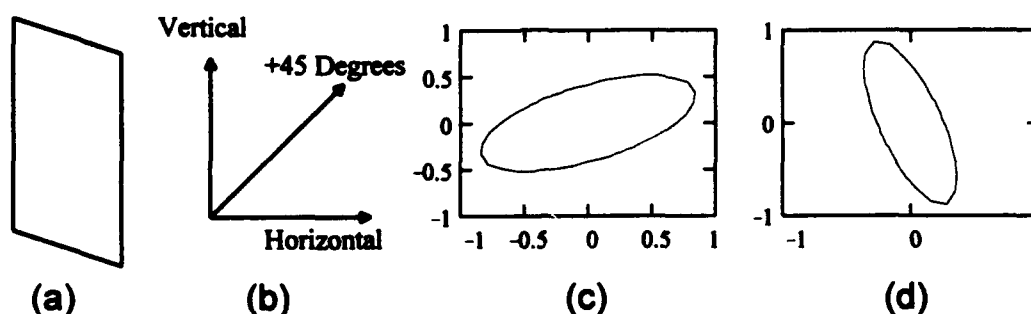


Figure 23. Sample #3 Geometry. Parts (a) and (b) show the wafer sample and its H/V orientation. Part (c) shows a type 1 spot (#3) and (d) shows a type 2 spot (#6). The handedness for the two types are in opposite directions.

Incoherent Feedback

In a few cases polarized feedback produced polarization switching in this VCSEL. In general, the position of the focus lens had a huge effect on whether polarization switching would occur. For the correct position, feedback coupled into the cavity very well, and good switching occurred. For a slightly different position, feedback had no effect, presumably because of poor coupling. This VCSEL may be more sensitive to coupling than the other VCSELs because it has the shortest cavity length. There is less room for mismatches between the field in the cavity and the field from the feedback.

The best feedback results are shown in Figure 24. All these spots initially had polarization type 1, which is more horizontal than vertical. The polarization of the feedback was chosen as pure vertical, which was easier to produce than linear polarization at another angle or elliptical polarization. In all three spots, the polarization moved toward vertical polarization when feedback was applied. At the same time, the overall degree of polarization (V) was significantly reduced, from $V \approx 1$ to $V \approx 0.2-0.3$.

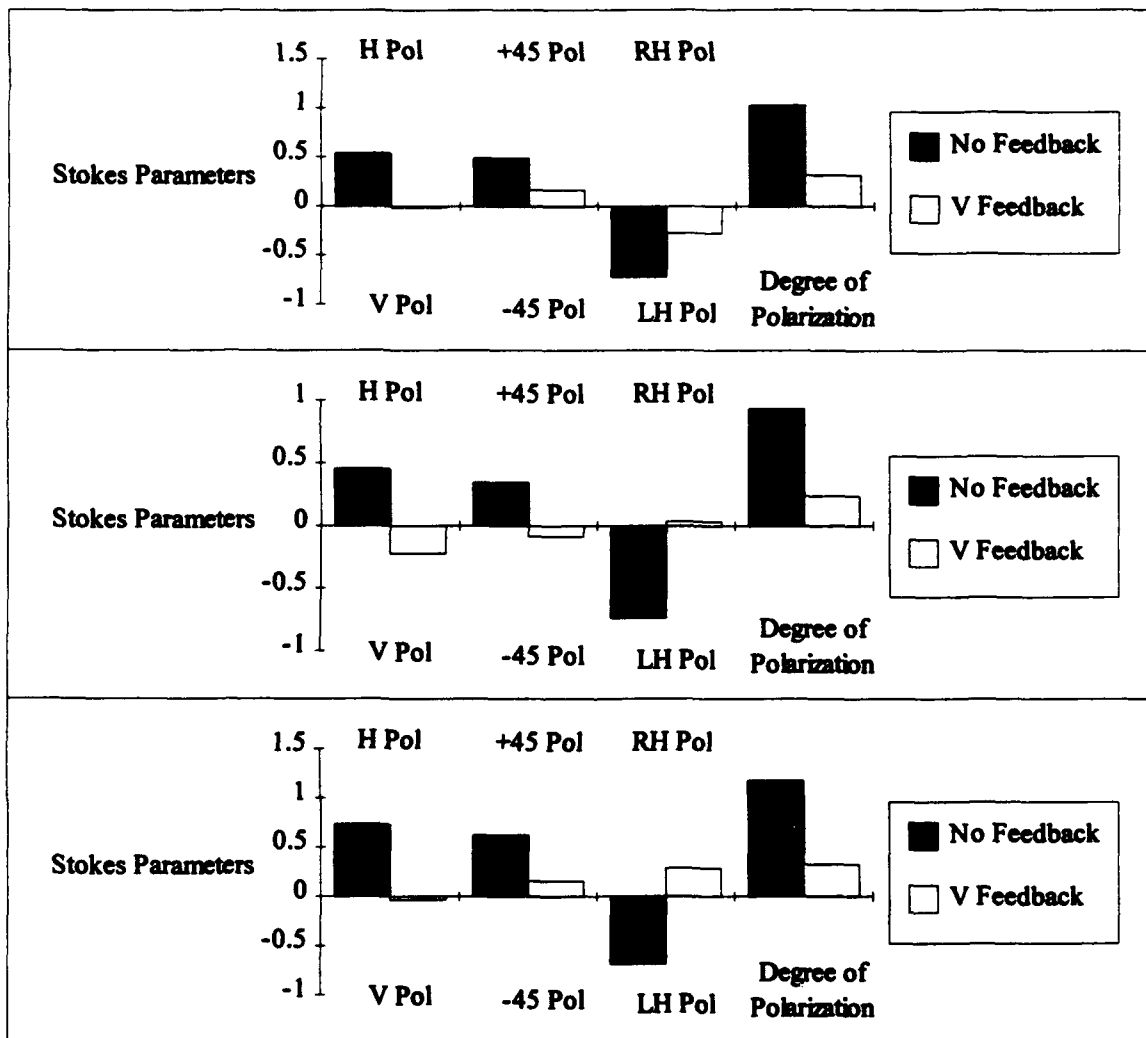


Figure 24. Polarization Switching for Three Spots on Sample #3. Fraction of vertical light being fed back is about 20%.

The spots did not last long enough to run a battery of tests with varying feedback fractions; these measurements were with about 20% feedback, the maximum possible in this configuration. The changes in the Stokes parameters are similar to what was seen in sample #2 at the crossover points where $S_1=0$. Larger feedback fractions would probably result in more complete switching.

V. Conclusions and Recommendations

The rare occurrence of expected polarization feedback effects makes clear conclusions very difficult. The most general conclusion is that producing feedback effects is considerably more difficult than expected. This is good news for VCSEL users trying to prevent feedback from coupling back into the laser.

It also seems clear that incoherent feedback is a much smaller problem than coherent feedback. That is, it takes a lot more incoherent feedback to affect a VCSEL's polarization than coherent feedback. It took on the order of 0.01 to 0.10 of the VCSEL intensity to produce noticeable polarization changes. On the other hand, from theoretical predictions and other experiments (Chung, 1991), coherent feedback fractions as small as 3×10^{-7} have noticeable spectral effects on VCSELs. The He-Ne laser, which has a much lower feedback susceptibility factor than a VCSEL, experiences complete polarization switching with coherence feedback fractions around 0.001. One would expect coherent feedback in VCSELs to have a much greater effect than the incoherent feedback studied in this effort.

The effect of pump spot asymmetry on the VCSEL polarization (sample 3) shows that optically pumped VCSELs are not immune to unintentional anisotropy. The difficulty of precisely aligning the pump direction with the VCSEL, plus the fact that the focusing lens has some small aberrations, makes it difficult to remove externally induced anisotropy from the experiment. In fact, although careful alignment was done, the apparent polarization preferences in samples 1 and 2 may be partially due to pump beam-induced anisotropy.

Clearly any future experimental work on this topic should strive for coherent feedback. A number of techniques can improve the coherence length of VCSELs. Electrical pumping (vice optical pumping) with a well regulated current source should improve coherence. It would also eliminate the need for many of the optical elements

which caused a polarization bias in the measurements. If that is not feasible, pumping with a diode laser at the appropriate wavelength will help considerably, as demonstrated in this experiment. In fact, combining a stable diode laser pump with a VCSEL that can lase through its substrate should allow coherent feedback studies.

The theoretical basis for this work needs to be improved greatly. Most studies of semiconductor gain regions have focused on TE vs. TM polarizations, a distinction that does not apply to VCSELs. Instead, VCSEL designers need to know if there are preferential directions within a crystalline plane. The work being done at the University of Virginia, where VCSELs are being grown in a $\langle 110 \rangle$ direction, should greatly illuminate this subject.

The theoretical work on vector lasers could be adapted to semiconductor lasers without too much difficulty. The differences between VCSELs and the gas lasers for which the theory was developed lie primarily in the gain and dispersion terms, as described in Chapter III.

The same body of work can be used to analyze incoherent feedback in quasi-isotropic lasers. While the study of coherent feedback is probably richer in its variety of effects, a VCSEL is far more likely to encounter incoherent feedback. The notable exception is when a VCSEL is directly coupled into an optical fiber, and the feedback off the coupling interface is extremely close.

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