

# Elliptical Polarization Emission From GaAlAs Laser Diodes in an External Cavity Configuration

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**Abstract**—We report the experimental operation of an external-cavity laser capable of oscillating in TE, TM, and elliptical-polarization states. An intracavity polarizer is used to force the laser to emit polarized radiation with TE and TM components whose wavelength can be changed by rotating the polarizer. A simple model based on the Jones matrix and steady-state rate equations is used to explain experimental data. Theoretical results for near threshold operation accurately predict the TE and TM power as a function of polarizer angle as well as the polarization dependence of wavelength.

## I. INTRODUCTION

THE majority of semiconductor lasers naturally oscillate in a transverse-electric (TE) mode. For most applications of laser diodes, this is an acceptable, if not preferred, mode of operation. However, with an increased interest in devices that require transverse-magnetic (TM) oscillation or injection such as polarization switches [1], or second-harmonic generators [2], a compact inexpensive TM source is a necessity. Until recently, devices requiring TM mode operation have relied either on strained layer laser diodes [3] or on simply rotating the output of a laser diode oscillating in a TE mode. The first method has proven expensive and the latter does not easily lend itself to coherent arrays, and hence cannot easily operate at a high power. With these limitations in mind, we study the forced TM oscillation of GaAlAs quantum well devices by means of a polarization selective component in the cavity of the laser. The experimental and theoretical techniques developed in this paper are general ones and may be applied to other laser structures as well as other material systems. While considerable effort has been spent on the investigation of forced TM oscillation through external injection [4]–[9] and pure TM operation in waveguides [10]–[12], there has been only limited investigation of TM operation through a polarization selective component [13], [14]. By examining the pure TE, pure TM, and the intermediate states of polarization, one can better understand the capabilities of a laser diode operating as a TM source as well as an optical switch. In fact, we show that for an external cavity laser operating under a forced polarization state, the laser output is generally single

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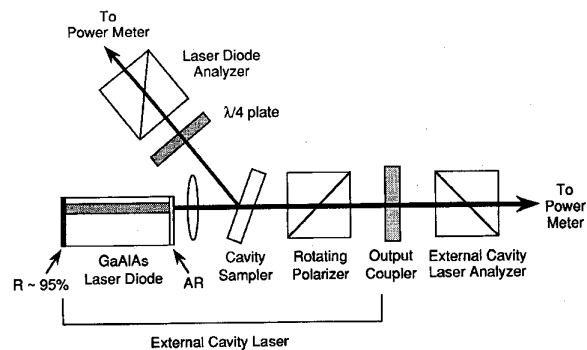


Fig. 1. Schematic illustration of external cavity laser with internal polarizer.

mode. The wavelength is tunable with respect to polarization state, and the output power can be accurately estimated.

## II. EXPERIMENT

We begin by examining an external cavity laser with a rotating polarizer within the cavity as shown in Fig. 1. The GaAlAs laser diode has a reflective coating ( $R \sim 95\%$ ) on one facet, and an antireflection (AR) coating on the facet facing the polarizer. A cavity sampler, that is comprised of a silica substrate with a low reflectance ( $R = 3\%$ ) coating on the side facing the laser diode and an AR coating on the other side, is used to sample the radiation that is emitted from the laser diode. An output coupler ( $R = 37\%$ ) completes the external cavity. The experiment consists of measuring the power at the output coupler and at the cavity sampler for different internal polarizer angles, determining the state of polarization of the radiation at the output of the external cavity laser as well as in the laser diode itself, and measuring the lasing wavelength.

The state of polarization of the radiation at the output of the external cavity laser is determined by measuring both the parallel and perpendicular components of power (with respect to the laser diode junction) by using an analyzer at the output coupler.

The state of polarization of the radiation in the laser diode is determined through measurement of the Stokes parameters [15] at the output (AR coated facet) of the laser diode via the cavity sampler. Briefly, the Stokes parameters are determined by measurement of the parallel and perpendicular components of power along with power measurements taken at  $45^\circ$  (with respect to the laser diode junction) with and without a  $\lambda/4$  plate oriented with its fast axis at  $0^\circ$  (i.e., parallel to the laser diode junction). From the Stokes parameters it is possible

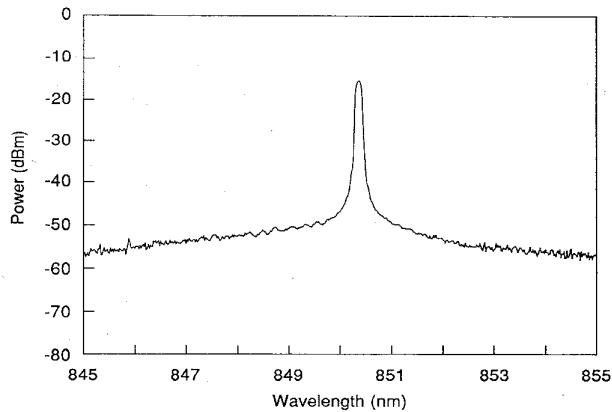


Fig. 2. Measured spectral output from the external cavity laser with internal polarizer angle at  $30^\circ$  operating at a current of 52 mA. The vertical scale is the power coupled into a fiber at the input of the optical spectrum analyzer.

to determine the rotation angle of the major axis of the polarization ellipse as well as the ellipticity angle. The tangent of the ellipticity angle gives the ratio of the minor axis to the major axis of the polarization ellipse. A zero ellipticity angle, or correspondingly, a zero minor to major axis ratio, is indicative of linearly polarized radiation. Alternatively, the amount of beam ellipticity may be expressed by the phase difference between the two orthogonal components of the polarization ellipse. The exact determination of these quantities is detailed in [15].

Measurements were repeated for three single-quantum-well (SQW) GaAlAs lasers (SDL, Inc. model SDL-5419-C).

### III. EXPERIMENTAL RESULTS

All three laser diodes oscillate in a single-longitudinal mode with a side-lobe suppression ratio greater than 20 dB. A typical spectrum measured with an Anritsu model MS9002A optical spectrum analyzer is shown in Fig. 2. The measured linewidth is limited by the resolution bandwidth (0.1 nm) of the optical spectrum analyzer. The polarizer angle,  $\theta$ , at  $0^\circ$  corresponds to pure TE operation and at  $90^\circ$  corresponds to pure TM operation. For intermediate angles, we note two different types of behavior that are best explained through consideration of the spontaneous emission curves. Fig. 3 shows spontaneous emission spectra polarized parallel and perpendicular to the laser diode junction for two representative laser diodes. Fig. 3(a) is the spontaneous emission spectrum for a laser diode exhibiting the first type of behavior, namely elliptical emission. We shall refer to this laser diode as laser diode 1. For this laser diode, the parallel and perpendicular spontaneous emission curves are spaced by 5.6 nm. Fig. 3(b) is the spontaneous emission spectrum for a laser diode that predominantly exhibits the second type of behavior, polarization switching. This laser diode shall be referred to as laser diode 2. For this laser diode, the peaks of the spontaneous emission curves are separated by 12.6 nm. For both lasers, we note the polarization state at the output coupler can be different from the state of the laser diode. Polarization is always linear

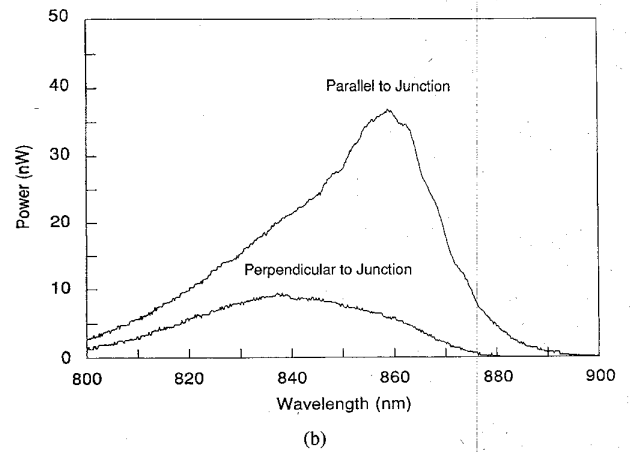
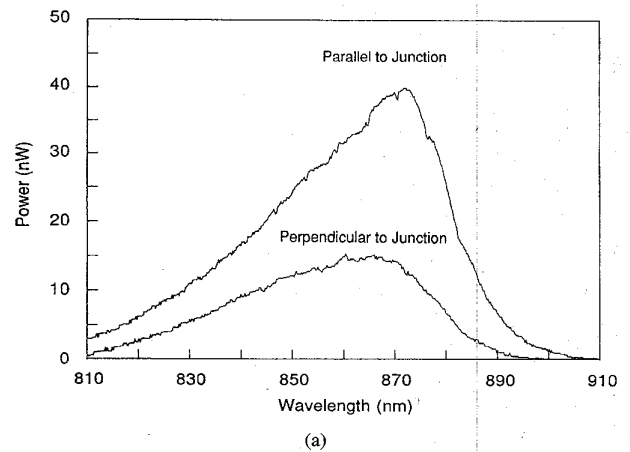
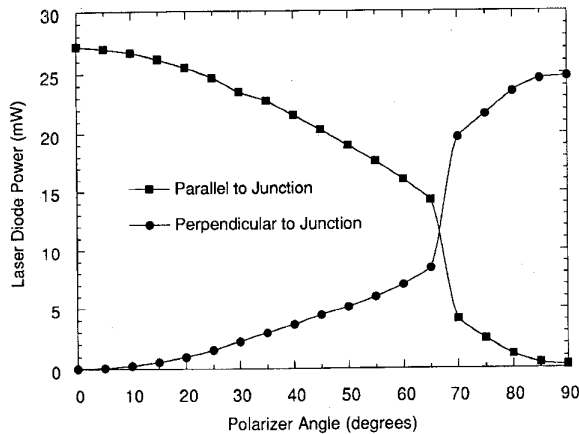


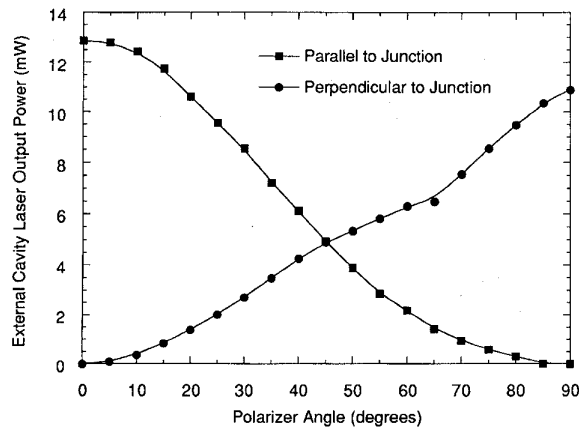
Fig. 3. Spontaneous emission spectrum for (a) laser diode 1 and (b) laser diode 2. The vertical scale is the power coupled into a fiber at the input of the optical spectrum analyzer.

at the output coupler because the linear polarizer removes the beam ellipticity.

The elliptical polarization emission occurs for laser diodes with closely spaced components of the spectrum, such as laser diode 1. This particular laser diode has a TE threshold of 22 mA, a TM threshold of 27 mA, and the measurements shown are for operation at 52 mA. In this case, the feedback from the output coupler combined with the polarizer alters the lasing state of the laser diode such that the rotation of the polarization ellipse is pulled toward the feedback state. This behavior is seen in Fig. 4(a) and (b) which are the measured power parallel and perpendicular to the junction, both at the cavity sampler and at the output coupler, respectively. For Fig. 4(a), the laser diode power is determined by measuring the power in the beam reflected off the low reflectance surface of the cavity sampler and correcting it for the cavity sampler reflectivity. As the figures show, the output of the laser diode is neither purely parallel nor perpendicular to the junction for polarizer angles between  $0^\circ$  and  $90^\circ$ . Such behavior is indicative of a mixed state of polarization. We can further examine the state of polarization by plotting the rotation angle of the major axis of the polarization ellipse along with the minor to major axis ratio of the ellipse. These two quantities are shown in



(a)



(b)

Fig. 4. (a) Laser diode power for external cavity laser containing laser diode 1 presented as a function of internal polarizer angle. (b) Output power of the external cavity laser containing laser diode 1 as a function of internal polarizer angle. The square points are the measured power parallel to the junction and the circles are measured power perpendicular to the junction. Lines are included purely as a guide to the eye.

Fig. 5. From Fig. 5, it is apparent that the feedback not only changes the rotation angle, but promotes a substantial amount of ellipticity in the beam. The ellipticity reaches a maximum for polarizer angles for which there is substantial and nearly equal gain for both the parallel and perpendicular components. In this region, the corresponding phase difference between the two orthogonal components exceeds  $90^\circ$  (as determined from the Stokes parameters). The result is a rotation angle which exceeds  $90^\circ$  for this range of polarizer angles. Furthermore, as the polarizer is rotated, the cavity loss, feedback, and gain are altered, thus forcing the frequency to change linearly. The wavelengths at  $0^\circ$  and  $90^\circ$  correspond to the TE and TM mode wavelengths, respectively. The total change in the wavelength as the polarizer rotates from TE to TM, which is equal to the distance between the spontaneous emission peaks, is indicative of the relationship between the spontaneous emission peaks and the gain peaks.

The polarization switching behavior observed in laser diodes with widely spaced parallel and perpendicular spontaneous

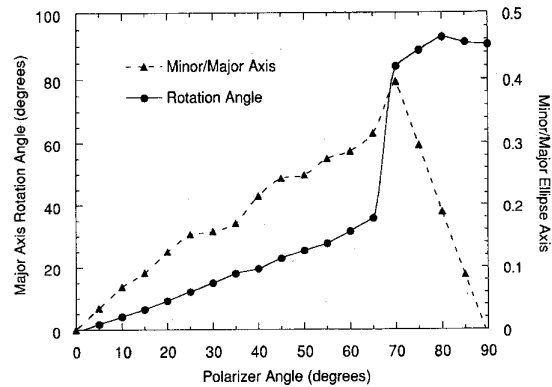


Fig. 5. Polarization state of laser diode 1. Circles represent rotation of the major axis of the polarization ellipse with respect to the axis parallel to the laser diode junction. Triangles represent the minor to major axis ratio of the polarization ellipse. Lines are included purely as a guide to the eye.

emission spectra is seen in the laser diode power measured at the cavity sampler. This laser diode has a TE threshold of 17 mA, TM threshold of 27 mA, and measurements are taken at 52 mA. Fig. 6(a) is the power measured parallel and perpendicular to the junction of the laser diode at the cavity sampler where the method of measurement was the same as that used in Fig. 4(a). Fig. 6(b) is the power measured at the output coupler. For this laser, the feedback fails to significantly rotate the polarization ellipse to any intermediate state. Rather, only under strong feedback can the rotation be significantly altered. Such feedback forces an abrupt change in the state of polarization as the laser diode switches from TE to TM operation. We also note a sharp decrease in the power, both at the output coupler and at the cavity sampler, for specific angles of the polarizer. This region occurs just before the laser switches from TE to TM and corresponds to insufficient gain in either mode. Consequently, for these angles the laser diode is operating under amplified spontaneous emission (ASE). A large region of ASE is generally indicative of marked switching behavior. Moreover, for widely spaced spontaneous emission spectra, the amount of beam ellipticity decreases while the switching behavior becomes more dominant. As can be seen from Fig. 7, the rotation angle of laser diode 2 is minimal. The amount of ellipticity, which reaches a maximum before and after the large ASE region, is substantially reduced in comparison to laser diode 1. Also, as with laser diode 1, the wavelength of operation is a function of the polarizer angle  $\theta$ . Fig. 8 shows the measured wavelength dependence as well as an estimate of the wavelength through a linear fit. The linear fit will be used in conjunction with the model.

A thorough discussion of both types of behavior is presented with the predictions of the model described in the following section.

#### IV. MODEL

For external-cavity lasers operating near threshold, we have developed a simple model based on the Jones matrix [13], [16] and the carrier and field rate equations [6] at steady state. This model can predict the power parallel and perpendicular to the junction as a function of polarizer angle as well as the

threshold carrier density. The assumptions involved in such an analysis are, first, that the laser is operating near threshold (we find the results accurate at least until twice TM threshold), and secondly, that the laser is temporally stable, and finally, that there is no external feedback.

For the first step, each element is represented as a Jones matrix that operates on the field components. The field is represented by the vector  $\mathbf{F}$  as

$$\mathbf{F} = \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}, \quad (1)$$

where  $E_1$  is the field polarized parallel to the junction and  $E_2$  is the field polarized perpendicular to the junction. The field values may be complex. In the following analysis, the subscript 1 is assigned to variables referring to the parallel component, and the subscript 2 refers to the perpendicular component. The matrix describing the laser diode is given as

$$\mathbf{L} = \begin{bmatrix} G_1 & K_1 \\ K_2 & G_2 \end{bmatrix}. \quad (2)$$

The terms  $K_1$  and  $K_2$  account for the coupling through spontaneous emission of the parallel and perpendicular components of the field. The net gain,  $G_j$  ( $j = 1, 2$ ), is given as [17]

$$G_j = \exp\left(\frac{1}{2}(g_j - \alpha_j) + i\phi_j\right), \quad (3)$$

where  $g_j$  is the modal gain given as [6]

$$g_j = \Gamma_j \sigma_j(\lambda)(N - N_{0,j})l. \quad (4)$$

In (4),  $\Gamma_j$  is the confinement factor,  $\lambda$  is the lasing wavelength,  $\sigma_j(\lambda)$  is the gain cross section,  $N$  is the carrier density,  $N_{0,j}$  is the carrier density required for transparency, and  $l$  is the length of propagation in the laser diode. The loss term,  $\alpha_j$ , shown in (3) is [18]

$$\alpha_j = (1 - \Gamma_j)\alpha_c l, \quad (5)$$

where  $\alpha_c$  is the cladding loss. The final term in (3), the phase acquired through propagation and carrier induced antiguiding [18], is [19]

$$\phi_j = \frac{2\pi}{\lambda} n_j l - \frac{1}{2} \Gamma_j \sigma_j(\lambda) R N l, \quad (6)$$

where  $R$  is the carrier induced antiguiding factor and  $n_j$  is the effective index of the parallel or perpendicular component of the polarization. It is extremely important to include this phase term and to differentiate between the index of refraction in either component. Although the difference in index is very small, the difference in phase between the parallel and perpendicular polarization is the root of the ellipticity in the beam as it exits the laser diode.

The gain for the parallel and perpendicular components are approximated as parabolic functions because the wavelength is never more than 15 nm from the peak of the gain and the linewidth is estimated at 40 nm. We assume that  $\sigma_j$  in (4) varies with wavelength as [20]

$$\sigma_j(\lambda) = \sigma_{0,j} \left(1 - \frac{1}{2} \left(\frac{\lambda - \lambda_p}{\Delta\lambda}\right)^2\right), \quad (7)$$

where  $2\Delta\lambda$  is the full width at half maximum (FWHM) of the gain curve, and  $\lambda_p$  is the wavelength at the peak of the gain curve. The peak of the gain curve is assumed to be coincident with the peaks of the parallel and perpendicular components of the spontaneous emission curves. It is imperative that the wavelength be explicitly incorporated into the model. Ignoring the wavelength produces inaccurate and erroneous results.

The matrix representing the highly reflective facet is [16]

$$\mathbf{R}_{\text{HR}} = \begin{bmatrix} r_{h1} & 0 \\ 0 & r_{h2} \end{bmatrix} \quad (8)$$

where  $r_{h1}$  is the highly reflective facet's reflectivity for the parallel polarization, and  $r_{h2}$  is the highly reflective facet's reflectivity for the perpendicular polarization. These values are allowed to be different for generality.

The next element included in the model is the polarizer whose matrix is given by [16]

$$\mathbf{P} = \begin{bmatrix} \cos^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \sin^2 \theta \end{bmatrix}. \quad (9)$$

The output coupler, represented in manner similar to (8), is [16]

$$\mathbf{R} = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix}, \quad (10)$$

where  $r_1$  and  $r_2$  are the reflectivity values for the two polarizations. We must also include the phase accumulated through travel in air. This is accomplished through the inclusion of the matrix  $\mathbf{AP}$  shown in (11) to be

$$\mathbf{AP} = \begin{bmatrix} \beta & 0 \\ 0 & \beta \end{bmatrix}. \quad (11)$$

The phase  $\beta$  is [19]

$$\beta = \exp\left(i \frac{2\pi}{\lambda} 2l_{\text{air}}\right). \quad (12)$$

where  $l_{\text{air}}$  is the unidirectional length of propagation in air.

The matrix describing the operation of the laser is the product of the matrices as the radiation makes one round trip. We choose to examine the radiation as it exits the laser diode. The net matrix at the output of the laser diode is given as [16]

$$\mathbf{J} = \mathbf{P} \cdot \mathbf{R} \cdot \mathbf{P} \cdot \mathbf{AP} \cdot \mathbf{L} \cdot \mathbf{R}_{\text{HR}} \cdot \mathbf{L}. \quad (13)$$

The matrix elements of  $\mathbf{J}$  are denoted as

$$\mathbf{J} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \quad (14)$$

where the elements of  $\mathbf{J}$  are

$$a_{11} = \beta(r_{h1}G_1^2 + r_{h2}K_1K_2)(r_1 \cos^4 \theta + r_2 \sin^2 \theta \cos^2 \theta) + \beta(r_{h1}G_1K_1 + r_{h1}K_1G_2) \times (r_1 \sin \theta \cos^3 \theta + r_2 \sin^3 \theta \cos \theta), \quad (15)$$

$$a_{12} = \beta(r_{h1}G_1^2 + r_{h2}K_1K_2)(r_1 \sin \theta \cos^3 \theta + r_2 \sin^3 \theta \cos \theta) + \beta(r_{h1}G_1K_1 + r_{h1}K_1G_2) \times (r_1 \sin^2 \theta \cos^2 \theta + r_2 \sin^4 \theta), \quad (16)$$

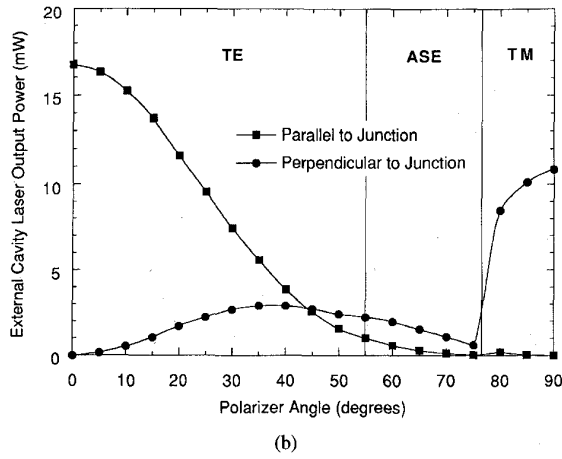
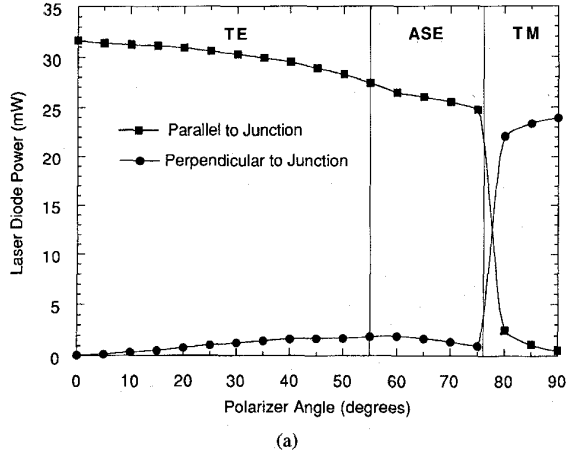


Fig. 6. (a) Laser diode power for external cavity laser containing laser diode 2 presented as a function of internal polarizer angle. (b) Output power of the external cavity laser containing laser diode 2 as a function of internal polarizer angle. The square points are the measured power parallel to the junction and the circles are measured power perpendicular to the junction. Lines are included purely as a guide to the eye.

$$a_{21} = \beta(r_{h1}K_1K_2 + r_{h2}G_2^2)(r_1 \sin \theta \cos^3 \theta + r_2 \sin^3 \theta \cos \theta) + \beta(r_{h1}G_1K_2 + r_{h2}K_2G_2) \times (r_2 \sin^2 \theta \cos^2 \theta + r_1 \cos^4 \theta), \quad (17)$$

and

$$a_{22} = \beta(r_{h2}G_2^2 + r_{h1}K_1K_2)(r_2 \sin^4 \theta + r_1 \sin^2 \theta \cos^2 \theta) + \beta(r_{h1}G_1K_2 + r_{h1}K_2G_2) \times (r_1 \sin \theta \cos^3 \theta + r_2 \sin^3 \theta \cos \theta). \quad (18)$$

We must examine the radiation at the laser diode because we will use the information we derive to describe the state of the laser diode. The linear polarizer alters that state by altering the ratio of power it feeds back as well as removing any ellipticity on the beam, thus removing critical information about the phase of each component of the polarization as it exits the laser diode. We, therefore, look at the field at the laser diode first, then propagate the resulting field through the polarizer and output coupler to examine the output power.

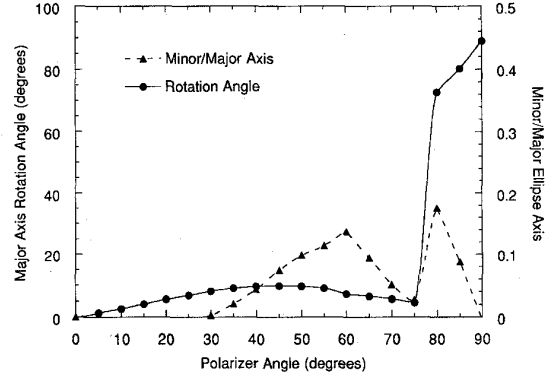


Fig. 7. Polarization state of laser diode 2. Circles represent rotation of the major axis of the polarization ellipse with respect to the axis parallel to the laser diode junction. Triangles represent the minor to major axis ratio of the polarization ellipse. Lines are included purely as a guide to the eye.

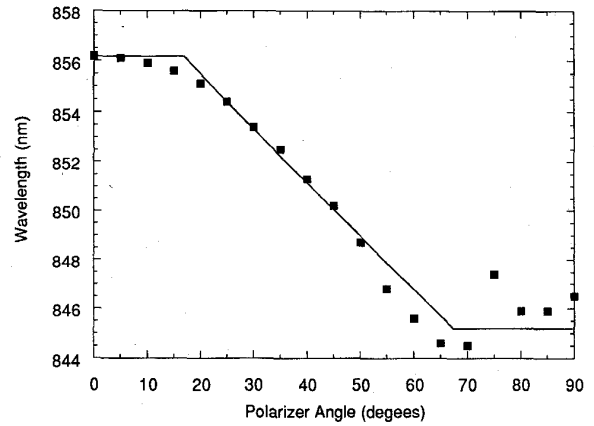


Fig. 8. Wavelength as a function of polarizer angle. Points marked with a square represent measured wavelengths for external cavity laser containing laser diode 2. The line represents the estimated wavelength.

Having derived a model for the operation of this device, we must now apply the assumptions stated earlier to simplify the terms and lend meaning to the model. First, we are looking at solutions not too far above threshold. We assume coupling between the polarization components is through the carrier density and the feedback, therefore, the value of the coupling coefficients  $K_j$  can be assumed zero. For single-frequency operation, we can also estimate the wavelength as a linear function such as the estimate shown in Fig. 8. If a more accurate estimate is desired, one can set the round-trip phase of the effective mode, as given by the matrix elements, equal to an integral number of  $2\pi$  and solve for the resulting wavelength. We find, however, that a simple linear approximation provides accurate enough results. The approximations we use are reflected in our choice of parameters not in the model itself. Consequently, we can easily change the values of  $K_j$  as well as examine two independent linear states of polarization if the device we examine behaves in such a manner. Because the device is stable, after one round trip the vector field  $\mathbf{F}$  must return to its original value. In mathematical form, this

statement is simply  $\mathbf{J} \cdot \mathbf{F} = \mathbf{F}$  or

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}. \quad (19)$$

The ratio of the power parallel to the junction to the power perpendicular to the junction can be written as

$$\left( \frac{E_1}{E_2} \right)^2 = \left( \frac{a_{12}}{1 - a_{11}} \right)^2. \quad (20)$$

We shall refer to the quantity determined by (20) as  $\gamma$ .

Examination of the elements of the matrix  $\mathbf{J}$  leads to the conclusion that  $\mathbf{J}$  is a singular matrix. The singularity in  $\mathbf{J}$  results from the singularity of the matrix  $\mathbf{P}$ , which represents the operation of a polarizer. In order to have a nonsingular matrix, we would have to include reflections from the polarizer. This would violate the premise of this linear analysis and give erroneous results. In order to correctly incorporate feedback effects, one would have to model this system as a coupled cavity. The singularity of the matrix implies that the determinant is zero [21]. Using this fact and (19) gives

$$a_{11} + a_{22} = 1. \quad (21)$$

This expression is nothing more than the mathematical statement that the round trip gain of the elliptical mode is 1, and the phase accumulated on the beam after one round-trip is an integral number of  $2\pi$ . In order to solve these equations for the power ratio, we use the parameters given in Table I to evaluate (3) through (12). We now have gain and loss terms purely in terms of the carrier density  $N$ . We can then use these expressions in (21) to determine the exact value of the carrier density  $N$  at steady-state and thus the elements of  $\mathbf{J}$ . We find that the carrier density we use is approximately 1.4 times the carrier density required for transparency. Using (20), we can then determine the ratio of parallel power to perpendicular power.

Having determined the ratio of the parallel to perpendicular power, we can now use the rate equations at steady state to calculate the photon density and hence the actual power. The carrier rate equation is [6]

$$\frac{dN}{dt} = P - \frac{N}{\tau_s} - v_1 \sigma_1(\lambda) \Gamma_1 S_1 (N - N_{0,1}) - v_2 \sigma_2(\lambda) \Gamma_2 S_2 (N - N_{0,2}). \quad (22)$$

In (22),  $N$  is the carrier density,  $P$  is the pump current given in carriers/m<sup>3</sup>/s,  $\tau_s$  is the carrier lifetime,  $v$  is the group velocity of each component of the polarization, and  $S$  is the photon density in each component of the polarization. At steady state, (22) is equal to zero. Additionally, the steady-state carrier density is known from the Jones matrix analysis. By substituting  $\gamma S_2$  for  $S_1$ , we can solve (22) for the photon density perpendicular to the junction, then use the ratio from the Jones matrix to solve for the photon density parallel to the junction. The result is the photon density in each mode. Additionally, if further confirmation of the results are

TABLE I  
PARAMETER VALUES

Parameter	Symbol	Value
carrier recombination rate	$A_{21}$	$0.5 \times 10^{-9} \text{ s}^{-1}$
length of diode	$l$	750 $\mu\text{m}$
spontaneous emission width (TE and TM SQW)	$\Delta\lambda$	40 nm
active region index	$n_a$	3.60
cladding region index	$n_c$	3.50
effective index	$n_j$	3.55, 3.59
cladding loss	$\alpha_c$	1000 $\text{m}^{-1}$
confinement factor TE	$\Gamma_{TE}$	0.02
confinement factor TM	$\Gamma_{TM}$	0.018
output coupler (TE and TM) field reflectivity	$r_1$ and $r_2$	0.61
high reflectivity coated facet field reflectivity	$r_{h1}$ and $r_{h2}$	0.97
wavelength	$\lambda$	830-860 nm
one-way propagation length in air	$l_{\text{air}}$	22 cm
peak gain cross section (laser 1)		
parallel to junction	$\sigma_1$	$1.38 \times 10^{-19} \text{ m}^2$
perpendicular to junction	$\sigma_2$	$1.29 \times 10^{-19} \text{ m}^2$
transparency carrier density for		
TE operation	$N_{01}$	$1.5 \times 10^{24} \text{ m}^{-3}$
TM operation	$N_{02}$	$1.46 \times 10^{24} \text{ m}^{-3}$
antiguinding factor	$R$	3

needed, one can examine the photon rate equation (neglecting spontaneous emission) given as [6]

$$\frac{dS}{dt} = v_1 \sigma_1(\lambda) \Gamma_1 S_1 (N - N_{0,1}) + v_2 \sigma_2(\lambda) \Gamma_2 S_2 (N - N_{0,2}) - \frac{S_1}{\tau_{p,1}} - \frac{S_2}{\tau_{p,2}}. \quad (23)$$

In (23), the photon lifetime  $\tau_p$  is estimated from the cavity losses to be [18]

$$\frac{1}{\tau_{p,j}} = \frac{c}{n_j} \left( \frac{n_c}{n_j} (1 - \Gamma_j) \alpha_c + \frac{1}{l} \ln \left( \frac{1}{r_{h,j}} \right) + \frac{n_j}{l_{\text{air}}} \ln \left( \frac{1}{r_{\text{eff},j}} \right) \right). \quad (24)$$

In (24),  $r_{\text{eff},j}$  is the effective reflectivity of the external cavity as determined by the polarizer and output coupler. By substituting  $\gamma$  into (23) and solving for a nontrivial solution, we can estimate the threshold carrier density. This approximation tends to be an under estimate because we cannot model all the loss mechanisms, but the behavior is similar.

With this model, we have a thorough, analytic description of the device behavior.

## V. RESULTS OF MODEL

We first calculate the ratio of power parallel to the junction to the power perpendicular to the junction using both the estimated and the measured wavelengths. Both these ratios, as well as the measured ratio, are shown in Fig. 9 for an

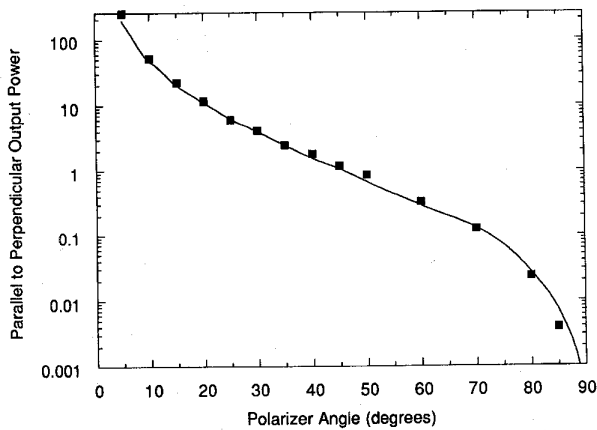
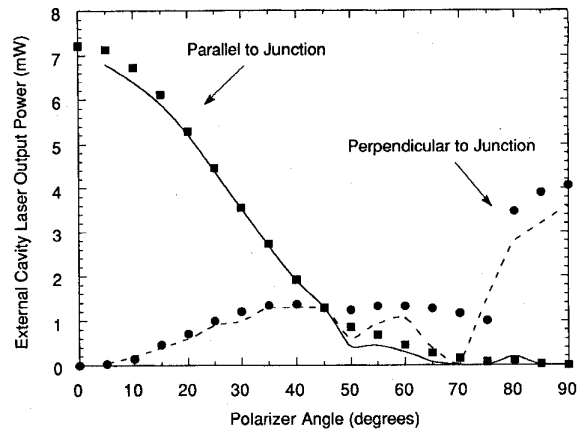


Fig. 9. The log of the ratio of the external cavity laser output power parallel to the junction to the power perpendicular to the junction plotted with respect to the polarizer angle. The solid line represents theoretical values using the estimated wavelengths and squares are the experimental power ratio.

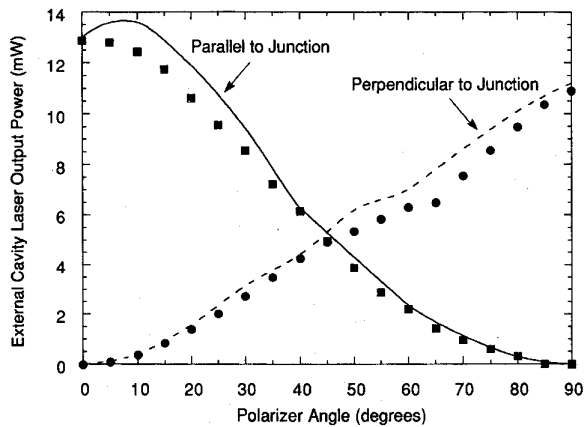
external cavity laser with laser diode 3. This laser diode has a TE threshold of 23 mA, TM threshold of 36 mA, and measurements are taken at 52 mA. Laser diode 3, while exhibiting predominantly switching behavior, shows a slight amount of ellipticity. Because this laser diode has a slight amount of ellipticity, it is an ideal choice to demonstrate the versatility of this algorithm. The model is able to identify even slight traces of either type of behavior accurately. Because this algorithm is accommodating, if the measured wavelength is unknown, we see that the linear approximation is sufficient. If one wanted to calculate the wavelength without making an approximation, one would only have to set the round-trip phase determined by the Jones matrix equal to an integral multiple of  $2\pi$  and solve for the wavelength. We, however, find the linear approximation sufficient. As is also apparent, the measured and predicted values are nearly identical.

We also note the threshold carrier density calculated from the rate equations and compare this to the threshold determined from L-I curve measurements. For laser diode 3, the calculated threshold carrier density corresponds to a threshold current of 18 mA when the polarizer is set to  $0^\circ$ . The measured threshold current for TE lasing is 22 mA. The measured and calculated behavior is similar for all three lasers. The lowest threshold is for pure TE operation which this laser was designed to support. The threshold rises as the mixed state grows and reaches a high point as the laser goes through the region in which we measure ASE. The threshold drops slightly as the laser reaches a region where it lases. This region need not be a mixed state. Rather, it can be a region of attenuated TM lasing. In either case, the threshold drops as the laser approaches pure TM lasing.

From the rate equations, we are also able to calculate the absolute power. We first calculate the power in the laser diode, then propagate the radiation through the polarizer to compare it with measured output. The comparison of powers is shown in Fig. 10(a), for the cavity with laser diode 3, and in Fig. 10(b), for the cavity with laser diode 1. As is apparent from Fig. 10, this model predicts accurately the behavior of the laser that is predominantly switching, as well as the laser that



(a)



(b)

Fig. 10. Output power of external cavity laser containing (a) laser diode 3 exhibiting switching as a function of internal polarizer angle. (b) Laser diode 1 exhibiting ellipticity as a function of internal polarizer angle. The solid lines are the theoretical estimate of the output power parallel to the junction while the dotted lines are the theoretical estimate of the output power perpendicular to the junction.

is strongly mixed state. This is a direct result of incorporating frequency dependence into the model as well as using the steady-state rate equations. By letting the peaks of the lasing gain be determined by the spontaneous emission spectrum, we force the model to implicitly incorporate the separation in frequency of the parallel and perpendicular gain. Then, by allowing the wavelength to vary as a function of polarizer angle, the model will determine the gain in each component and hence the lasing state of the laser diode. In other words, this model is quite robust. We note, in particular, that the model predicts the region where the output is reduced and the laser does not lase. At this point we calculate a slightly lower power than we measure, because the model we use for the rate equations assumes a single mode of operation and the region of spontaneous emission has power at many different frequencies.

## VI. DISCUSSION

The measurement of elliptical emission from a laser diode is interesting and unexpected. The external cavity laser examined

here is comprised of a birefringent medium within a lasing cavity. In this case, the gain and the birefringence are coincidental. For lasers with closely spaced gain curves, the laser diode is able to extract a significant amount of gain from both the parallel and perpendicular components at a single wavelength. As the feedback is altered, the composition of the lasing mode is changed. The laser diode looks for a single wavelength that can satisfy the round-trip gain condition for both components of the radiation. Effectively, the cavity loss and gain are functions of the polarizer angle and so correspondingly is the lasing wavelength. For this reason, the wavelength scans linearly. It is also for this reason that any model describing the behavior must include frequency dependence of the gain. This frequency dependence causes the change in the ratio of the power as well as in the output power. The parallel and perpendicular radiation is coupled through both the feedback and the carrier density. Because there is a large amount of parallel and perpendicular gain for all the wavelengths between TE and TM operation, the laser can sustain stable lasing for almost all wavelengths and is thus tunable. The elliptical output of the laser diode arises from the difference in index of refraction and confinement factor between the parallel and perpendicular components of the radiation. Carrier induced antiguiding also contributes to the beam ellipticity because the induced phase change is proportional to the gain cross-section which differs for the two components at any given frequency. This ellipticity is only present at the laser diode and not at the output coupler because the linear polarizer removes the beam ellipticity. However, if the polarization selective component in the cavity was something other than a linear polarizer, the laser would emit elliptical radiation at the output facet. This effect can contribute to the tunability of such a device. Furthermore, for laser 1 we note only a small region of ASE ( $\sim 2^\circ$ ) with respect to polarization angles. This is a direct result of the large amount of gain in both components. Not only are the individual gain components high, the lasing mode sees a net gain which is the superposition of both the gain components. Therefore, the net gain overcomes the loss for nearly all polarizer angles and their resulting wavelengths. Consequently, lasers exhibiting elliptical output are more likely to retain their stability while demonstrating tunability.

Polarization switching with the internal polarizer is not unlike polarization switching seen under external TM feedback conditions [9]. In this case, the polarizer decomposes the TE radiation emitted from the laser diode into two components determined by the axes of the polarizer. The output coupler then feeds this radiation, that now has components in both the parallel and perpendicular directions, back into the laser diode. The result is attenuated TE feedback along with limited TM feedback. As the polarizer is rotated from 0 to 90 degrees, the TE feedback is further attenuated and the TM feedback is increased until the laser switches from TE operation to TM operation. For certain polarizer angles (usually centered about polarizer angles of  $65^\circ$ ), there is insufficient gain in either the TE or the TM mode for the laser diode to lase. For this region, the laser diode undergoes ASE.

Switching behavior is a result of spontaneous emission curves that are widely spaced. When the gain in the two

modes are widely spaced with respect to wavelength, it is difficult for the laser diode to extract significant gain from both components while operating at a single wavelength. Consequently, the feedback is insufficient to promote coupling between the two modes. The polarizer then acts like an attenuator. The cavity loss is increased and the operating wavelength is changed. The gain at the corresponding wavelength is less than for pure TE operation. When the wavelength is shifted far enough away from the TE peak, yet not close enough to the TM peak to allow TM lasing, the laser diode enters a region of ASE. The extent (with respect to wavelength and hence polarizer angle) is determined by the spacing of the gain curves. Widely spaced gain curves generate a greater spread in wavelengths. Consequently, there is a larger region for which the laser diode has insufficient gain in either or both components for the laser to lase. Eventually, the polarizer angle alters the cavity loss such that the wavelength corresponds to TM operation. There is some hysteresis in this behavior as there is in all switching behavior.

It is important to note, while the laser diode is emitting either TE or TM radiation, the output coupler passes components along both axes. This is a result of the linear polarizer. One can show, that a TE source passed first through a polarizer angle at some intermediate angle then through a TM polarizer, will show resultant radiation along the TM axis. This need not be indicative of the lasing state of the laser diode. However, it is this radiation that will be coupled out of the external cavity for use.

When operating TM with modulation, slight changes in external feedback should not alter the polarization state of the laser diode if stability is to be achieved. For a laser diode undergoing switching, the polarization state will not change until sufficient feedback is introduced. In this manner, such a laser may be more stable under modulation conditions.

## VII. CONCLUSION

We have determined that a simple linear model will explain the near threshold behavior of laser operating under a forced polarization state. We recognize the output of a laser diode need not be either TE or TM, but an elliptical mode determined by both components.

For lasers unable to operate in an elliptical mode due to widely spaced gain curves, the laser diode exhibits TE-TM switching. We also note a region of ASE resulting from competition between stability and sufficient gain that can be extended, or shortened, by careful tailoring of the gain curves.

By modeling and measuring external cavity lasers operating with different polarization states, we better understand the nature of TE and TM modes. Correspondingly, we can utilize our knowledge toward the better design of optical switches and TM mode lasers.

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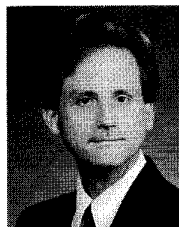
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