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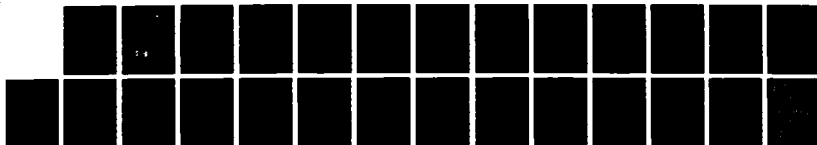RESEARCH LAB   E M GARMIRE 10 APR 88 TR-0086(6925-04)-1

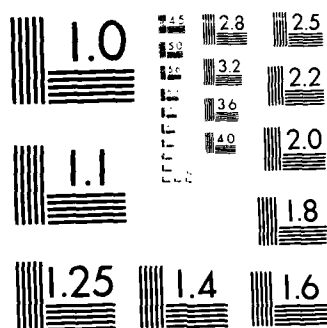SD-TR-88-55 F04701-85-C-0086   F/G 9/3   NL

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Tolerances for Phase Locking of Semiconductor Laser Arrays

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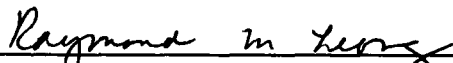SELECTED
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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The fabrication and operating conditions for semiconductor laser arrays to be phase-locked are described. The analysis is based on a linear theory of the locking of coupled oscillators. Results show that the refractive index of adjacent lasers must be the same to ~ 10^{-4}. This puts close tolerances on fabrication if phase-locking is to be maintained. The average aluminum concentration in adjacent stripes must be the same to within ~ 10^{-4}, while the average epilayer thickness must be the same to within 0.2%, or a tolerance of 3 Å on the active layer. Changes in refractive index due to free carrier injection provide an additional tolerance condition, which translates to a requirement that the stripe width and contact resistance be uniform to within a few percent. In addition, because thermal profiles may be detrimental, careful heat-sinking is required. These fabricational tolerances support the fact that high quality epilayers such as grown by moleculer-beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) are usually required for phase-locked laser arrays, and that photoresist processing and bonding must be done carefully.

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FIGURES

I. INTRODUCTION

A. LOCKING CONDITION FOR LASERS

When lasers are locked, their free-running frequencies ω_i are pulled into a common oscillation frequency ω_o. Basov [1] first showed that when two identical, parallel lasers are coupled by transverse diffraction, as shown in Figure 1, the condition for locking to occur is given in terms of the frequency difference between lasers as

$$\frac{|\omega_2 - \omega_1|}{\omega_o} = \frac{2|\omega_i - \omega_o|}{\omega_o} \leq \frac{2\Gamma}{nkL} \; , \tag{1}$$

where Γ is the fraction of light field from one laser which is coupled in a single pass into the adjacent laser, $k = \omega/c$, L is the length of the laser, and n is its refractive index. This equation states that the difference in free-running frequencies which is allowed between the two lasers is twice the allowed deviation from the locked oscillation frequency.

In parallel semiconductor lasers, the coupling occurs not by diffraction but by directional coupling [2]. An approximate expression for the fraction of field coupled when the coupling is weak is $\Gamma = KL$, where K is the coupling coefficient and has units of length^{-1}. Thus, expressed in terms of the coupling coefficient,

$$\frac{|\omega_2 - \omega_1|}{\omega_o} \leq \frac{2K}{nk} \; . \tag{2}$$

This equation can be compared to that for injection-locked oscillators, which was first given by Adler [3], and has been adapted for lasers by Tavis [4]:

$$\frac{|\omega_2 - \omega_1|}{\omega_1} \leq \left[\frac{aL - \ln R}{kL}\right]\left[\frac{E_c}{E_1}\right] \; , \tag{3}$$

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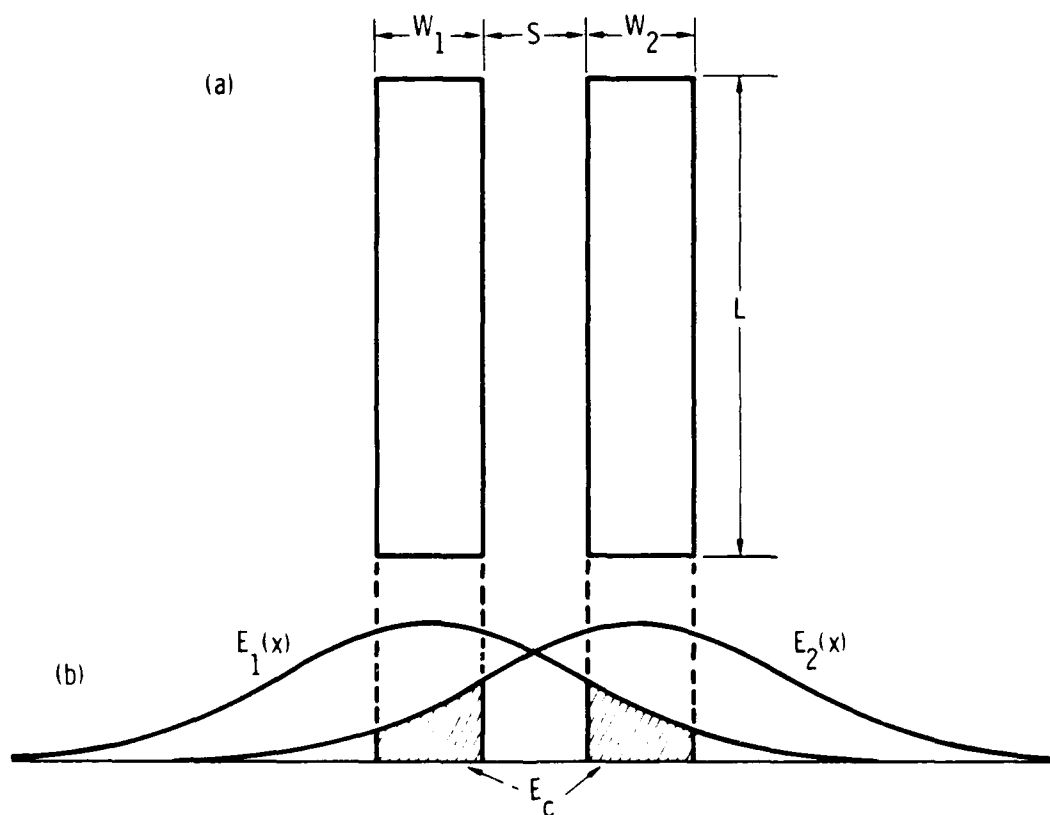
Figure 1. Geometry for Parallel Lasers With Transverse Coupling.
(a) Top view, showing lasers of length L, inner edge
separation S, with widths W_1 and W_2 and free-running
resonant frequencies ω_1 and ω_2, respectively.
(b) Spatial distribution of the fields of each laser,
showing the field overlap within the laser stripe which
causes the coupled field E_c (cross-hatched).

where E_1 is the field in laser 1, and E_c is the field coupled from laser 2 into laser 1, a is the loss per unit length in the laser, and R is the reflectivity of the end facets. Equations (1) and (3) can be related through the fact that $\Gamma = E_c/E_2$ when the fields in both lasers are equal, i.e., $E_2 = E_1$. The difference in these expressions is the factor $2/(aL-\ln R)$, which for GaAs lasers is typically the order of unity. Thus for these lasers, the bandwidth allowed for injection locking is typically comparable to that required for parallel locking of lasers.

When there are N interacting lasers, Eq. (1) is generalized to the following expressions, originally derived by Katz [5]:

$$\left| \sum_{i=1}^{M} E_i^2 \ (\omega_o - \omega_i) \ \omega_o \right| \leq \left(\frac{\Gamma}{nkL} \right) E_{M+1} \ E_M \ , \tag{4}$$

$$M = 1,2 \ldots (N-1)$$

subject to the constraint that the oscillation frequency ω_o is given by

$$\left| \sum_{i=1}^{N} E_i^2 \ (\omega_o - \omega_i)/\omega_o \right| = 0 \ . \tag{5}$$

This corresponds to N equations, each requiring that the appropriate sum of weighted frequency differences be less than the specified amount. Assuming the frequencies deviate randomly, Eq. (4) is most stringent for only two lasers. This is because the condition on the magnitude of the sum of deviations means that, when more lasers are included, their deviations tend to cancel out. Thus, the most stringent condition on locking will be that for two lasers. Thus, in this report, only the locking condition between two lasers will be considered, which, for nonidentical lasers can be written as

$$\frac{|\omega_1 - \omega_2|}{\omega_o} \ , \ \left(\frac{2\Gamma}{nkL} \right)\left(\frac{E_2}{E_1} \right) \ , \tag{6}$$

where fields E_2 and E_1 are inside lasers 2 and 1, respectively.

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B. VARIABLES AFFECTING LOCKING

The variables affecting the locking are those contained in Eq. (6). These are the following:

a. Free-running oscillation frequencies of the lasers, ω_1, ω_2.

b. Fields in each laser, E_1, E_2.

c. Coupling between lasers, Γ.

d. Optical path length of the laser, $nkL = n\omega L/c$.

Since the left-hand side of Eq. (6) is the difference of two large numbers, small changes in either of the resonant frequencies can cause the lasers to be outside the locking range. The free-running laser frequencies are the most sensitive variables affecting locking and will be considered first. Small changes in the other variables will not affect the locking range. Of the other variables, only the fields in each laser can be expected to undergo large changes and therefore affect locking. Large variations in the optical fields may occur, particularly near threshold, so that tolerances which affect the threshold and the corresponding optical fields are important. However, these are already understood in the context of laser theory and will not be discussed here.

C. TOLERANCES ON THE FREE-RUNNING LASER FREQUENCY

An estimate for the required tolerance on the free-running laser frequencies, $\delta\omega$, can be numerically determined by setting $E_2 = E_1$:

$$\frac{|\omega_1 - \omega_2|}{\omega_0} \leq \frac{\delta\omega}{\omega_0} \equiv \frac{2\Gamma}{nkL} = 3.2 \times 10^{-4} \; \Gamma , \tag{7}$$

for $L = 250 \; \mu m$, $k = 2\pi/\lambda$, $\lambda = 0.83 \; \mu m$, and $n = 3.3$. We will show later that typically $\Gamma \sim 0.1$. Because Eq. (7) represents a small frequency deviation, and implies $\Delta\lambda \sim 0.5 \; \text{Å}$, this report will look into the tolerances on laser fabrication and operation to ensure that the free-running laser frequencies remain within this locking range.

D. COMPARISON OF LOCKING CONDITION WITH INTERMODE SPACING

It is important to compare the locking condition with the intermode spacing. The resonant frequency is determined by requiring that the optical phase per pass equal an integer number of π; $nkL = m\pi$. Then $\omega_0 = ck = m\pi c/nL$. It is straightforward to show that the frequency spacing between adjacent modes is

$$\delta\omega_s = \frac{\pi c}{n_e L} \tag{8}$$

where n_e is the effective refractive index for light in a dispersive medium. That is, $n_e = n[1-(\lambda/n)(dn/d\lambda)]$. Thus

$$\frac{\delta\omega_s}{\omega_0} = \frac{\pi}{n_e kL} . \tag{9}$$

This intermode spacing can be compared with the locking condition:

$$\frac{\delta\omega_s}{\omega_0} = \left[\frac{\delta\omega}{\omega_0}\right]\left[\frac{\pi n}{2n_e\Gamma}\right] . \tag{10}$$

If the intermode spacing $\delta\omega_s$ is larger than the locking range $\delta\omega$, as the resonant frequency of one laser is varied continuously with respect to a second laser, the lasers will lose lock before the second laser can jump to the next order mode. If, on the other hand, the locking range is larger than the intermode spacing, lasers with different mode numbers m may be able to lock. The condition that the locking range is larger than the intermode spacing ($\delta\omega > \delta\omega_s$) requires that the fraction of field coupled per pass obeys

$$\Gamma \geq \frac{\pi n}{2n_e} . \tag{11}$$

In semiconductor lasers, $n = 3.3$ and $n_e = 3.6$ [6]. Thus locking of adjacent modes requires $\Gamma \geq 1.4$. However, the physical situation and the analysis of

Basov hold only for $\Gamma < 1$; that is, for relatively weakly coupled lasers. Thus, according to this theory, adjacent modes with different mode numbers are not able to pull into lock together. We therefore assume the same mode number and require that any two modes be within the locking range for phase-locking. This implies severe requirements on fabricational tolerances, which will now be discussed.

II. ANALYSIS

A. TOLERANCES ON REFRACTIVE INDEX

The resonant frequency is determined by the optical path length of the cavity; i.e., $\omega \equiv ck = m\pi c/nL$. For cleaved semiconductor lasers, the facets are atomically flat, so that L can be assumed to be a constant. Variation in resonant frequency comes from variations in the refractive index, and the resonant frequency requirement translates to a requirement on the average refractive index over the path length of the laser. This gives $\delta\omega/\omega = -\delta n/n$. Thus the tolerances on the refractive index are:

$$\frac{\delta n}{n} \leq \frac{2\Gamma}{nkL} \quad \text{or} \quad \delta n \leq \frac{2\Gamma}{kL} . \tag{12}$$

Numerically, locking requires

$$\delta n/n \sim 3.2 \times 10^{-4}\Gamma, \quad \text{or} \quad \delta n < 10^{-3}\Gamma .$$

This is a very high degree of tolerance, and requires that laser arrays must be fabricated very carefully. Numerical evaluation of the criteria for fabrication and operation to ensure operation within this regime follows.

This analysis has assumed that adjacent modes have the same mode number m. It is possible to consider a case in which adjacent modes have different values of m and different values of the refractive index, but oscillate at the same frequency, so that they may lock. If looked at in this way, there are discrete regimes which may in principle lock to adjacent lasers, but other regimes will not lock. This is shown schematically in Figure 2, which shows the regions of varying refractive index and the corresponding mode number which will lock to a given frequency and mode number for $\Gamma = 0.5$. Since the existence of discrete regions of refractive index variation which will allow locking is not particularly useful, this case will not be considered further. We will tacitly assume from here on that all modes have the same mode number m.
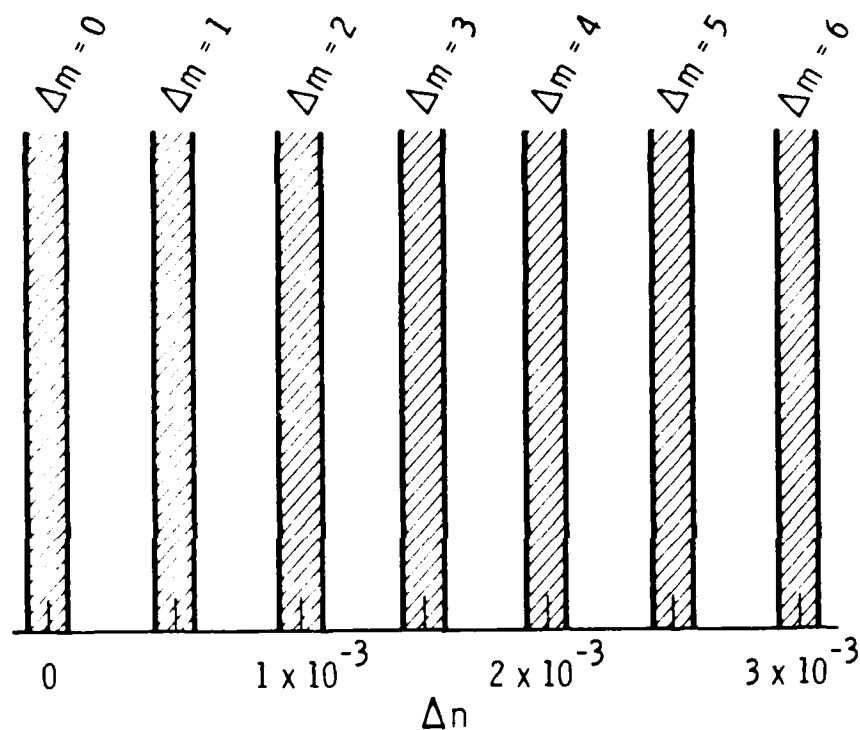
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Figure 2. Schematic Indicating Regions of Refractive Index
Difference Between Adjacent Lasers That Will Be Within
the Locking Regime. Also indicated is the difference
in the number of wavelengths that fit in adjacent lasers.

The refractive index depends on:

a. The bulk properties of the GaAlAs medium,

b. The waveguiding properties of the double heterostructure,

c. The electrical properties of the device and

d. The gain properties of the laser medium.

We will find that of all these possible effects, the changes in refractive index due to the AlAs concentration and the thickness of the active layer provide the most serious tolerance which must be maintained to ensure phase locking.

B. TOLERANCE ON ALUMINUM CONCENTRATION

In the III-V alloy semiconductors, refractive index variations will be introduced if there are variations in composition. The $Ga_{1-x}Al_xAs$ lasers typically have x ~ 6% in the active region, to help maintain lattice match. Furthermore, in the cladding layers x ~ 40%. The refractive index is related to x through [6]:

$$n(x) - n(GaAs) = 0.65x .$$ (13)

Thus the absolute tolerance on x is related to variations in the refractive index through

$$\delta x = \delta n \cdot 0.65 .$$

The locking condition can be translated to a requirement on aluminum concentration uniformity through Eq. (12):

$$\delta x < \frac{2\Gamma}{0.65 \; kL} \sim 1.6 \times 10^{-3} \Gamma .$$ (14)

This result indicates that when $\Gamma = 0.1$, the average AlAs concentration in adjacent 250-μm-long stripes must be the same to within 1.6×10^{-4} in order for locking to be observed. This high degree of tolerance often requires the

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new technologies of metal-organic chemical vapor deposition (MOCVD) or
molecular-beam epitaxy (MBE).

C.   REQUIREMENTS ON TEMPERATURE UNIFORMITY

Another phenomenon which can cause loss of mode locking due to changes in
the "bulk" optical properties of the laser is nonuniform heating of the array
due to thermal nonuniformities in the heat sink. We have shown in a recent
paper that there is a requirement that adjacent elements in the array operate
at the same temperature to less than a degree [7]. This requirement comes
about from the fact that the resonant laser frequency is a function of tem-
perature; typically, about 3 Å/°C [6]. Writing the free-running wavelength as
a linear function of temperature:

$$\lambda = \lambda_o + aT , \tag{15}$$

where $a = 3$ Å °C, and since

$$|\delta\omega/\omega| = |\delta\lambda/\lambda| = |(a/\lambda)\delta T| ,$$

the required tolerance for locking becomes

$$\delta T \cdot \frac{2\lambda\Gamma}{a n k L} . \tag{16}$$

This gives a tolerance δT 0.09°C for $\Gamma = 0.1$.

We have made a study of the thermal distribution in arrays placed on
copper heat sinks and found that locking will be lost at the highest operating
powers due to thermal gradients. If diamond heat sinks are used, however, we
have found that locking is always maintained [7]. Another method for reducing
the thermal gradients is to use a heat-spreading layer under the laser which
has the same physical width as the laser array [8].

D.   TOLERANCE DEPENDENCE ON WAVEGUIDE PROPERTIES

Since the laser light is confined within a waveguide, the refractive
index to be considered is the effective refractive index of the guided mode,

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which depends on the thickness and width of the waveguide. The effective
refractive index is defined as the ratio of the guided-mode propagation
constant to the free-space propagation constant:

$$n_{eff} \equiv \beta / k \ .$$

Although the propagation constant β depends both on the thickness of the epi-
taxial layer and on the width of the stripe, using the Effective Index Method
described by Kogelnik [9], these two dependences can be calculated indepen-
dently. We calculate first the dependence on stripe width.

For analyzing the dependence of the effective index on stripe width, W,
we use the model of a graded index waveguide, with the $\cosh^{-2}(2x/W)$ refractive
index profile. For the lowest order mode, the effective index is given by
[Ref. 9, page 56]

$$n_{eff}^2 = n_s^2 + \frac{(2s)^2}{k^2 W^2} , \tag{17}$$

where s is given by

$$2s = (1 + V^2)^{1/2} - 1 \ .$$

The well-known V parameter is given by

$$V = kW \ (2n_s \Delta n)^{1/2} , \tag{18}$$

where Δn is the peak index increase in the center of the waveguide stripe and
n_s is the refractive index of the substrate. We calculate the dependence of
the effective index on the width of the waveguide, W. The derivative of n_{eff}
with respect to W is given by

$$\frac{\partial n_{eff}}{\partial W} = \frac{[(1 + V^2)^{1/2} - 1]^2}{(1 + V^2)^{1/2}} \left[\frac{1}{nk^2 W^3}\right] . \tag{19}$$

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From this expression we obtain the tolerance requirements for the width of the guided layer:

$$\frac{\delta W}{W} = \left[\frac{\delta n}{n}\right]\left[nkW\right]^2 \frac{(1 + V^2)^{1/2}}{\left[(1 + V^2)^{1/2} - 1\right]^2} \ . \tag{20}$$

This expression says that the tolerance on waveguide width may be larger than that for the refractive index by the factor $[nkW]^2$ as well as by the factor

$$G(V) = \frac{(1 + V^2)^{1/2}}{\left[(1 + V^2)^{1/2} - 1\right]^2} \ . \tag{21}$$

This expression will be evaluated numerically below and it will be found that typically this G is on the order of 2.

To evaluate the dependence of the effective index on epilayer thickness, it is necessary to consider step-index waveguides. However, for step-index guides, the effective index can be calculated only approximately, as follows. In order to determine the dependence of the guided mode propagation constant on waveguide dimensions, it is most convenient to relate β to p, the exponential decay constant outside the waveguide. This relation comes through

$$\beta^2 = p^2 + n_s^2 k^2 \ . \tag{22}$$

Since the guided wave is near cutoff, it is possible to use an approximate expression derived by Marcuse [10] in order to obtain an analytic estimation of the waveguide tolerances. That approximate expression is

$$p = \frac{(1 + V^2)^{1/2} - 1}{D} \ , \tag{23}$$

where $V = kD(2n_s \Delta n)^{1/2}$ and D is the thickness of the waveguide.

The condition for locking requires calculating the quantity $\delta n_{eff}/n_{eff}$, which is given by

$$\frac{\delta n_{eff}}{n_{eff}} = \frac{\delta \beta}{\beta} = \frac{p \delta p}{\beta^2} = \frac{p \delta p}{(nk)^2} \ , \tag{24}$$

where $n_{eff} \approx n$. However, the approximate solution given by Eq. (23) allows a calculation of δp in terms of the waveguide thickness D:

$$\delta p = \left[\frac{V^2}{D(1 + V^2)^{1/2}} - \frac{(1 + V^2)^{1/2} - 1}{D} \right] \left[\frac{\delta D}{D} \right] \ . \tag{25}$$

Combining Eqs. (23) - (25) gives the relation between the waveguide thickness changes and the refractive index tolerance:

$$\frac{\delta D}{D} = n^2 k^2 D^2 \, G(V) \left[\frac{\delta n}{n} \right] \ , \tag{26}$$

where $G(V)$ is given by Eq. (21). In other words, the approximate expression for the step index guide is the same as the exact expression for the $\cosh^{-2}$ index profile, where W is replaced by D. In both cases the requirement for locking is [from Eq. (12)]:

$$\frac{\delta D}{D} = \frac{2 n k D^2}{L} \, G(V) \Gamma \ . \tag{27}$$

This equation represents the tolerance requirements for either a graded index guide, or a step index guide close to waveguide cutoff. It therefore represents the tolerances on the epitaxial waveguide thickness and also on the stripe width. We will find that the closest tolerance appears to be on the epilayer thickness.

E. TOLERANCE ON EPILAYER THICKNESS

In order to numerically analyze Eq. (27), it is necessary to determine the V parameter for the double heterostructure laser waveguide and therefore to calculate G. The refractive discontinuity between the waveguide and

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cladding is given by the difference in aluminum arsenide concentrations, which is typically $\Delta x = 0.3$. Since the refractive index discontinuity is $\Delta n = -0.65\ \Delta x$, it has a numerical value of the order of $\Delta n = 0.2$. Typical thicknesses for the active region are $D = 0.2\ \mu m$. These values give $V = 1.74$, and Eq. (21) gives $G = 2.0$. Plugging this into Eq. (26) gives

$$\delta D/D = 50(\delta n/n) \ .$$

Notice that the tolerance on the epitaxial layer thickness is fifty times less stringent than on the refractive index. Since $\delta n/n < 3.2 \times 10^{-4}\Gamma$, thickness variations of the order of $\delta D/D < 0.016\Gamma$ will be tolerated. The necessity to control average epilayer thickness to $\sim 0.2\%$ (assuming $\Gamma = 0.1$) is one reason why MOCVD or MBE is usually used in the fabrication of locked laser arrays. This is a requirement of $3\ \text{Å}$ on the average flatness of the $2000\ \text{Å}$ layers.

F. TOLERANCE ON STRIPE WIDTH

As far as the stripe width is concerned, estimates of the tolerances can be made without detailed knowledge of the transverse waveguide properties. This is because the requirement of single transverse mode operation for each stripe means that $0 < V < \pi/2$. $G(V)$ has its minimum value, and the tolerance is therefore the most severe for the largest value of V. Therefore, the tolerance may be calculated using $G(\pi/2)$. Inserting numbers into Eq. (21), $G = 2.5$. Using Eq. (27) and interchanging D for W, the stripe width, we obtain the tolerance on stripe width as

$$\frac{\delta W}{W} = \frac{2nkW^2}{L} 2.5\Gamma \ . \tag{28}$$

For $W = 3\ \mu m$, $\Gamma = 0.1$, $\delta W/W = 0.5$. This means that changes in the average stripe width of 50% will not affect the locking. The stripe width is clearly not an important tolerance which must be maintained, insofar as the optical properties are concerned.

G. MODEL FOR TRANSVERSE COUPLING OF WAVEGUIDES

The coupling coefficient can be approximated by assuming that the transverse mode profiles are effectively those of a graded index guide of the form

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$sech^2$ $(2x/W)$. This analysis was performed and it was found that, to a good approximation, two waveguides, operating at cutoff for the next-to-lowest order mode, have a coupling coefficient given by

$$K = (8/nk_oW^22)_e\ -2d/W \tag{29}$$

where d is the center-to-center spacing between the waveguides. The maximum coupling occurs when $W = d$, which means

$$K_{max} = 0.172\lambda/nd^2 \tag{30}$$

When $\lambda = 0.85\ \mu m$, $d = 10\ \mu m$, $n = 3.3$ in a laser of length 250 μm, the maximum fraction of coupled field is

$$\Gamma_{max} = K_{max}L = 10\% \ .$$

This is the value we have used in estimating the tolerances.

The results of the analysis on the tolerance conditions for locking show that the average thickness of the epitaxial layer and its average refractive index are the two most crucial parameters which must be controlled in laser fabrication. This means that the starting material is critically important to the success of locked laser arrays.

h.   TOLERANCE REQUIREMENTS ON ELECTRICAL PROPERTIES

In addition to epitaxial growth tolerances, the refractive index is affected by changes in the density of carriers in the active region. This means that if the current changes, the refractive index will change. Numerical analysis shows that this effect puts a condition on the stripe width. The analysis follows.

The change in refractive index due to free carriers is given by [11]

$$|dn| = [\frac{N\lambda^2}{\varepsilon_o n8\pi^2}][\frac{e^2}{m^*c^2}]\ , \tag{31}$$

where N is the carrier density, e is the electron charge, and m^* is the effective mass of the carriers. At a wavelength of 0.83 μm in GaAs this can be numerically evaluated to $|dn/n| = 3 \times 10^{-4} N$, where N is the carrier density in units of 10^{18}/cc.

The carrier density is related to the current and geometry through

$$N = \frac{I\tau}{WLDe} ,$$ (32)

where I is the total current, τ is the carrrier lifetime ($\sim$ 3 nsec), and WLD is the volume of the active region.

Equations (31) and (32) can be combined to express a requirement on the difference in currents between adjacent lasers to remain locked:

$$I_2 - I_1 \leq \left[\frac{dn}{n}\right]_m [WLD] \left[\frac{\varepsilon_o 8\pi^2 n^2 m^* c^2}{\lambda^2 \tau e}\right] .$$ (33)

where $[dn/n]_m$ is the maximum index difference which will be locked. For the dimensions assumed above (L = 250 μm, W = 3.4 μm, D = 0.2 μm), $I_2 - I_1 \leq$ 30 $[dn/n]_m$. The locking requirement $dn/n = 3 \times 10^{-5}$ for $\Gamma = 0.1$ puts limits on the allowed current difference between adjacent lasers of $\sim$ 1 mA. The operating current for these lasers is on the order of 100 mA, so the tolerance on the current uniformity is 1%.

The tolerance condition on current relates to fabricational tolerances, because changes in stripe width from one laser to the next, as well as changes in resistivity, will cause the current to change. When the current density at the contact is uniform, the total current through any one laser is proportional to its stripe width. Thus the tolerance of 1% on current translates to a tolerance of 1% on the average stripe width. Furthermore, for a given voltage drop, the current is inversely proportional to the resistivity in the ohmic contact. Thus the tolerance of 1% in current translates to a tolerance of 1% on the resistivity above each of the lasers.

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The result of this analysis is that the free carrier contribution to the change in refractive index causes a tolerance condition on the current to each laser, thereby specifying a tolerance on stripe width and resistivity for each laser. These tolerances are the order of 1%, which can be achieved with careful fabrication.

III. CONCLUSIONS

In this report we have analyzed the tolerances on fabrication which arise when the locking condition is imposed on arrays of semiconductor lasers. We have found that the epilayer fabrication must be of high quality to maintain the required tolerances. We also found that current tolerances on the order of 1% means that photoresist processing and ohmic contact fabrication must be kept under careful control.

It should be emphasized that the tolerances calculated here are for the average of each of the quantities averaged over the laser. Clearly, variations along the length of the laser will be much less critical to locking than variations across the laser array. This is important to keep in mind during fabrication.

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