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Current wavelength dependence of mode emission in DH-GaAs lasers

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Abstract The threshold current dependence on mode energy is calculated through a self-consistent calculation method that takes into account temperature, carrier out-diffusion and optical losses. We define a new parameter r which is energy dependent and represents the fraction of light propagating into the gain region, relative to the direction parallel to the junction plane. In analysing the threshold current density (Jth) dependence on active layer width we obtain an increase in Jth for active layers thinner than 0.07pm and observe that Jth becomes less sensitive to mode energy. This last result indicates that multimode semiconductor lasers with thin active regions are more appropriate for optical communication applications, since the very small difference in threshold current for different longitudinal modes provides a modulation signal with reduced noise.

1. Introduction

Although the optical guiding mechanisms observed in GaAs/GaAlAs stripe geometry double heterostructure (DH) lasers have been extensively studied in past years[1-5], not all assumptions implicit in mathematical models have been discussed. On mathematically describing the threshold behavior of DH lasers, several processes occurring in the laser devices must be considered: current spread, junction temperature increase, carrier out-diffusion, optical losses, etc. In this work we are looking for a precise dependence of gain and threshold current on mode wavelength and, in doing so, the laser is dinamically described by a model where the optical waveguide is modeled by a two dimensional complex dieletric constant. We assume that the real and imaginary parts of dieletric constant are interdependent

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and its spatial variation, in the active and neighbouring layers, is considered. The calculations include the junction temperature dependence on current and a well defined dependence of refractive index on carrier density. The calculations also include the dependence of gain and refractive index on mode energy. Some of these aspects as current spread and the effect of local carrier concentration on gain have been discussed in detail in previous analyses[6-7] even though, except as discussed by Paoli[8], the junction temperature increase was not included. In this work we propose a complete model which involves all of these aspects in a self-consistent way, assuming also the explicit influence of the longitudinal mode energies. A mode confinement factor related to the direction parallel to the junction plane is dynamically determined and its influence on laser behavior is discussed. The threshold conditions are analysed with spectral mode discrimination for different active region widths and the results are compared with experimental data available in literature.

2. Initial considerations

The present calculation is carried out for a GaAs planar stripe double heterostructure laser operating continuously at room temperature. The method proposed takes into account the junction current density dependence on junction temperature. When a laser is in operation most of the input power is dissipated as heat, causing an increase in the active region temperature, which in turn, induces changes in the junction current density. This dependence is evaluated by an iterative self-consistent calculation which provides temperature and current profiles for the direction parallel to the junction plane. The carrier distribution profile is then calculated including carrier out-diffusion. These calculations have been analysed in detail in a previous work[g].

The resulting carrier and temperature profiles along the junction plane induce two competing and opposite effects on the real part of the refractive index: a) an inverted refractive index profile, or anti-guiding profile, due to injected carriers, that tends to defocus the laser mode, and, b) a positive increment to the refractive index profile due to temperature, that tends to focus the mode. The injected carrier provides also the main disturbance on the imaginary part of the refractive index. Unfortunately, as far as we know, the exact dependence of the absorption coefficient on temperature is not available in the literature and so, will not be included. The dependence of the complex refractive index of the active layer on carrier concentration was exactly evaluated by Mendoza-Alvarez et al.[10] for different photon energies. From Mendoza-Alvarez data we observe that the strong dependence of the absorption losses on mode energy causes the main influence on the calculations when we are looking for the spectral response of the laser diode.

3. Waveguide model

In order to find the solutions for the eletromagnetic modes propagating along the waveguide we look for solutions of the wave equation[11] :

$$\Delta^2\psi(x,y,z) + \bar{N}^2(x,y)k^2\psi(x,y,z) = 0 \tag{1}$$

Here $\psi(x,y,z)$ represents the eletromagnetic field, $k = 2\Pi/\lambda$ (λ is the vacuum wavelength of the field) and $\bar{N}(x,y)$ is the complex refractive index that must include carrier and temperature effects. (See figure 1 for coordinate system.)

Bars over letters indicate complex variables and N = N $+\, iK$, where the extinction coeficient K is related to the absorption coefficient a by:

$$K = \alpha\lambda/4\Pi \tag{2}$$

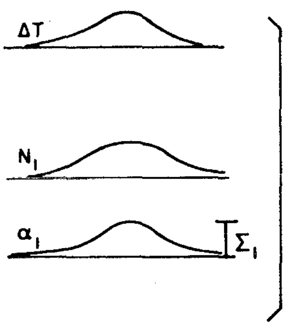
If we assume that the perturbation on the refractive index may be represented by a smoothly varying symmetric function:

$$\Delta\bar{N}(x,y) = \bar{\delta}\mathrm{sech}^2(y/y') \tag{3}$$

the refractive index variation around its unperturbed value will be given by:

$$\bar{N}(x,y) = \begin{cases} \bar{N}_0\{1 - 2(\bar{\delta}_0/\bar{N}_0)[1 - \mathrm{sech}^2(y/y')]\}^{1/2} & |x| <= d/2 \\ \bar{N}_1\{1 - 2(\bar{\delta}_1(x)/\bar{N}_1)[1 - \mathrm{sech}^2(y/y')]\}^{1/2} & |x| > d/2 \end{cases} \tag{4}$$

where: $\bar{N}_1$ and $\bar{N}_0$ are the maximum values of the refractive index outside and inside the active region (approximation already used by many authors[12,14]).



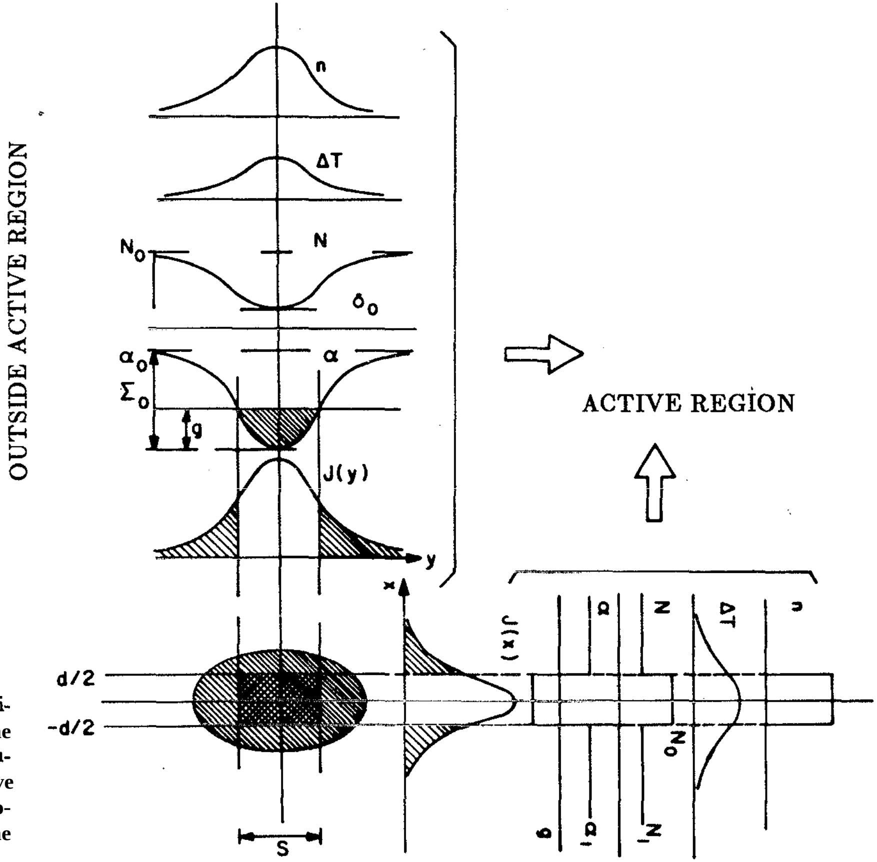


Fig. 1 - Definition of the Cartesian coordinate system relative to the DH lasers and the schematic representation of spatial distribution of temperature variation ΔT, refractive index N, carrier density n and absorption coefficient a. S is the stripe width, and d is the active region width.

y' measures the width of the perturbation, $\bar{\delta}_0$ and $\bar{\delta}_1$(x) are complex variables that represent the maximum value of the refractive index perturbation inside (do) and outside $(\bar{\delta}_1(x))$ the active region. $\bar{\delta}_0$ depends on temperature and carrier concentration and $\bar{\delta}_1(x)$ depends on temperature gradient in the x direction.

We assume that:

$$\bar{\delta}_1(x) = \bar{\delta}_1 e^{-b(x-d/2)} \quad |x| > d/2$$

$$\bar{\delta}_1(x) = \bar{\delta}_1 e^{+b(x-d/2)} \quad |x| < d/2 \tag{5}$$

where the parameter b is related to the temperature gradient due to thermal diffusion in the x direction.

Now we may look for solutions of equation (1) using the method of separation of variables:

$$\psi(x,y,z) = X(x)Y(y)Z(z) \tag{6}$$

The solutions for the fundamental transverse mode along the x and y directions are[12] :

$$Z(z) = Z_0 e^{ik\bar{\gamma}z} \tag{7}$$

$$X(x) = \begin{cases} X_0 e^{-\bar{p}x} & |x| > d/2 \\ A\cos(\bar{q}x + \theta) & |x| < d/2) \end{cases} \tag{8}$$

$$Y(y) = Y_0\{\cosh(y/y')\}^{\bar{\mu}} \tag{9}$$

q and $\bar{\gamma}$ are propagation constants in the x and y directions; A, X_0, Y_0 and Z_0 are normalization constants; $\bar{p}$ measures the optical field penetration through the neighbouring layers; $\bar{\mu}$ defines the field configuration and satisfies the conditions:

$$\bar{\mu}(\bar{\mu} - 1) = 2\bar{N}_0 k^2 y'^2 \bar{\delta} N_{\text{eff}} \tag{10a}$$

$$\text{Real}(\bar{\mu}) < 0 \quad , \quad \text{Im}(\bar{\mu}) > 0 \tag{10b}$$

Equation (10a) allow us to say that the propagating mode along the active region will be guided by an effective refractive index $\bar{\delta}N_{\text{eff}}$ that takes into account the perturbations occured in the active and neighbouring regions. Equation (10b) ensures solution convergency when y$- > \infty$. From the calculations we obtain:

$$\bar{\delta}N_{\text{eff}} = \bar{\delta}_0 + 2\bar{N}_1\bar{\delta}_1(1 - \Gamma)/\bar{N}_0(1 + h) \tag{11}$$

Where:

$$h = b/2\text{Real}(\bar{p})$$

h represents the relation of the heat diffusion (b) and **mode** penetration, **Real($\bar{p}$), measured in** the active region neighbouring **layers**.Γ is the well known confinement factor[8].

The real and imaginary parts of $\bar{\delta}N_{\text{eff}}$ may be written in a more convenient **way as:**

$$\text{Real}(\bar{\delta}N_{\text{eff}}) = \delta N fc\Gamma + C\Gamma\Delta T + C'((1-\Gamma)/(1+h)\Delta T \quad (12)$$

$$\text{Im}(\bar{\delta}N_{\text{eff}}) = \Gamma\Delta K_n \quad (13)$$

where: δNfc is the perturbation in **the** refractive index due to free carrier injection;

AT is the temperature increase;

C and C'are **thermal** constants found in the **literature**[13]: $C = 5.7 \times 10^{-4}$ K^{-1} for **GaAs** and $C' = 5.0 \times 10^{-4}$ K^{-1} for **GaAlAs.**

In equation 12 the second term represents the refractive index perturbation due **to** temperature effect occurring in the active region and the **last** term represents the perturbation occurring outside the active region. ΔKn (eq. 13) is the perturbation **in** the imaginary part of refractive index (absorption coefficient), due to free carrier concentration.

The complex variable $\bar{\mu}$ **(which** defines the field configuration) is calculated and we obtain:

$$\text{Real}(\bar{\mu}) = [1/2 + (1/4 + A)^2 + B^2]^{1/4} \cos\phi/2 \quad (14)$$

$$\text{Im}(\bar{\mu}) = [(1/4 + A)^2 + B^2]^{1/4} \text{sen}\phi/2 \quad (15)$$

and

$$A = 2k^2 y_0'^2 N_0 \text{Real}(\bar{\delta}N_{\text{eff}}) \quad (16)$$

$$B = 2k^2 y_0'^2 N_0 \text{Im}(\bar{\delta}N_{\text{eff}}) \quad (17)$$

$$\phi = \arctan(B/(1/4 + A)) \quad (18)$$

With the above equations the eletromagnetic field configuration is ccmpletely determined taking into account **temperatue**, carrier injection and photon energy dependence, due to the dependence of the complex refractive index on these parameters.

4. Mode Gain

The effective mode gain may be calculated by[11] :

$$G = \frac{\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy |X^2||Y^2| \alpha(x,y)}{\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy |X|^2 |Y|^2} \tag{19}$$

where $\alpha(x, y)$ represents tbe absorption or gain coefficient along the transversal directions to the laser waveguide.

Following the functional form used to describe the complex refractive index perturbation we assume that:

$$\alpha(x,y) = \begin{cases} \alpha_0 - \Sigma_0 \operatorname{sech}^2(y/y') + \alpha_{fc} \operatorname{sech}^2(y/y'|) & |x| <= d/2 \\ \alpha_{fc}^1 + \Sigma_1 \operatorname{sech}^2(y/y') & |x| > d/2 \end{cases} \tag{20}$$

and, a illustrated in Fig. 1:

α_0 is the material absorption coefficient that depends on degree of doping, temperature and photon energy;

α_{fc} and α_{fc}^1 are the free carrier absorption losses;

Σ_0 and Σ_1 are the maximum pertubations in the absorption coefficient due to free carrier absorption.

Using equations (8), (9) and (20) we may obtain from equation (19):

$$G = \Gamma\alpha_0 - \Gamma(\Sigma_0 - \alpha_{fc})\tau - \tau(1-\Gamma)\alpha_{fc}^1 + (1-\Gamma)\tau\Sigma_1 \tag{21}$$

where

$$r = \frac{\int_0^{\infty} \operatorname{sech}^{2(1-a)}(y/y')dy}{\int_0^{\infty} \operatorname{sech}^{-2a}(y/y')dy} - \frac{-2.\text{Real}(\bar{\mu})}{1 - 2.\text{Real}(\bar{\mu})} \tag{22}$$

and

$$a = \text{Real}(\bar{\mu})$$

Frateschi and Castro[14] developed a sofisticated model to calculate threshold current including guiding mechanism. They compared their results with ours, obtained with'this approxirnative model, and no significant divergence was found.

As $\Sigma_0 = \alpha_0 + g$, the threshold conditions obtained when the gain coefficient equals the total losses, may be written **as:**

$$g(h\nu) = 1/(\Gamma\tau)[\Gamma(1-\tau)\alpha_0+(1-\Gamma)\tau\Sigma_1+\Gamma\tau\alpha_{fc}+(1-\Gamma)\tau\alpha^1_{fc}+(1/L)\ln(1/R)] \quad (23)$$

In this equation the **first and** second terms represent the lateral absorption of **modal** light inside ($\Gamma(1-\tau)\alpha_0$) and outside ($(1-\Gamma)\tau\Sigma_1$) the **laser** active region. This **last** term takes into account the incremental heating effect due to the absorption coefficient of the neighbouring layers. Its infuence can be considered negligible for thick active regions ($\Gamma \sim 0.5$), but this may not be the case for very thin active layer ($\Gamma \sim 0.05$), when the laser behavior is strongly dominated by the thermal effects occurring in the vicinity of the active region. Such behavior is confirmed by the **results** presented in ref. 15-16.

The new parameter τ represents the fraction of light propagating in the active region where gain is available or in the incremental absorption region created **by** heating in the neighbouring layers. It is **mostly** dependent on **mode wavelength** and as the confinement factor Γ, τ tends asymptotically to 1 as shown in fig. **2.**

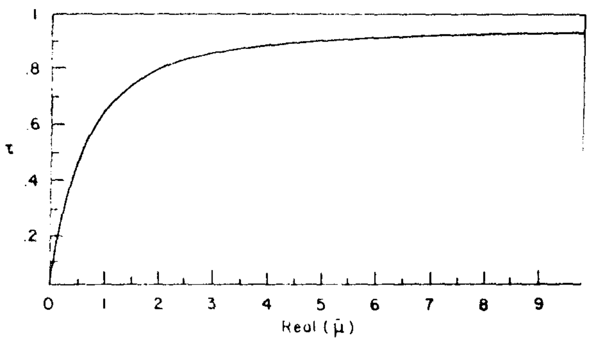


Fig. 2 - Confinement factor τ as a function of Real ($\tilde{\mu}$)

The usual expression for gain coefficient at threshold is:

$$G = 1/\Gamma[\alpha_i + (1/L)\ln(1/R) \quad (24)$$

where:

$$\alpha_i = \Gamma \alpha_{fc} + (1 - \Gamma)\alpha^1_{fc} + \alpha_s + \alpha_c \tag{25}$$

α_s is the scattering loss[17] and α_c is the coupling loss[18].

Comparing this equation with eq.(23), we observe some differences. The first one comes from the two first additional terms of eq (23), corresponding to the lateral absorption of light and which are not considered in eq.(24). The second one, of main importance, brings into consideration the dependence of these terms on photon energy due mainly to the absorption coefficent. This improves the analysis about the threshold current dependence on photon energy. Fig.3 illustrates these differences. The gain coefficient and total losses are computed from eq.(23) and eq.(24). As expected, the gain coefficient is the same for both cases (depends on the material), but the total losses show a quite different behavior depending on the equation used. In this calculation we assume that the carier diffusion length is 3.6μm [9].

5. Results

The results presented in this section were computed, unless specified in the text, for a 13 μm proton bombarded stripe DH laser operating continuously at room temperature. The equations were solved for each longitudinal mode independently. For a given injected current the temperature and carrier density distribution within the active region were computed as discussed in ref. 9. The resulting variation on the refractive index is then calculated as a function of mode energy, temperature and carrier density. Since the conditions for achieving guiding mechanism are satisfied, the lasing mode will be considered as the one that, with increasing current, first satisfies the condition specified, by eq.(23). For all lasers studied, the junction temperature increase (AT ~5K) was not sufficient to induce real refractive index guiding mechanism. So, from now on, we are dealing with DH gain guided lasers. In Fig. 4 we show the distribution of temperature, carrier density, refractive index and absorption coefficient along the junction plane obtained, as discussed above, for 0.2μm active region thickness laser, operating at threshold.

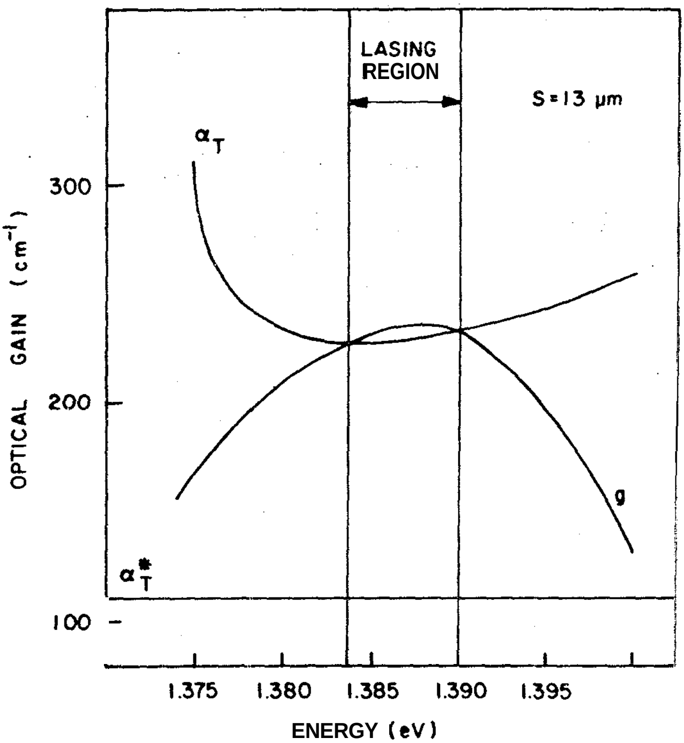


Fig. 3 - Gain coefficient and total losses as computed from eq.(23) (this work) and from the usual expression given by eq.(24). α_T^*.

On analysing the influence of the different parameters on lasing we obtain that the r factor is a weak function of laser physical characteristics S, d and L, as a consequence of its sensitivity to the active region temperature and charge density. It rapidly saturates with current and is strongly dependent on mode energy (Fig. 5). We notice that higher energy modes have higher r factors, even though, higher r values do not mean lower threshold currents due to the fast increase in the absorption losses due to increasing mode energy. In other words, I_{th} is not simply the result of the field concentration in the gain region, but it also depends on the total lateral absorption losses.

Fíg. 6 shows how threshold current density J_{th} depends on mode energy $(h\nu)$ for different values of active region widths. The curves show a tip down U shape whose minimum shifts to higher energies (higher r factors) as the active region

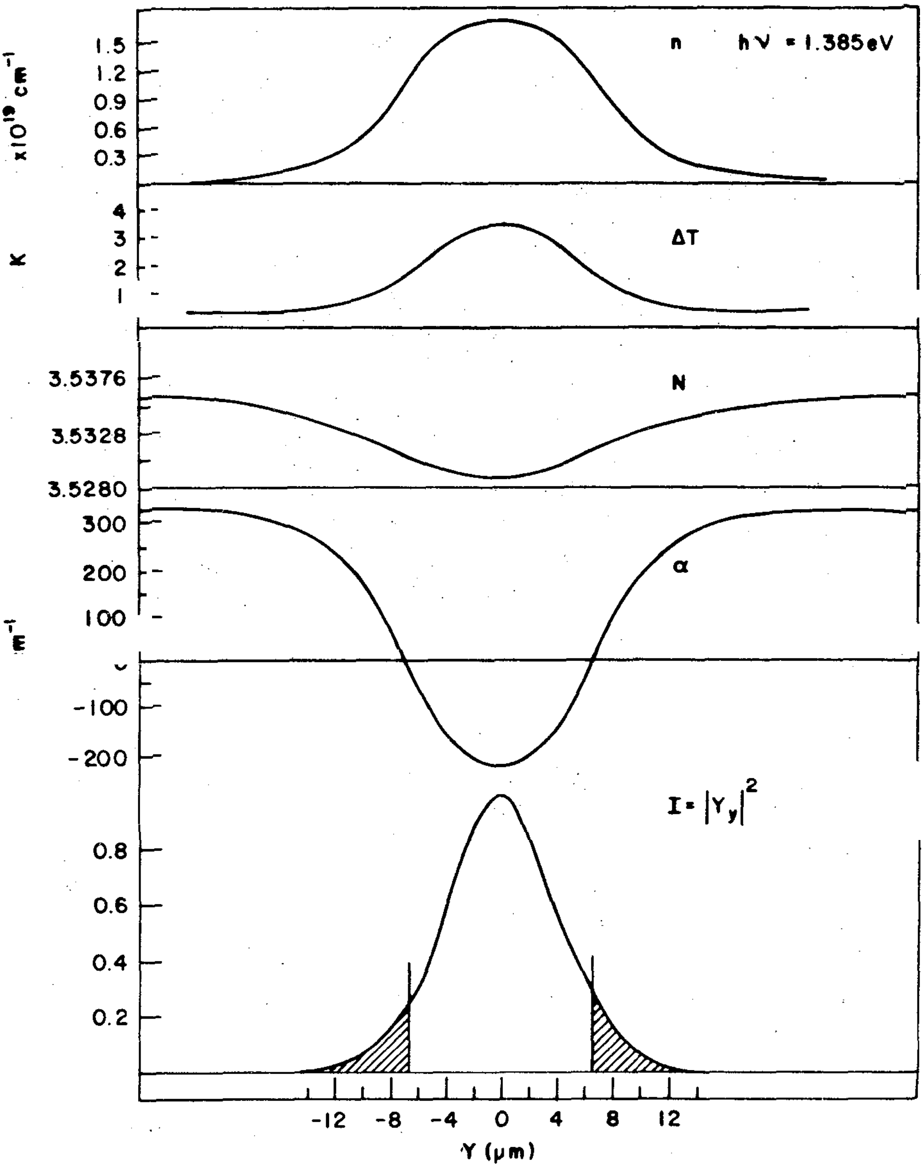


Fig. 4 - Calculated carrier density, temperature variation, refractive index, absorption coefficient and relative mode intensity profiles for the y direction. The laser parameters are: d = 0.2 μm, L = 350 μm and carrier diffusion length = 2.8 μm.

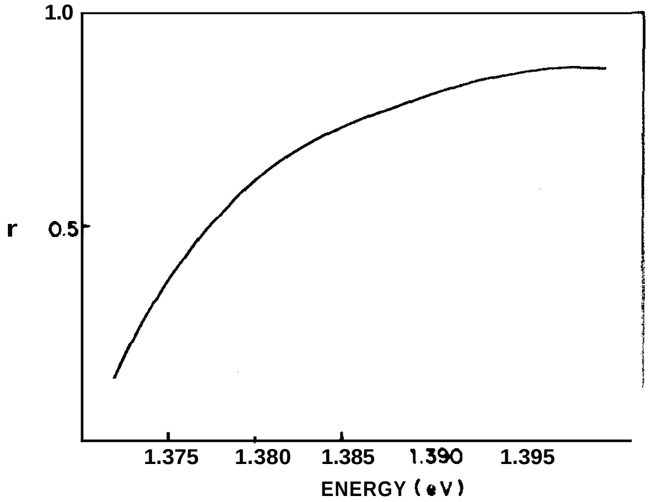


Fig. 5 - The dependence of the *r* factor with mode energy. This curve indicates that higher energy modes are confined to the gain region, while large wavelength modes are "spreaded".

thickness is reduced[19]. We observe that the minimum value of J_{th} decreases with d up to 0.07 μm, bellow which it steadly increases. Decreasing values of d cause the $J_{th} \times h\nu$ curves to become wider and less sensitive to mode energy. This behavior is mainly due to the dependence of gain and absorption losses on mode energy[10]. Due to the increasingly higher carrier density necessary to achieve threshold, for decreasing d, the gain spectra turns to be wider and flatter. Moreover, the difference in the absorption losses of different modes is smaller for higher energies, which is the case of thin d, in contrast to its deep dependence on mode energy in the low energy range (thick d). This "flatness* makes multimode lasers with thin active region more appropriate for optical communication application. Our results are quite similar to the experimental ones obtained by Rossi et all[20]. In their experiment they forced one mode frequency $h\nu$ to oscillate alone in the laser cavity. They selected each energy using a diffraction grating in the back side of the laser to feedback the cavity for that specific photon energy. This is, experimentally, similar to our theoretical procedure to calculate threshold for modes of different energies.

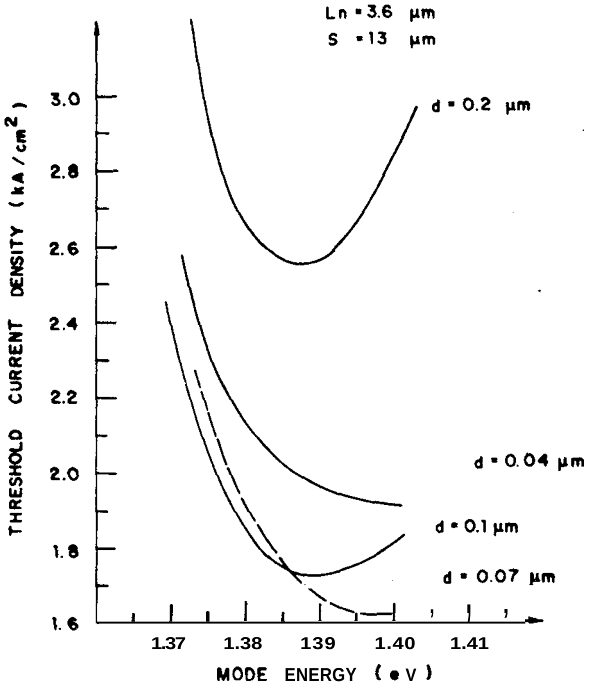


Fig. 6 - Dependence of threshold current density on mode energy for different active layer thicknesses. The minimum threshold current density occurs for increasing mode energy as thickness is reduced.

In Fig.7 the theoretical results are compared with experimental data obtained by Tsang[21] for broad area DH GaAs lasers prepared by MBE. The continuous curve represents our theoreticl results for lasers with Al mole fraction difference between the active and confinement layers x = 0.6. As we can see, the agreement is very good even for active layer widths close to the limit where quantum effects must be considered.

6. Conclusion

In conclusion, we have computed and analysed the DH GaAs lasers taking into account temperature effect, carrier out-diffusion and discriminating longitudinal

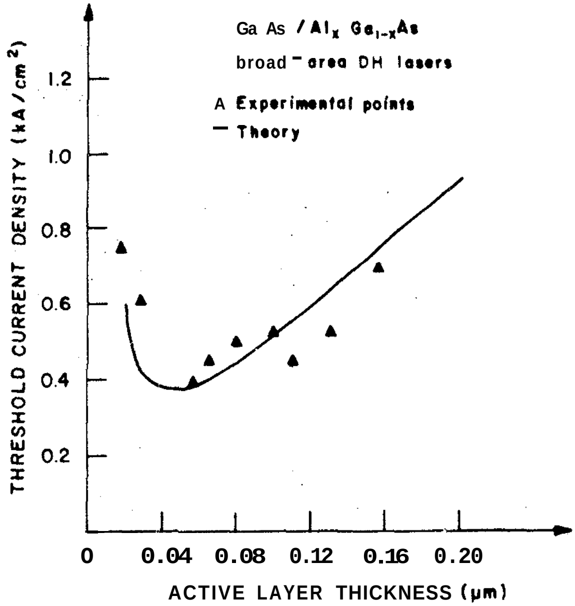


Fig. 7 - The calculated dependenee of J_{th} on active layer thickneas is compared with experimental data of ref. 21 for a broad-area DH laser.

modes. For all lasers analysed we observed only gain guiding mechanism and we define a τ factor that represents the extent of the optical field in the direction parallel to the active region. Our results indicate that threshold condition can be achieved since 50% of the optical mode is confined to the gain region, but this requires higher currents as is the case of tong wavelength modes. Despite the approximations used in our model, the results are in pretty good agreement with experimental results and do not deviate significantly from theoretical resultõ obtained from sofisticated calculations.

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Resumo

Neste trabalho estuda-se a dependência da corrente limiar com a energia do modo através de um cálculo auto-consistente que leva em conta a temperatura, difusão de portadores e perdas óticas. Define-se um novo parâmetro τ que é função da energia do modo e representa a fração da luz que se propaga na região de ganho relativa à direção paralela ao plano da junção. Para lasers com espessuras de camada ativa menores que $0.07\mu m$ observa-se que a corrente limiar é pouco sensível a energia do modo longitudinal. Isto torna estes lasers multimodos indicados para aplicações em sistemas de comunicação pois permitem obter sinais de modulação com baixo nível de ruido.