Linewidth Characteristics of Vertical Cavity Surface Emitting Lasers

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Abstract

Spectral linewidth of vertical cavity surface emitting (VCSE) lasers are investigated theoretically. The impact of various structure parameters on linewidth have been identified and the results are used to optimize laser dimensions to achieve minimum threshold current density for a specific value of linewidth-power product. The study indicates clearly that narrow linewidths can be obtained in these short cavity- lasers when they are fabricated with high facet reflectivities (>0.99) and short active region thickness. Linewidths less than 100KHz are expected at 1mW output power at room temperature in quantum well VCSE lasers realized with 0.999 facet reflectivity.

1- Introduction

Vertical cavity surface emitting (VCSE) lasers have attracted considerable attention recently because of their potential applications in parallel optoelectronic systems, including large capacity lightwave communication [1-3]. The many attractive features of these advanced lasers such as dynamic single-mode operation (due to short cavity), sharpe circular beam with low divergence angles compatible with optical fibers, and the possibility of fabricating densely packed two-dimensional laser arrays are behind the extensive research in this area.

VCSE lasers are expected to be good candidates for light sources in optical communication systems because of their stable longitudinal mode oscillation.

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However, their relatively large spectral linewidths are still a problem to be solved. In fact, a very narrow linewidth less than 1MHz is required for laser diodes in coherent optical communications [4]. Further, the semiconductor laser with narrow linewidth is also very useful for expanding the transmission distance in order to avoid the chromatic dispersion of single-mode fiber in intensity modulation-direct detection systems. To the author knowlege, the narrowest linewidth reported to date for VCSE lasers is 50MHz obtained from a well designed 5.5μm GaAs/AlGaAs diode emitting 1.4mW power at room temperature [5]. Other experimental results have given linewidths as high as 1A* for VCSE lasers fabricating from GaAs or GaInAsP material systems [6, 7]. Recently, Uchida et al. [8] have discussed in a brief letter the possibility of obtaining a very narrow linewidth by fabricating VCSE lasers with high facet reflectivities using multilayer distributed reflectors (DBRs).

The purpose of this paper is to provide a comprehensive study of the spectral linewidth of VCSE lasers. The impact of various structure parameters: cavity length, active region thickness, facet reflectivity, intrinsic loss coefficient, and operating temperature, are evaluated in detail. The results can be used as guidelines to optimize these advanced lasers to achieve very narrow linewidth operation. The study indicates clearly the possibility of realizing a VCSE laser having linewidth-output power product as low as 1MHz. mW at room temperature. Thus, the linewidth of these lasers can be improved to a level which is comparable or better than those of conventional semiconductor lasers.

The analysis in this paper is applied to a GaInAsP/InP VCSE laser with a circular buried heterostructure (CBH) (see Fig. 1a). This structure has been proposed by Uchiyama et al. [9] for the purpose of effectively confining current in the active region and has been adopted by different researchers [1-3, 10]. To reduce threshold current density, high facet reflectivities (more than 0.9) have been applied to this structure using multilayer DBR technique [11]. By performing detailed investigations for this structure we conclude that the low threshold carrier density, associated with the high facet reflectivity and the small active volume, will reduce the impact of Auger process to the carrier recombination rate.

It is worth to mention here that in VCSE lasers carrier injection takes place through the mirror configuration. This may lead to heating problems if the facet reflectivity is associated with relatively large resistance. To reduce this effect, highly doped semiconductor layers are usually used to fabricate the contact layer [10] in
addition to the DBR region [8]. Further, a ring electrode has been introduced in some structures to separate the reflecting mirror from the electrode [1].

II- Model and Basic Equations

The analysis is based on single-mode laser rate equations. The linewidth of the lasing mode is expressed as [12].

\[ \Delta F = (1 + \alpha^2) \frac{R_{sp}}{4\pi P} \]  

(1)

where \( \Delta F \) represents the FWHM of the lineshape which is assumed to be Lorentzian, \( R_{sp} \) is the spontaneous emission rate coupled to the lasing mode, \( P \) is the total photon population in the cavity, and \( \alpha \) is the linewidth enhancement factor due to the amplitude-phase coupling of the mode through the change in carrier density.

The laser is treated as a three-section structure: active region and two passive sections. Each passive section may be modeled as an equivalent external reflector with frequency-independent effective length \( L_{eff} \) and frequency-dependent effective reflectivity \( R \), as shown in Fig. 1b. Both \( L_{eff} \) and \( R \) are related to the parameters of the multilayer DBR and can be estimated using coupled mode theory as discussed in [13]. To make the analysis more general, we assume asymmetric passive sections. The optical confinement factor can be written as

\[ \Gamma = \frac{d}{d_n g_0} \frac{n_g}{(L_1)_{eff} n_g 1 + (L_2)_{eff} n_g 2} \]  

(2)

where \( d \) is the active region thickness, \( n_g \) is the group refractive index, and the subscripts 0, 1, and 2 denote respectively, the active region, front passive section, and rear passive section. Equation 2 assumes unity lateral confinement factor (due to relatively large lateral dimensions used in this paper) and therefore \( \Gamma \) also represents the longitudinal confinement factor. When the difference in refractive index between the active region and the passive sections are neglected, then \( \Gamma \) reduces to the filling factor.

The output power emitted from the front facet is calculated from the photon population using the following expression

\[ P_{out} = \chi h f (v_g)_{eff} \alpha_m P \]  

(3)
where,
\[
\chi = \frac{(1 - R_1) \sqrt{R_2}}{(1 - R_1) \sqrt{R_2} + (1 - R_2) \sqrt{R_1}}
\]
(4a)

\[
\alpha_m = -\frac{1}{2L} \ln (R_1 R_2)
\]
(4b)
\[
(v_g)_{\text{eff}} = c_0 \left\{ (1/L) \left[ d n_{go} + (L_1)_{\text{eff}} n_{g1} + (L_2)_{\text{eff}} n_{g2} \right] \right\}^{-1}
\]
(4c)

In eqns. 3 and 4, \(c_0\) is the speed of light in vacuum, \(h\) is Planck's constant, \(f\) is the lasing frequency, \(\alpha_m\) is the distributed mirror loss, \(L = d + (L_1)_{\text{eff}} + (L_2)_{\text{eff}}\) is the effective cavity length, \(R_1\) and \(R_2\) are the effective front and rear facet reflectivities respectively. Further, \(\chi\) represents the ratio of output power emitted from the front facet to the total output power, and \((v_g)_{\text{eff}}\) denotes the effective group velocity of the laser cavity.

Using eqn. 3 into eqn. 1 and expressing \(R_{SP}\) as \(v_{go} \Gamma g n_{sp}\) [12], \(g\) is the material gain coefficient and \(n_{sp}\) is the spontaneous emission factor, yields the following expression for \(\Delta F\)

\[
\Delta F = \Gamma^2 \Delta F_0
\]
(5a)

with

\[
\Delta F_0 = \frac{\chi \frac{hf}{v_{go}} \alpha_{m0} g n_{sp} (1 + \alpha^2)}{4\pi P_{\text{out}}}
\]
(5b)

and

\[
\alpha_{m0} = -\frac{1}{2d} \ln (R_1 R_2)
\]
(5c)

Here, \(\Delta F_0\) represents the linewidth for a single-section laser having a cavity length \(= d\) [14]. Equation 5a stresses the influence of optical confinement factor on laser linewidth. The benefit of increasing cavity length is quite apparent with improvements of \(\Delta F\) proportional to \(L^{-2}\). These results are in accord with those reported for conventional semiconductor lasers realized with external reflectors or external cavities [15].
The optical gain coefficient is calculated using the empirical relation $g = a(n-n_0)$, where $a$ is the material gain parameter, $n_0$ is the carrier density at transparencey, and $n$ is the carrier density in the active region. Above lasing, the carrier density is clamped at threshold, $n_{th} = \tau_e J_{th}/(q d)$. Here $J_{th}$ is the threshold current density, $q$ is the electronic charge, and $\tau_e$ is the effective carrier lifetime which can be expressed as [12].

$$\frac{1}{\tau_e} = \gamma_e = (\gamma_e)_L + (\gamma_e)_B + (\gamma_e)_A$$  \hspace{1cm} (6)

where $(\gamma_e)_L = A$, $(\gamma_e)_B = B n$, and $(\gamma_e)_A = C n^2$ represent, respectively the linear (nonradiative), bimolecular (radiative) and Auger (nonradiative) carrier recombination coefficients.

III- Illustrative results

The calculations that follow are for a GaInAsP/InP VCSE laser operating at 1.55μm wavelength. The linewidths are estimated at $p_{out} = 1$ mW for two values of the enhancement factor: $\alpha = 5$ and $\alpha = 2.5$. The first value corresponds to active region filled with a bulk semiconductor material while $\alpha = 2.5$ denotes a quantum-well (QW) active region [16-17]. Unless otherwise stated, the values of the parameters used in the analysis is given in Table 1. To simplify the calculations, we have choosen the effective cavity length $L$ and the effective facet reflectivity $R_1 = R_2 = R$ as independent quantities rather than estimating them from the DBR parameters.

A-Influence of Facet Reflectivity

The variations of laser properities with facet reflectivity are depicted in Figs. 2 and 3 assuming $d = 3$ μm, $L = 10$ mm, internal loss coefficient $\alpha_{int} = 40$/cm, and operating temperature $T = 300$K Figure 2a shows plots of the threshold current density $J_{th}$ and threshold carrier density as a function of $R$. The values of $n_{th}$ are estimated by equating the gain coefficient $\Gamma (n_{th} - n_0)$ to total cavity loss $\alpha_{tot} = \alpha_m + \alpha_{int}$. Note that $n_{th}$ decreases linearly with $R$ since the mirror loss $\alpha_m$ can be approximated by $(1-R)L$ when $R > 0.9$. In addition, increasing facet reflectivity will decrease almost linearly the threshold current density. This result indicates a linear dependence of carrier recombination rate on facet reflectivity, and therefore $\gamma_e$ is dominated by the bimolecular component. To explore this result further, we plot in Fig. 2b the
contributions of various recombination terms to the rate of carrier recombination $\gamma_e$. Figure 2b reveals that the impact of Auger process on carrier life time is reduced as $R$ tends to 1 due to the reduction of $n_{th}$ in this region.

The impact of facet reflectivity on spontaneous emission factor $n_{sp}$ and linewidth are shown respectively in Figs. 3a and 3b. $n_{sp}$ can be considered as a measure of population inversion and has been calculated using the relation $n_{sp}=n_{th}/(n_{th}-n_0)$. The spontaneous emission factor increases from 1.5 at $R=0.9$ to 2.5 at $R=0.99$ which can be explained by the reduction in $n_{th}$ associated with increasing $R$. Figure 3b highlights the importance of realizing VCSE lasers with $R > 0.98$ to get a very narrow linewidth. Recently, Wang et al. have fabricated a GaAs/AlGaAs multiple quantum well VCSE laser employing DBRs having high reflectivities of 0.99 centered at 0.85 $\mu$m [16]. It is worth to stress here that eqn. 5 predicts that $\Delta F$ is proportional to $\alpha_{m} = a_{th} \alpha_{m} = [\alpha_0 + (i/\Gamma) (\alpha_m + \alpha_{int})] \alpha_{m}$, which explains the nonlinear dependence of the linewidth on the facet reflectivity as shown in Fig. 3b.

**B- Influence of Cavity Length and Active Region Thickness**

To illustrate the impact of cavity length $L$ on the laser characteristics, we show the results of simulation at $d=3 \mu$m, $\alpha_{int}=20/cm$, and $R_1=R_2=0.99$. Figure 4a displays the variations of $J_{th}$, $\gamma_e$ and $n_{sp}$ with cavity length while Fig. 4b shows the $L$-dependence of $\Delta F$. Similar calculations have been performed in Figs. 5 to examine the effect of the active region thickness when $L=10 \mu$m. Careful investigation of Figs. 4 and 5 highlights the following facts:

(i) The threshold current density increases almost linearly with cavity length at a rate 0.65 KA/cm$^2$ per $\mu$m. This behaviour can be attributed to the increase in the total intrinsic losses outside the active region [=($L-d$) $\alpha_{int}$]. In contrast, there is an optimum active layer thickness which minimizes $J_{th}$, ($d_{opt} = 1.25 \mu$m). Notice that decreasing $d$ will increase the carrier density since $\alpha_{tot}$. $L$ does not change for fixed value of $L$. Recall that $J_{th} = qd \gamma_e n_{th}$, the existing of optimum value of $d$ is apparent. In fact, theoretical investigation carried out by other researchers [1-3] have pointed out that $d_{opt}$ is more critical as $R$ approaches 1.

(ii) The rate of carrier recombination $\gamma_e$ increases linearly with cavity length while it nonlinearly decreases with $d$.

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(iii) Increasing $L$ or decreasing $d$ reduces the spontaneous emission factor $n_{sp}$. This can be explained by noting the increase in $n_{th}$ associated with these variations in cavity dimensions. It is worth to emphasize here that $n_{sp}$ may take values greater than two if the VCSE laser structure is not optimized. This is in contrast to conventional lasers where $n_{sp}$ is usually less than 2 [12].

(iv) Lower values of spectral linewidth can be obtained by fabricating the laser diode with large cavity length and small active region thickness. This statement can be justified by writing eqns. 5a-5c as

$$\Delta F = \frac{\chi \hbar f v_{go}^2 (1 + \alpha^2) n_{sp} [d, L] \cdot \alpha_m [L] \cdot [\alpha_m [L] + \alpha_{int}]}{4\pi P_{out}}$$  \hspace{1cm} (7a)$$

$$\Delta F = \frac{\chi \hbar f v_{go}^2 (1 + \alpha^2) [(d/L)\alpha_o + \alpha_{int} + \alpha_m] \alpha_m}{4\pi P_{out}}$$  \hspace{1cm} (7b)$$

where the dependence of various parameters on $d$ and $L$ is expressed implicitly and $\Gamma$ is replaced by the filling factor $(d/L)$ in eqn. 7b. Both the linewidth and spontaneous emission factor are linearly related to the active region thickness. However increasing the cavity length has a stronger effect on reducing $\Delta f$ as compared with the case when $d$ is reduced. For example, increasing the cavity length from 5$\mu$m to 10$\mu$m reduces the linewidth from 7.9MHz to 2.2MHz when $P_{out}=1$mW, $\alpha=2.5$ and $d=3\mu$m. The linewidth ratio is $2.2/7.9 = 0.278$ which is slightly greater than $(5/10)^2 = 0.25$ due to variation of $n_{sp}$ in addition to $\alpha_m$ with cavity length. In the other hand, reducing the thickness of the active region from 4$\mu$m to 2$\mu$m produces linewidth reduction factor=1.6MHz/2.7MHz=0.6, assuming $L=10\mu$m.

C-Influence of Intrinsic losses

Equation 7a reveals that the spectral linewidth increases linearly with intrinsic loss coefficient which is a well-known result for conventional semiconductor lasers [15]. However, in VCSE lasers, an additional effect comes from the variation of $n_{sp}$ with $\alpha_{int}$ which is more pronounced in these lasers. This is illustrated in Fig. 6 where the $\alpha_{int}$ - dependence of both $n_{sp}$ and $\Delta F$ are shown when $R=0.99$, $L=10\mu$m and $d=3\mu$m. In the ideal case when $\alpha_{int}$ tends to zero, a residual linewidth exists.
which is equal to 1.8MHz (6.3MHz) when $\alpha=2.5$ (5) at $p_{\text{out}}=1\text{mw}$. This residual linewidth is directly proportional to $\alpha_m^2$ (see eqn. 7a) and therefore can be reduced by increasing the cavity length and facet reflectivity.

Simulation results corresponding to variation of $J_{\text{th}}$ and carrier recombination rate $\gamma_e$ with $\alpha_{\text{int}}$ are included in Fig. 7. The contributions of the three recombination processes to $\gamma_e$ are also included here for comparison purpose. Note that all the three components of recombination rate have linear dependence on $\alpha_{\text{int}}$ with the highest contribution comes from the bimolecular process.

**D-Influence of Operating Temperature**

To study the impact of temperature "T" on the lasing characteristics, the model uses temperature dependent material gain parameters [18]: $a(T)=a(300k) [1+a_T(T-300)]$ and $n_o(T)=n_o(300k) [t+n_T(T-300)]$, with $a_T=3.8 \times 10^{-3}$ /K and $n_T=3.9 \times 10^{-3}$ /K. Further, $a(300)$ and $n_o(300)$ denote, respectively, $a$ and $n_o$ evaluated at $T=300K$ as given in Table I. The effect of temperature on intrinsic losses and refractive index are neglected for simplicity. Figure 8a and 8b depict respectively the temperature dependence of both $n_{\text{sp}}$ and $\Delta F$ assuming $L=10\mu\text{m}$, $d=3\mu\text{m}$, $R=0.99$, and $\alpha_{\text{int}}=20/\text{cm}$. Notice that both $n_{\text{sp}}$ and $\Delta F$ peak around 300k. This behaviour can be understood by expressing the spontaneous emission factor as $n_{\text{sp}}=\left[\Gamma a_o+\alpha_m+\alpha_{\text{int}}\right]/\left[a_m+a_{\text{int}}\right]$. Therefore, $n_{\text{sp}}$ is maximum when $(1/a). \partial a/\partial T=-(1/n_o). \partial n_o/\partial T$. This condition occurs at $T=300k$ according to the values of $a_T$ and $n_T$ adopted here. Changing the operating temperature from 300k to 50k will reduce $\Delta F$ to the third. Note that at $T=50k$, the linewidth approaches 0.7MHz when $\alpha=2.5$ and $P_{\text{out}}=1\text{mw}$.

It is worth to discuss here the variation of threshold current and carrier recombination rate with temperature for these lasers. Due to the shortage of information in the literature concerning the temperature dependence of the recombination coefficients A, B and C, they have been taken as constant to get first order estimation of the temperature-induced effects. The calculated $J_{\text{th}}$ and $\gamma_e$ at various temperatures are plotted as solid lines in Figs. 9a and 9b, respectively. However, these results cannot explain the reported experimental data which have shown a stronger temperature dependence of $J_{\text{th}}$ [1-3]. This implies that the variation of the recombination rate coefficients with temperature must be taken into account. The dotted lines in Fig. 9a represents a plot of the relation $J_{\text{th}}=J_0 \exp (T/T_0)$, with $T_0$ is the Characteristic temperature of the GaInAsP/InP VCSE laser. We have used
$T_0=70k$ in accord with the experimental results [1], and $J_0=0.276 \text{ kA/cm}^2$ to match earlier calculations at $T=300k$. The corresponding values of $\gamma_e$ are shown as a dotted line in Fig. 9b which indicates a stronger dependence on temperature compared with earlier calculations.

IV-Discussion

It is clear from the previous section that to achieve narrow linewidth operation at a specific output power, the laser must be designed with large cavity length, narrow active region thickness, high facet reflectivities, low intrinsic losses, and small linewidth enhancement factor. However, changing the structure parameters will introduce variations in the threshold current density. Therefore, when the goal is to realize a laser which gives a specific linewidth-power product, it is better to optimize the diode structure to get minimum $J_{th}$. To illustrate this, we consider a VCSE laser fabricated with $R=0.99$, $\alpha_{int}=10$/cm and $P_{out}=1$mW at $T=300K$.

Figure 10a shows curves corresponding to constant linewidths of 1MHz, 2MHz and 4MHz plotted in the L-d plane. The associated values of threshold current densities are displayed in Fig. 10b. The calculations are performed for $\alpha=2.5$ laser. The optimum structure dimensions, $L_{opt}$ and $d_{opt}$, which yield minimum threshold current density, $(J_{th})_{min}$, are summarized in Table II. Additional data related to $\alpha=5$ structure are also included in this table for comparison purpose. The following remarks are observed under the condition of constant $\Delta F$, $P_{out}$. (i) The active region thickness is almost linearly related to the cavity length. (ii) $L_{opt}$ is an increasing function of the linewidth enhancement factor "$\alpha$" and decreasing function of $\Delta F$. $P_{out}$. (iii) Increasing $\alpha$ or decreasing $\Delta F$. $P_{out}$ results in increasing the level of the minimum threshold current.

In order to get a picture of the ultimate performance that can be achieved in a well-designed VCSE laser, we have used the following parameters in the analysis: $L=10\mu$m, $R=0.999$, $d=0.4\mu$m, and $\alpha_{int}=5$/cm. Increasing the facet reflectivity will effectively reduce the spectral linewidth since $\Delta F$ depends on $\alpha_m^2$. (Increasing $R$ from 0.99 to 0.999 reduces the mirror losses from $10$/cm to $1$/cm assuming $L=10\mu$m). The model predicts $\Delta F=32$ KHz and 116 KHz at $\alpha=2.5$ and 5 respectively when the laser emits 1mW power from one facet at room temperature. These values are less than reported results for conventional semiconductor lasers.
operating without external reflectors [8]. The threshold current is estimated to be 3.5KA/cm² for this VCSE structure.

To achieve CW operation of the VCSE lasers at room temperature the heat dissipation must be considered. As mentioned by one of the referees, laser heating affects largely the nonlinear processes such as Auger recombination. Moreover, heating will rise the laser junction temperature with respect to heat sink temperature. The current leakage outside the active region is also a strong function of device temperature. In fact the large current leakage could also enhance the Auger recombination process and internal absorption [19]. These effects will lead to higher threshold current and can be used to explain the large difference observed between experimental data and theoretical prediction obtained from the simplified model adopted here.

We have also simulated the performance of a VCSE laser taking into account heat dissipation. The calculations are based on eqns. 1-4 of reference [19] and assuming 500K/W thermal resistance in accord with the data reported in [1]. Other parameters used in the simulation are as given in Table 1. The result reveals that the rise in junction temperature with respect to the heat sink is within 10K. Reducing facet reflectivity will increase the temperature rise. (Temperature rise is almost proportional to $I_n(I_{th})$).

**Conclusion**

In this paper, we have theoretically analysed the spectral linewidth of vertical cavity surface emitting lasers. Simulation results showing the variations of threshold current density, spontaneous emission factor, carrier recombination rate, and laser linewidth as functions of various device parameters are presented. The main findings of the study are

(i) The cavity length and active region thickness can be optimized to yield minimum threshold current density for a given linewidth-power product.

(ii) Spontaneous emission factor larger than two is expected in these lasers when they are fabricated with very high facet reflectivity.
### Table (I)
List of Parameters Values

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#### Gain parameters (T=300K)

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#### Active region recombination rates

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<td>C</td>
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### Table (II)
Optimized Laser Parameters

R$_1$=R$_2$=0.99, $\alpha_{\text{int}}$=10/cm, P$_{\text{out}}$=1mW, T=300k

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<th>$\Delta F$ (MHz)</th>
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<th>d$_{\text{opt}}$ (μm)</th>
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Fig. 1: (a) Schematic view of a circular buried heterostructure surface emitting laser [1].
(b) External cavity model.
Fig. 2: (a) Threshold current density, $J_{th}$ and threshold carrier density, $n_{th}$ versus facet reflectivity, $R$.
(b) Carrier recombination rates versus facet reflectivity.
Fig. 3: Spontaneous emission factor $n_{sp}$ (a) and laser linewidth $\Delta F$ (b) as functions of facet reflectivity.
**Fig. 4:** Variation of lasing characteristics with effective cavity length, $L$.

(a) Threshold current density, carrier recombination rate, and spontaneous emission factor versus cavity length.

(b) Laser linewidth versus cavity length.
Fig. 5: Variation of lasing characteristics with active region thickness, d.
(a) Threshold current density and carrier recombination rate.
(b) Laser linewidth for $\alpha=2.5$ and $\alpha=5$ structures.
Fig. 6: $\alpha_{\text{int}}$-dependence of spontaneous emission factor and linewidth.

Fig. 7: $\alpha_{\text{int}}$-dependence of carrier recombination rates and threshold current density.
Fig. 8: Effect of temperature, T on spontaneous emission factor (a) and linewidth (b).
Fig. 9: Effect of temperature on threshold current density (a) and carrier recombination rate (b).

--- temperature independent recombination coefficients

............... using empirical relation for J(T)
Fig. 10: Active region thickness (a) and threshold current density (b) versus cavity length for different values of linewidth and assuming linewidth enhancement factor $\alpha=2.5$.

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$\Delta F = 1$MHz  ........ $\Delta F = 2$MHz  .......................... $\Delta F = 4$MHz
Notes


References


