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Coupled Waveguides in GaN-based Lasers

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Abstract

GaN-based lasers include, apart from the separate confinement waveguide, a parasitic GaN buffer waveguide. The effect of coupling between the active laser waveguide and the buffer waveguide on the lasing modes is studied in terms of coupled mode formalism and a round-trip analysis. Assuming a low reflectivity internal mirror, Fabry-Perot modes with an intensity envelope, which resembles experimental measurements is obtained. The gradual change in the modes, taking part in the round-trip model, is presented as a function of wavelength and temperature. The influence of temperature changes on the peak wavelength of the output spectrum, predicted by this analysis, are in good agreement with experimental reports.

1. Introduction

The rapid progress in implementation of *GaN*-based lasers[1] uncovered many peculiar properties of the III-Nitride material system[2-3]. One important feature of such lasers is the spectral distribution near threshold. Unlike semiconductor lasers implemented in other material systems, *GaN*-based lasers exhibit a Fabry-Perot (FP) mode-spectrum with an envelope of modes periodically modulated (side lobes). Such a mode spectrum is a manifestation of coupled cavity effects[4]. It has been proposed that the mode envelope modulation (the spectral satellites) stems from interference between a lasing mode propagating along the laser waveguide and an electromagnetic beam bouncing back and forth between the upper contact and the *GaN*-substrate interface[5], but the details of such interference were never worked out into a quantitative model. A similar modulated FP spectrum in GaAs-GaInAs lasers was modeled through a quantitative calculation of the interference properties when a guided laser mode is coupled to substrate modes[6], however, when scaling down the "substrate" thickness in such model to the thickness of the *GaN* epitaxial structure, the modulation of spontaneous emission does not correspond to the spectral periodicity measured in *GaN*-based lasers. The extremely stable single longitudinal mode operation of *GaN*-based lasers is also surprising, because the active layer of such lasers is likely to be at elevated temperatures during operation. The following considerations can provide a clue to understand these unusual properties:

(i) *GaN*-based lasers grown hetero-epitaxially, include a 2-3μm thick *GaN* layer next to the interface with the substrate. This layer serves as a material buffer to filter-out extended defects in the subsequent layers. The *GaN* buffer layer behaves also as an additional optical waveguide, which becomes coupled to the separate confined laser waveguide.

(ii) A large density of extended defects, typical of the material system, can behave as optical scattering centers, or as internal mirrors (contra-directional couplers), in the buffer layer.

(iii) Reflectivity differences or relative phase shifts at the end facets of the laser and the buffer waveguide may result in cavity modes with strong wavelength selectivity[7-9].

Here we present a detailed analysis of the waveguide properties of *GaN*-laser structure. We clarify the parametric dependence of the various waveguide modes of the structure and the coupling among them. A round-trip coupled-cavity formalism is applied to find the FP modes and their threshold gain. Lateral as well as longitudinal coupling is considered. We show that an extended defect with a modest reflectivity (~2%) can produce a spectral distribution that explains well the experimental modulated FP spectrum. By using analytic expressions for the refractive indices of the structure, the temperature evolution of the lasing mode is studied.

2. Analysis of the N-Layer Lossless Waveguide

The electromagnetic field in a multi-layer, piecewise constant refractive index structure can be obtained by matching the boundary conditions of the lateral electric fields of the constituent layers at each interface[2]. This leads to a 2×2 transmission matrix formalism. For sinusoidal time varying fields with TE-polarization, the field $E_i(x,z,t)$ propagating in $\hat{z}$ direction can be written as:

$$\mathrm{E}_i(x,z,t) = \varepsilon_{y,i}(x)\exp[j(\omega t - \beta_i z)] \qquad (1)$$

In Eq.(1), β_i is the propagation constant and $\varepsilon_{y,i}$ is the amplitude of the field (variation in ŷ lateral direction ignored), which solves the wave equation:

$$\frac{\partial^2 \varepsilon_{y,i}}{\partial x^2} - (\beta_i^2 - k_0^2 n_j^2)\varepsilon_{y,i}(x) = 0 \qquad (2)$$

where $k_0 = 2\pi/\lambda_0$ is the wavenumber, n_j is the refractive index of the *j-th* layer and λ_0 is the vacuum wavelength.

The general solution of Eq.(2) has the form:

$$\varepsilon_{y,i}(x) = A_j \exp\{\gamma_j (x - D_j)\} + B_j \exp\{-\gamma_j (x - D_j)\} \qquad (3)$$

where $\gamma_j = (\beta_i^2 - k_0^2 n_j^2)^{1/2}$, A_j, B_j are complex coefficients and D_j is the position of the boundary between layer *(j-1)* and layer *j* relative to the cladding, D_1 equals to 0.

Continuity of the electric field and its derivative provide the following relations:

$$\begin{bmatrix} A \\ B \end{bmatrix}_{j+1} = \begin{bmatrix} \frac{1}{2}\left(1+\frac{\gamma_j}{\gamma_{j+1}}\right)\exp\{\gamma_j d_j\} & \frac{1}{2}\left(1-\frac{\gamma_j}{\gamma_{j+1}}\right)\exp\{-\gamma_j d_j\} \\ \frac{1}{2}\left(1-\frac{\gamma_j}{\gamma_{j+1}}\right)\exp\{-\gamma_j d_j\} & \frac{1}{2}\left(1+\frac{\gamma_j}{\gamma_{j+1}}\right)\exp\{\gamma_j d_j\} \end{bmatrix} \cdot \begin{bmatrix} A \\ B \end{bmatrix}_j \qquad (4)$$

$d_j \equiv D_{j+1} - D_j$ is the thickness of the *j-th* layer.

The 2×2 matrix of Eq.(4) is the transfer matrix, T_j. The coefficients of substrate and cladding layer are connected by a recursive relationship:

$$\begin{bmatrix} A \\ B \end{bmatrix}_{sub} = T_N \cdots T_1 \begin{bmatrix} A \\ B \end{bmatrix}_{clad} = T_{tot} \begin{bmatrix} A \\ B \end{bmatrix}_{clad} \qquad (5)$$

As boundary condition we'll have to take A_{clad} = 0 and B_{clad} = const. The requirement of decaying fields for large values of $|x|$ results in the condition $T_{tot,22}(\beta)=0$, whose eigenvalues are the propagation constants β_i of the i^{th} guided TE modes ($i=0, 1, 2, 3....$). Modes are labeled according to decreasing values of β_i i.e. $\beta_1 > \beta_2 > \cdots > \beta_N$. γ_j, A_j and B_j for each particular value of β_i are calculated and substituted into Eq.(3) to obtain the field profile of the modes, $\varepsilon_{y,i}$ (in the following, subscript y will be omitted).

3. Laser Structure and Waveguide Approximation

As an example, we consider the laser structure shown on Fig.(1) as representation of a typical GaN-based laser[10]. This rather complicated structure includes superlattices (layers 2 and 10) and an inhomogeneous layer (layer 4). In order to obtain a more tractable structure, we replaced in the following calculations thin layers ($d_j << \lambda$) by a single layer whose thickness is the sum of the thickness of the constituent layers and whose refractive index is the average refractive index of these layers. Thus, the superlattice layers, the multi-quantum well (MQW), the inhomogeneous layers and layers 6-7 were approximated by equivalent homogeneous layers.

The wavelength and composition dependence of the refractive indices of GaN and $Al_qGa_{1-q}N$ was obtained experimentally by spectroscopic ellipsometry in our previous work[12]. The composition (q) and temperature (T) dependence of the dielectric function of $Al_qGa_{1-q}N$ in the transparent region at elevated temperatures can be expressed as:

$$\varepsilon_{diel}(E_d, q, T) = C_d(q,T) + \frac{A_d(q,T)}{E_g^{1.5}(q,T)} \cdot \frac{2-\sqrt{1+p}-\sqrt{1-p}}{p^2} \qquad (6)$$

where $p = [E_d + i\tilde{\Gamma}(q,T)] / E_g(q,T)$, $A_d(q,T)$ and $\tilde{\Gamma}(q,T)$ are the transition strength parameter and the broadening of the fundamental transition, respectively, and the constant term $C_d(q,T)$ takes into account the contributions from higher energy transitions. $E_g(q,T)$ is the temperature-and composition-dependent band-gap of $Al_qGa_{1-q}N$, E_d is the photon energy and T is the temperature. The refractive index of the layers are given by:

$$n(E_d, q, T) = \left[\frac{1}{2}\left(\varepsilon_r(E_d,q,T) + \sqrt{\varepsilon_r(E_d,q,T)^2 + \varepsilon_{im}(E_d,q,T)^2}\right)\right]^{1/2} \qquad (7)$$

In Eq.(7) ε_r and ε_I are the real and the imaginary parts of the dielectric constant , respectively. The constants $C_d(q,T)$, $A_d((q,T)$ and $\tilde{\Gamma}(q,T)$ were used as fitting parameters. A quadratic best-fit procedure leads to the following composition and temperature dependence[11-12]:

$$A_d(q,T) = \left[79.30 - 8.37\cdot10^{-2}T + 6.73\cdot10^{-5}T^2 + (18.99 + 0.13T - 1.76\cdot10^{-4}T^2)q + 37.51q^2\right]eV^{1.5} \qquad (8a)$$

$$C_d(q,T) = 2.49 + 2.27\cdot10^{-3}T - 1.80\cdot10^{-6}T^2 - \left(0.74 + 4.61\cdot10^{-3}T - 5.33\cdot10^{-6}T^2\right)q \qquad (8b)$$

$$\tilde{\Gamma}(q,T) = \left[-8.69 + 4.13\cdot10^{-2}T + \left(248.24 - 0.19T\right)q^2\right]\cdot10^{-3}eV \qquad (8c)$$

Under operating conditions, the temperature of the layers is well above room temperature, mainly due to the relatively high resistance of the p-type region and the low thermal conductivity of the sapphire substrate. The estimated operating temperature is ~365K (a calculation is given in Appendix A).*InGaN* layers (in the multi-quantum well) were modeled by extrapolating $C_d(0,T)$, $A_d(0,T)$ and $\tilde{\Gamma}(0,T)$ along with *InN* energy gap, thermal expansion coefficient and *InGaN* Bowing parameter. The refractive indices of the cladding and the substrate are $n_{clad} = n_{air} = 1$ and $n_{sub} = n_{sapphire} = 1.68$. The refractive index diagram of the resulting simplified structure, calculated at $365K$, is shown in Fig.(2). (Layers are numbered by j, $1 \leq j \leq 13$).

A brief inspection of the refractive index profile shown in Fig.(2), leads to the following conclusions: (a) the complete structure may support a large quantity of guided modes; (b) the laser "active region waveguide" (around the *InGaN* quantum wells) could have been single moded, if the $Ga_{0.8}Al_{0.2}N$ cladding layers were infinitely thick; and (c) a "parasitic" waveguide is formed next to the substrate (the "buffer waveguide").

4. Guided Modes of the Laser Structure and Waveguide Coupling

Using the 2×2 matrix formalism described in section 2, and the refractive index profile of Fig.(2) we calculated the propagation parameters and field distributions for the TE bounded modes at $\lambda=405.5nm$. The whole structure supports about 40 TE modes, most of them are guided in the buffer waveguide. In Fig.(3), the field distribution of the first 6 normalized modes is plotted. One may observe that there is one mode, which is highly confined to the active (MQW) region, the 3rd mode. Among all β-values those of modes 3 and 4 are the closest. Moreover, these two modes have the strongest peak in the MQW region, and the highest values of confinement factor (Γ) to this region. These considerations make these two modes the natural candidates for coupling interaction. Their role in the round-trip analysis will be explained later. The field distribution of modes 3 and 4 is shown in greater detail in Fig.(4).

Further observation of the modal profiles in Fig.(4) reveals that *the structure can be regarded as composed of two coupled waveguides*: the "laser active waveguide" (WG-I) and the GaN "buffer waveguide" (WG-II). Since the lasing mode is obviously not the lowest order mode of the structure and it may switch from one mode to another one with wavelength or temperature, it is instructive to split the structure into two coupled waveguides and to make use of coupled wave theory, in order to get a basic understanding of the modal spectrum. WG-I supports a single TE mode and WG-II supports 9 TE modes. Modes with close values of β will exhibit strong coupling. In our case, the single mode of WG-I couples, at $\lambda=405.5nm$ and $T=365K$, with the 3rd mode of WG-II, both of them along with the corresponding waveguide structures are presented at Fig.(5).

5. Cavity modes and Frequency Selectivity

Consider two coupled waveguides in the laser resonator, with end-facet reflections r_I and r_{II}, respectively, as shown on Fig.(6). Suppose that each channel alone guides a mode with the propagation parameters β_I and β_{II} with the corresponding fields $\varepsilon_I(x)$ and $\varepsilon_{II}(x)$, and effective indices $n_{eff,I}$ and $n_{eff,II}$, respectively, (even if one of the waveguides is multi-mode, only a single mode is strongly coupled for certain values of β). The coupling coefficients between WG-I and WG-II are $\kappa_{I,II}$ and $\kappa_{II,I}$ respectively[9] . The laterally coupled combined structure will guide two supermodes with field profiles $w_I(x)$ and $w_{II}(x)$.

We proceed with defining the rest of the expressions needed for the formalism:

$$\beta_{av} = (\beta_I+\beta_{II})/2$$

$$\Delta=(\beta_I-\beta_{II})/2$$

$$s = \sqrt{\Delta^2 + \kappa_{I,II}\kappa_{II,I}} \qquad (9)$$

The supermode propagation constants are given by:

$$\sigma_{I,II} = \beta_{av} \pm s$$

The total field along the waveguide can be described approximately either in terms of individual modes:

$$\varepsilon(x,z) = a_I\varepsilon_I(x)e^{-j\beta_I z} + a_{II}\varepsilon_{II}(x)e^{-j\beta_{II} z} \qquad (10)$$

or in the terms of the supermodes:

$$\varepsilon(x,z) = b_I w_I(x)e^{-j\sigma_I z} + b_{II} w_{II}(x)e^{-j\sigma_{II} z} \qquad (11)$$

where a_l, b_l ($l=I$ or II) are the mode amplitudes. We can describe the field along the waveguide either by Eq.(10) or by Eq.(11). If the individual mode fields and the supermode fields are known, the total electric field at a fixed value of z could be described by one of the vectors:

$$A_v = \begin{bmatrix} a_I \\ a_{II} \end{bmatrix}, \qquad B_v = \begin{bmatrix} b_I \\ b_{II} \end{bmatrix} \qquad (12)$$

The former is the channel-mode representation, and the latter is the super-mode representation (We assume, in the following, that these vectors are normalized: $(|A_v| = |B_v| = 1)$. Both representations are interchangeable through the transformation[8-9] $A_v = V \cdot B_v$, where:

$$V = \begin{pmatrix} p_I & -p_{II} \\ p_{II} & p_I \end{pmatrix} \tag{13}$$

and

$$p_{I,II} = \sqrt{\frac{1 \pm \frac{\Delta}{s}}{2}} \tag{14}$$

It should be mentioned that the modal amplitudes, given in Eq.(12) are eigen-solution of the infinitely long waveguide structure. In real devices, two reflecting facets terminate the waveguide. The reflectivity at the end-facet depends on the refractive indices, facet tilt, roughness, coating etc, and therefore the reflectivity of WG-I can be slightly different from that of WG-II. This may be particularly relevant for GaN-based lasers, with etched (or polished) end mirrors.

Thus, a round trip analysis of the cavity has to be performed, in order to obtain the cavity modes of the structure. These modes will be a superposition of the eigen-modes as in Eq.(12).

The propagation of the field along the waveguide is easier to express in the super-mode representation (subscript *SM*), since the propagation matrix in this representation is diagonal:

$$P(z)_{SM} = \begin{pmatrix} e^{-j\sigma_I z} & 0 \\ 0 & e^{-j\sigma_{II} z} \end{pmatrix}. \tag{15}$$

The mirror reflectivity operator, on the other hand, is diagonal in the channel-mode representation (subscript *CM*):

$$R_{CM} = \begin{pmatrix} r_I & 0 \\ 0 & r_{II} \end{pmatrix} \qquad (16)$$

In the supermode representation, we have $R_{SM} = V \cdot R_{CM} \cdot V^{-1}$. In order to take into account the mentioned limitations of GaN technology, a slightly different value than r_I can be assumed for r_{II}. We realize that if $r_I \neq r_{II}$, R_{SM} contains non-diagonal terms, thus, the two modes w_I and w_{II} couple to each other upon reflection.

The oscillating mode of the resonator is the field that reproduces itself after one round trip: $T_{SM}B = B$, where $T_{SM} = R_{SM}^L \, P_{SM}(L) \, R_{SM}^R \, P_{SM}(L)$ is the round trip matrix in the super-mode representation (L is the waveguide length). Nontrivial solutions exist if and only if:

$$det(T_{SM}-I) = 0 \qquad (17)$$

Eq.(17) is the characteristic equation of the resonant cavity.

Coming back to the laser, we assume that excess carriers supply the gain in the laser only in the area of the MQW, therefore we can rewrite the gain as:

$$\begin{aligned} g_I(\lambda) &= \Gamma_I(\lambda) \cdot g_m(\lambda) + (1-\Gamma_I)\alpha_m \\ g_{II}(\lambda) &= \Gamma_{II}(\lambda) \cdot g_m(\lambda) + (1-\Gamma_{II})\alpha_m \end{aligned}, \qquad (18)$$

where $\Gamma_l(\lambda)$ $(l = I, II)$, is the confinement factor of the supermodes in the MQW layer, g_m is the material gain supplied by current; and α_m is the average absorption loss in the passive layers. For the purpose of this modeling, it is sufficient to calculate the propagation constants of the passive waveguides (real values of σ_l), since the imaginary part is neglible; and afterwards write ad hoc $\sigma_{l\_new} = \sigma_l + i\cdot(g_l/2),\ l=I,II$. When gain and/or loss in each layer are taken into account through a complex refractive index, the guided modes and their propagation constants may be slightly different than those of passive waveguides. However, these differences do not affect the main conclusions of this work. For solving Eq.(17), it is necessary to scan, for each wavelength, the value of g_m. The obtained wavelengths in which a solution of Eq.(17) is found are the FP modes, with wavelengths $\lambda_{j,FP}$. $g_m(\lambda_{j,FP})$ is the required material gain at each one of them. The photon population (emitted intensity) at a certain wavelength is proportional to[13]:

$$P_{out}(\lambda_{j,FB}) \propto \frac{\Gamma_{tot}(\lambda_{j,FB})}{\alpha_{tot} - g_{tot}(\lambda_{j,FB}) \cdot \Gamma_{tot}(\lambda_{j,FB})} \qquad (19)$$

where $\Gamma_{tot}(\lambda_{j,FP})$ is the total confinement factor of the round-trip cavity mode (the expression will be given later), α_{tot} represents the total losses (it was taken as a constant at a certain temperature) and $g_{tot}(\lambda_{j,FP})$ is the total gain at each mode, calculated as $g_{tot}(\lambda_{j,FP}) = \Gamma_{tot}(\lambda_{j,FP}) \cdot g_m(\lambda_{j,FP}) + (1-\Gamma_{tot}(\lambda_{j,FP}))\cdot\alpha_m$.

In a first attempt to understand the peculiar spectrum of *GaN*-based lasers, we have used Eq. (17) to calculate the FP resonance wavelengths $\lambda_{j,FP}$, and the gain $g_{tot}(\lambda_{j,FP})$. In our calculation we assumed a total cavity length $L=550\mu m$, average losses $\alpha_m=10cm^{-1}$, $\kappa=\sqrt{\kappa_{I,II}\kappa_{II,I}}=100cm^{-1}$, $r_I = 0.7$ and $r_{II} = 0.67$. We then used the obtained values of $g_{tot}(\lambda_{j,FP})$ to calculate the photon density spectrum at threshold. A slight modulation due to the coupled–cavity effect was observed in the final spectrum, but the strong side lobes typical of *GaN*-based lasers was not obtained. In order to better model the reported experimental observations, we invoke the fact that extended defects (grain boundaries) may be present at the material of WG-II, constituting internal partial mirrors. We thus replace r_{II} by[13]:

$$r_{eff,II} = r_\varepsilon \, e^{2j\beta_{II}L'} + \frac{(1-r_\varepsilon^{\,2})r_{II}}{1+r_\varepsilon r_{II} e^{2j\beta_{II}L'}} \qquad (20)$$

In Eq. (20), r_ε and L' are the partial reflectivity of an internal mirror (an extended defect) and its distance from the end facet. Inserting $r_{eff,II}$ instead of r_{II} in Eq. (16), with $r_\varepsilon = 0.02$, results in a photon density distribution as shown in Fig.(7). The value of L' was varied until the spectral periodicity matched the experimental results. Fig.(7) was obtained with $L' = 90\mu m$. One should note that the periodicity in the FP spectrum varies between different reports[1], reflecting the fact that such an "internal mirror" is related to material imperfections. Thus, value of L' may change from sample to sample. Therefore, we suggest that L' represents the distance between the exit mirror and the nearest grain boundary present in the GaN layer. Such grain boundaries may be the vertical facets of the hexagonal hillocks, which during the early stage of GaN film growth, merge into a uniform layer[1]. The fact that the introduction of $r_{eff,II}$ (Eq. (20)) in the round-trip equation (Eq. (17)) resembles the observed spectrum, suggests that the *longitudinal* coupled-cavity effect (and not the *lateral* effect) governs the emission properties of this type of lasers[14].

The total confinement factor, used in Eq. (19) is calculated as follows: we first define a *z-dependent* confinement factor in SM representation, using Eq.(11).

$$\Gamma_{tot}(z) = \frac{\int\limits_{MQW} \left| b_I w_I(x) e^{-j\sigma_I z} + b_{II} w_{II}(x) e^{-j\sigma_{II} z} \right|^2 dx}{\int\limits_{-\infty}^{\infty} \left| b_I w_I(x) e^{-j\sigma_I z} + b_{II} w_{II}(x) e^{-j\sigma_{II} z} \right|^2 dx} \qquad (21)$$

Using the orthonormal properties of w_I and w_{II} ; and the normalization of B_v, we obtain:

$$\Gamma_{tot}(z) = b_I^2 \Gamma_I + b_{II}^2 \Gamma_{II} + \Delta\Gamma(z) \qquad (22)$$

where $\Delta\Gamma(z)$ is an interference term, and its z dependence is $\sim exp[(\sigma_I - \sigma_{II})z]$. We then calculate the average value of this expression over the cavity, $\overline{\Delta\Gamma(z)} = \frac{1}{L}\int\limits_0^L \Delta\Gamma(z)dz$ and use this value in the following calculations. By using Eq. (22), Γ_{tot} is calculated *vs* wavelength.

6. Wavelength and Temperature Dependence of Lasing Mode

Given a waveguide structure with fixed refractive indices and fixed layer widths, all possible propagation constants and field profiles for guided modes are uniquely determined. Therefore, they also determine such mode properties as confinement factor in each layer. The modification of the refractive index with wavelength or with temperature will cause perturbations in the propagation parameters, and as a result, variations in the field profiles, confinement factors, and round trip cavity modes.

The use of photon energy and temperature dependent refractive indices (Eq. (7)) makes it possible to investigate the changes in lasing properties with wavelength and temperature. Although this model includes an over-simplified fraction of the waveguide parameters and complex propagation constants, it is useful to gain a qualitative understanding of the coupled cavity effect, and its wavelength and temperature dependence.

The refractive index of all the layers in the structure *decreases* with wavelength and *increases* with temperature. Their slopes, $\left|\frac{dn}{d\lambda}\right|$ and $\left|\frac{dn}{dT}\right|$ is steeper for layers in which E_g is closer to the actual photon energy, E_d [11]. Thus, the refractive index of the InGaN layers (the QWs, in particular) changes with wavelength more rapidly than that of GaN and AlGaN layers and as a consequence, the confinement factor into the MQW of WG-I channel mode is lowered with wavelength. In addition to that, the propagation constant of WG-I mode decreases at a higher rate than those of WG-II modes.

An important result is the change in the role of each one of the modes in terms of being the highest confined one (in the SM representation). We have calculated the propagation constants and the confinement factors of the laser modes (both SM and CM) at various wavelengths. Fig.(8a) shows the change in the propagation constants of WG-I and some of WG-II. As seen in Fig.(8a), the value of β_1 in WG-I crosses the values of the propagation constants of WG-II modes. Thus, the mode of WG-II that couples to the mode of WG-I changes (only modes with close values in propagation constants couple efficiently). In the wavelength range shown it is the 3rd mode, which acts as the coupled mode at the beginning of the range and the 5th one at the end of it. Fig. (8b) shows the corresponding change in the propagation constants of the supermodes. Each crossing point in propagation constants is an indication of a crossing point also in the SM confinement factors as shown at Fig.(8c). Fig.(9) represents the field profiles of three SM, which take part in the round-trip analysis in the range scanned at Fig.(8).

In order to apply this formalism to study the temperature dependence of the lasing wavelengths, we realized that the spontaneous emission just below laser threshold can be well approximated by a Lorenzian envelope[13] with a peak wavelength $(\lambda_0(T))$ corresponding to E_g, and use $E_g(T)$ of InGaN:

$$L(u) = \frac{2\pi^2}{h} \frac{\tau_{in}(T)}{1 + (2\pi \cdot c \cdot \tau_{in}(T))^2 \cdot u^2} \qquad (23)$$

where $u = 1/\lambda - 1/\lambda_0$, λ_0 is the central wavelength, τ_{in} is the *intraband relaxation time* and c is the speed of light in vaccum. The temperature dependence of τ_{in} was taken according to[15]. InGaN energy gap and τ_{in} both decrease with temperature, therefore the Lorenzian lineshape function not only shifts to higher wavelengths with temperature, but also broadens and reaches its peak value.

We then calculate $\lambda_{j,FP}(T)$ and $g_{tot}(\lambda_{j,FP}(T))$ and multiply the obtained spectrum by $L(u(T))$. The peak wavelength for each temperature is shown on Fig.(11). The moderate changes in λ peak values are caused when the maximum "moves" to the next FP mode in the same side lobe. The larger discontinuities in peak wavelength are caused when the maximum value is found in the adjacent side lobe. These results are in good agreement with the experimental results reported in reference 1.

8. Conclusions

In this work we have used a round-trip analysis along with coupled mode theory to model a *GaN*-based semiconductor laser spectrum. The effect of lateral and longitudinial coupled cavity effect were taken into account. By adding an internal mirror in the parasitic waveguide, we obtained a spectrum, which resembles experimental measurements. This internal mirror is probably derived from *GaN* extended defects (grain boundary). The spacing between such effects exhibits a length scale of the order of several tens of microns. This model also enabled us to explain the "jumps" in the peak wavelengths with temperature.

Another aspect of this work showed that the modes, which participate in the round-trip model, change gradually with wavelength. A similar phenomenon may also occur, if we could select a specific wavelength and study temperature influences on the modes that take part in the laser field.

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9. Appendix A.

LD CW operation temperature

The device CW operation temperature is taken as $T=365K$ (92°C). It is evaluated by the following formula $T_{(\text{device center})} = T_{\text{room}} + Z_T P_{in}(1-\eta) \sim T_{\text{room}} + Z_T IV(1-\eta)$, where Z_T is the thermal impedance (~50 K/W for GaN devices on sapphire[16]), I is the current, V is the applied voltage and η is the external quantum efficiency. By using typical values: I~150-200 mA, V~7-9 V, η~ 5 %[17] and T_{room}~25°C, one gets $T_{(device\ center)} \cong$ 75-111°C = 348-384K. The average value is 366K.

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