HW #2

Due 4/15/18 (Sunday)

Submit electronically to bSpace by midnight.

Use your favorite program (e.g., Matlab) for numerical calculation and plotting.

	Unit	GaAs	$Al_xGa_{1-x}As$, 0<x<0.45
Bandgap Energy	eV	1.424	1.424 + 1.247x
Electron Effective Mass	m_0	0.067	0.067 + 0.083x
Hole Effective Mass	m_0	0.5	0.5 + 0.29x
Dielectric Constant	ε_0	13.1	13.1 – 3x
Conduction Band Discontinuity	%	-	ΔE_C ~ 67% ΔE_g
Valence Band Discontinuity	%	-	ΔE_V ~ 33% ΔE_g

1. Consider a double heterostructure (DH) laser with $Al_{0.4}Ga_{0.6}As$ cladding layers and GaAs active (gain) layer. Use the Table above for their refractive indices. Note that refractive index $n = \sqrt{\epsilon_r}$, where ϵ_r is the relative dielectric constant. The active layer is 0.1μm thick. The laser is 200 μm long and 1 μm wide. Both mirrors are cleaved facets with a power reflectivity of 30%. The residue loss is 20 cm^{-1}. Assume the carrier lifetime is 1 ns (a constant value, which is an approximation). Use linear gain approximation $g = a \cdot (N - N_{tr})$ where $a = 10^{-16} cm^2$ and $N_{tr} = 10^{18} cm^{-3}$
   a. Solve the fundamental TE mode as outlined in class. Calculate and plot the optical field profile. (Or you can calculate it using Lumerical).
   b. Numerically calculate the optical confinement factor using the field profile in Part a).
   c. Find the "V parameter", $V = \frac{2\pi d}{\lambda}\sqrt{n_{Core}^2 - n_{Cladding}^2}$, of the DH waveguide. The condition for single mode is $V < \pi$. Is this waveguide single mode?
   d. Calculate the approximate confinement factor using $\Gamma = \frac{V^2}{2+V^2}$. Compare this with the numerical calculation in Part b).
   e. Find the threshold gain and threshold current of the laser
   f. What is the external quantum efficiency of the laser? Express your answers in both percentage (%) and in W/A.

2. In this problem, you will show that the laser output is basically amplified spontaneous emission. When we include the spontaneous emission term in the rate equation, the carrier concentration is very close to, but never reaches, the threshold value.

   The rate equations we discussed in class are:

$$\frac{dN}{dt} = \eta_i \frac{I}{qV_{active}} - \frac{N}{\tau} - v_g g(N) \cdot S$$

$$\frac{dS}{dt} = \Gamma v_g g(N) \cdot S - \frac{S}{\tau_p} + \Gamma \beta \cdot R_{sp}$$

where N is carrier concentration, S is the photon density; V_{active} is the volume of the active layer (i.e., laser width x length x thickness); τ is the carrier lifetime, $\frac{N}{\tau} = AN + BN^2$ (assume Auger recombination is negligible), $v_g=c/n_g$ is the speed of light in semiconductor; $g(N) = a\cdot(N - N_{tr})$ is gain coefficient. Here, we use linear gain approximation. Γ is the optical confinement factor; $\tau_p = \frac{1}{v_g(\alpha_m + \alpha_i)}$ is the photon lifetime; β is the spontaneous emission factor, i.e., the fraction of the spontaneous emission coupled to the lasing mode; and $R_{sp} = BN^2$ is the spontaneous rate.

a. In steady state, show that $S(N) = \dfrac{\Gamma\beta \cdot R_{sp}(N)}{1/\tau_p - \Gamma v_g g(N)}$ for both below threshold and above threshold.

b. In steady state, show that $I(N) = \dfrac{qV_{active}}{\eta_i}\left(\dfrac{N}{\tau} + v_g g(N)\cdot S(N)\right)$ for both below and above threshold.

c. Show that the output power $P(N) = \hbar\omega \dfrac{V_{active}}{\Gamma}\alpha_m v_g S(N)$.

d. Since both output power *P(N)* and current *I(N)* are both functions of *N*, we can plot the light-versus-current (L-I) curve using *N* as a parameter. Use the following parameters for the plot:

$$R_1 = R_2 = 30\%,\ N_{tr} = 10^{18}\ \text{cm}^{-3},\ a = 10^{-16}\ \text{cm}^2,\ \Gamma = 50\%$$
$$\alpha_i = 10\ \text{cm}^{-1},\ L = 300\ \mu\text{m},\ w = 1\ \mu\text{m},\ \text{t} = 0.1\ \mu\text{m},\ \tau = 1\ \text{nsec}$$
$$\eta_i = 100\%,\ \eta_r = 90\%$$
$$\beta = 10^{-2}$$
$$A = 2\times10^8\text{sec}^{-1},\ B = 10^{-9}\text{sec}^{-1}\text{cm}^{-3}$$
$$\lambda = 1550\ \text{nm},\ n_r = 3.5\ \text{(effective refractive index)}$$

Calculate and plot the L-I curve of the laser (i.e., *P(N)* versus *I(N)*) in both <u>linear</u> and <u>logarithmic</u> scales for the vertical axis. Choose the range of *N* such that the output power goes from 0 to ~ 10 mW.

Please note that the $N < N_{th}$ even above threshold, though it is getting closer and closer to N_{th} above threshold. To show clearly the behavior around threshold, you need to use a very fine increment for *N*. Alternatively, you can use non-uniform intervals with much denser points near N_{th}.

e. Plot the carrier concentration *N* as a function of current *I* for the same range of *I* as in part d. Again, use both linear and logarithmic scale for the vertical axis.

3. To show effect of β on the L-I characteristics, plot L-I curves for β= 0.001, 0.01, and 0.1 in the same graph. Choose the ranges of N such that the output power reaches 10 mW for all β's. Likewise, plot N-I curve for the three β values. Show your plots in log-linear and linear-linear plots for both families of curves