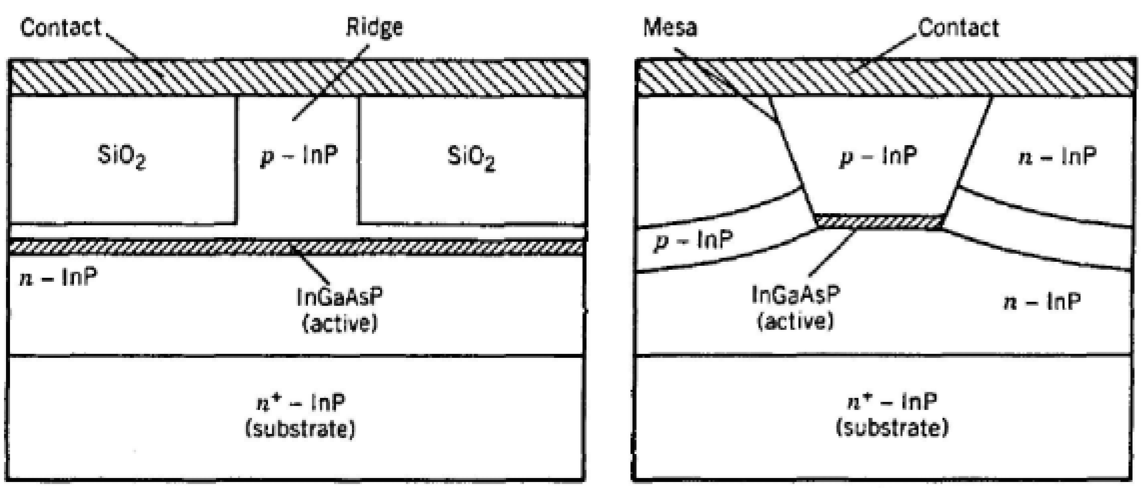
Keio University

CALAMVS GLADIO FORTIOR 1858

Hiroyuki Tsuda's Laboratory - 2019

Report of exercice 1-Laser diode



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1 Static characteristics

Laser diode modulation characteristics are well described by a set of equation called rate equations. Those equations are shown below :

$$\frac{\mathrm{d}P}{\mathrm{d}t} = g(N)P + \beta\frac{N}{\tau_r} - \frac{P}{\tau_p} \tag{1}$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{I}{eV} - N\left(\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}\right) - g(N)P \tag{2}$$

Where

$$g(N) = a(N - n_0) \tag{3}$$

And

$$\frac{1}{\tau_s} = \left(\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}\right) \tag{4}$$

The different parameters and constants present in the equations above are defined in table 1.

Symbols	Quantity	Typical values	Units
P	Photon density	Depending on I	cm^{-3}
N	Electron density	Depending on I	cm^{-3}
I	Injection current	Varying	A
τ_p	Photon life time	$1.0 * 10^{-12}$	s
τ_r	Radiative recombinaison time	$3 * 10^{-9}$	s
τ_{nr}	Nonradiative recombinaison time	$1 * 10^{-9}$	s
τ_s	carrier life time	$7.5 * 10^{-10}$	s
$g(n)$	gain	Depending on n	σ^{-1}
β	Rate of spontaneous emission coupled to the laser mode	$1 * 10^{-5}$	.
a	gain coefficient	$3.0 * 10^{-6}$	cm^3s^{-1}
n_0	carrier density threshold	$1.0 * 10^{18}$	cm^{-3}
V	Volume of cavity	$1.0 * 10^{-9}$	cm^3
e	elementary charge	$1.602 * 10^{-19}$	$C = \mathrm{A}s$

TABLE 1 – Laser diode parameters and constant symbols, values and units

For a given system, the following observation can be noted :

— From equation 1 and from the physics of light emission in semiconductors, the rate of creation of the photon density in the system, $\frac{\mathrm{d}P}{\mathrm{d}t}$, is given by the rate of simulated emission and spontaneous emission and the rate of destruction of photons is given by $\frac{P}{\tau_p}$ which increases as the photon life time decreases meaning that the photons are lost faster.

— From equation 2 and knowing semiconductor physics we also have two effects. Firstly, the slope of electron density N increases with the current because it means that the voltage applied increases as well and that the built in electric field is reduced, the electrons and holes therefore diffuse and their number increases in the active region. And secondly, the slope of N decreases as the carrier lifetime decreases and as there is stimulated emission this is because stimulated emission induces recombination of electrons and holes which are not anymore present in the system.

1.1 Analytical resolution

Let's now analyse the static characteristics of such a system. Static characteristics means that the current stays constant and that the the time derivatives in the equations 1 and 2 can be set to zero. Also, in equation 1 the term $\beta\frac{N}{\tau_r}$ is several orders of magnitude smaller than the two other terms and can therefore be neglected. We then have a threshold value for photon emission given by a current such that $g(n)\tau_p = 1$. The resolution can be divided in two cases.

The first corresponds to currents such that $g(n)\tau_p < 1$, the photon density P = 0 and $N = \frac{I\tau_s}{eV}$. Then, as soon as the threshold value $g(n)\tau_p = 1$ is reached it leads to a carrier density $n_{th} = \frac{1}{a\tau_p} + n_0$ and a current threshold

$$I_{th} = \frac{eVN_{th}}{\tau_s} = \frac{eV}{\tau_s}\left(n_0 + \frac{1}{a\tau_p}\right). \tag{5}$$

And finally for $g(n)\tau_p > 1$ and by still neglecting spontaneous emission in 1. We can substitute the value $g(n)P$ found in equation 2 and input it in equation 1 which gives

$$P = \frac{\tau_p}{eV}(I - I_{th}). \tag{6}$$

Since the photon density has been obtained, the power emitted at one facet can be obtained. Each photon emitting an energy $\hbar\omega$ we then compute the power emitted at one facet, for a volume V, by

$$P_e = \frac{1}{2}(v_g\alpha_{mir})\hbar\omega PV. \tag{7}$$

The factor of $\frac{1}{2}$ is present because it emits power from the two facets, here we consider only one facet. Also $v_g\alpha_{mir}$ appears to take into account the rate at which photons escape from the device. Here α_{mir}, the mirror loss, is given by

$$\alpha_{mir} = \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right) \tag{8}$$

where L is the cavity length and R is given by

$$R = \left(\frac{n-1}{n+1}\right)^2. \tag{9}$$

For typical semiconductors we have n ≈ 3.5 this means a value of R ≈ 0.31. And because the photon life is given by $\tau_p = \frac{1}{v_g(\alpha_{mir}+\alpha_{int})}$ equation 7 can be rewritten as

$$P_e = \frac{\hbar\omega}{2e}\frac{\eta_{int}\alpha_{mir}}{\alpha_{mir}+\alpha_{int}}(I - I_{th}). \tag{10}$$

In this equation, the term η_{int} corresponds to the internal quantum efficiency of the system, it is almost 1 for a semiconductor laser. And the internal loss has value $\alpha_{int} = 10cm^{-1}$.

1.2 Numerical simulations

In figure 1 the effect of the different parameters on the P-I curves profile are studied. These parameters are increased from 50% of their initial values up to 150% of it. The three parameters used where : the gain coefficient a, the cavity length L and the mirror reflectivity $R = R_1 = R_2$.

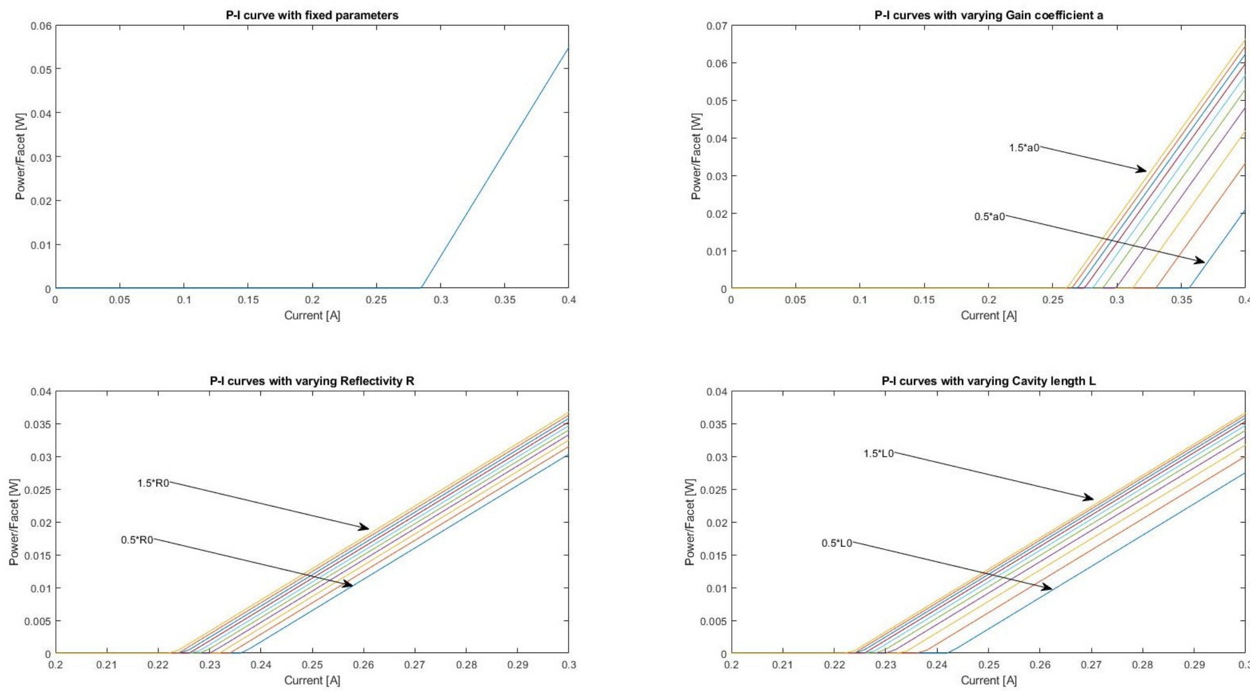

FIGURE 1 – P-I profile of the laser diode under the variation of different parameters

At first, considering the plots with varying parameters in figure 1, the curves have exactly the same profile. Before the current threshold, the value of the output power is zero. After, the power increases linearly with the current. This is due to the linear relationship between P_e and I given in equation 10.

A second important effect is that the curves shift from right to left as the value of the parameter increases. This is displayed by the arrows on figure 1. This is due to the fact that the threshold current is inversely proportional to those parameters, which can be seen by combining the expression of the threshold current in 12 and the relation $\tau_p = \frac{1}{v_g(\alpha_{mir}+\alpha_{int})}$. This relationship between the threshold current and each parameter is displayed in figure 2. It is important to notify that in the case of the parameters a and L the relationship is inversely proportional while in the case of the reflectivity, the current is proportional to logarithm of the inverse of the reflectivity raised to the square.

And finally it is observed from the graphs that once the threshold is reached, the value of the power is around 10 to 20 % of the current.

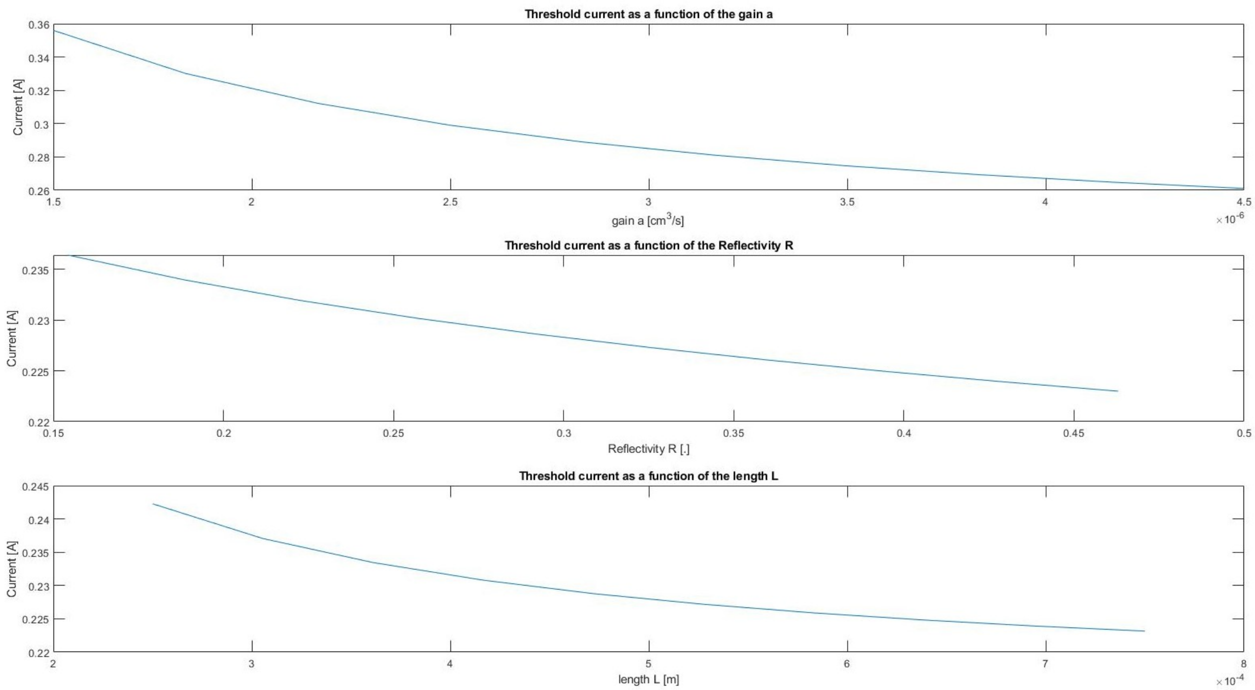

FIGURE 2 – P-I profile of the laser diode under the variation of different parameters

2 Dynamic characteristics

2.1 Comment on the Matlab simulation

The system of equation given by equation 1, 2 and 3 is a system of non-linear differential equation with varying input $I(t)$. It is solved using initial conditions P_0 for P and N_0 for N. Those conditions are given by

$$P_0 = \frac{\tau_p}{eV}(I_B - I_{th}). \tag{11}$$

We have the value of P_0, this makes us able to solve for N_0 :

$$N_0 = \frac{\frac{I_B}{eV} + an_0 P_0}{\frac{1}{\tau_s} + aP_0} \tag{12}$$

The Matlab function choose to solve this system will be ode45.