LASER Transmitters

1 OBJECTIVE

Investigate the L-I curves and spectrum of a FP Laser and observe the effects of different cavity characteristics. Learn to perform parameter sweeps in OptiSystem.

2 PRE-LAB

A laser depends on three main components to function: gain medium, energy pump and resonator. In a semiconductor laser, a current source is used to inject carriers into the gain medium. The carriers in the gain medium pass their energy and emit photons by spontaneous and stimulated emission. Finally, the photons are confined in the optical cavity and emitted through one of the facets. Modifying or controlling any of these components can have observable and quantifiable effects on the performance of the laser.

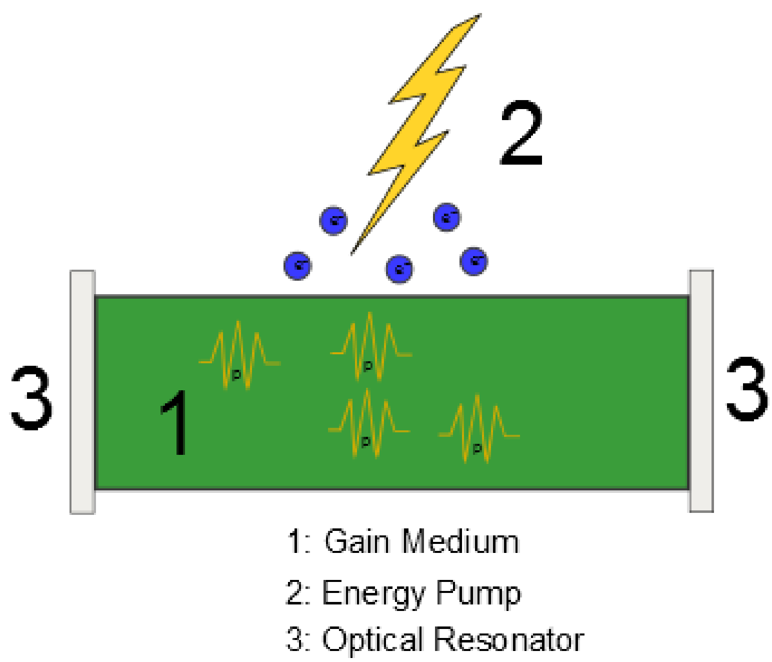

Figure 1: Schematic demonstrating the main components in a laser.

2.1 GAIN AND THRESHOLD

There are two regimes of laser operation: before threshold, where losses are larger than the gain, and at threshold, where the losses match the gain. When an optical mode cannot sustain itself for a complete roundtrip of the cavity there is a low number of photons in the cavity and the dominant source of photons is spontaneous emission. Once an optical mode is able to make an entire trip, the number of photons increases dramatically and the dominant source of photons switches to stimulated emission.

The relationship between losses and gain in a Fabry Perot cavity can be expressed by:

$$e^{gL}\sqrt{R_1R_2}e^{-\alpha_{int}L}e^{-2i\beta L} = 1, \tag{1}$$

where g is the gain experienced by the optical mode, L is the length of the cavity, R is the reflectivity of the facets, α_{int} is the internal losses and β is the phase constant.

The modal gain, g, is naturally dependent on the current injected into the gain medium and can be approximated by:

$$g = \sigma_g(N - N_t), \tag{2}$$

where σ_g is the differential gain, N is the carrier density and N_t is the carrier density at transparency.

<u>Questions:</u>

2.1.1 What effect does increasing the reflectivity of the end facets have on the threshold current?

2.1.2 Manipulating the equation for the threshold condition express the quantity α_{mir} in terms of the reflectivity. Hint: The equation will take the form of $g = \alpha_{mir} + \alpha_{int}$

2.1.3 For a cavity with gain 110 cm^{-1} and loss 35 cm^{-1} calculate the required length of the cavity to reach threshold, assuming total mirror loss of 0.4. What is the restriction on the phase constant?

2.1.4 For the cavity described above what is the threshold carrier density? Assume differential gain of 4×10^{-16} cm^2 and transparent carrier density of 1×10^{18} cm^{-3}.

2.2 Laser Rate Equations

As an optoelectronic device, a Laser is governed by the interaction between electrons and photons in the active region. For a single mode laser, the number of electrons to number of photons can be described by two coupled differential equations:

$$\frac{dP}{dt} = GP + R_{sp} - \frac{P}{\tau_p}, \tag{3}$$

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_c} - GP, \tag{4}$$

P = number of photons	τ_p = photon lifetime	q = electron charge
N = number of electrons	τ_c = carrier lifetime	I = injected current

R_{sp} = rate of spontaneous emission into the lasing mode

G = net rate of stimulated emission

For lasers with more optical modes, simply adding more coupled equations can be used to extend the model, but the solution becomes more complex. G, the net rate of stimulated emission is linked to the modal gain, g, and group velocity by:

$$G = g v_g. \tag{5}$$

The group velocity and photon lifetime are related to the loss of the cavity as:

$$\frac{1}{\tau_p v_g} = \alpha_{mir} + \alpha_{int}. \tag{6}$$

Questions:

2.2.1 Assuming a spontaneous emission rate approaching 0, write the rate equations in steady state form.

2.2.2 Using this form of the rate equation determine the threshold condition and the subsequent expression for the threshold current.

2.2.3 Determine the threshold current for the cavity in the previous questions with an active region area of 0.3 μm^2 and carrier lifetime of 1.5 ns.

In addition to the threshold current another important and easily extractable quantity of a laser is the slope efficiency, which relates the input current to the output optical power. From the steady state equation derived in question 2.2.1, it can be written as:

$$P_e = \frac{hf}{2q} \frac{\eta_{int}\alpha_{mir}}{\alpha_{mir}+\alpha_{int}} (I - I_{th}). \tag{7}$$

In equation 7, *hf* is the energy of the photons with *h* as Planck's constant and *f* the frequency. Furthermore, η_{int} is the internal quantum efficiency, which is the ratio of photons created by stimulated emission to electrons injected into the active region. Above threshold, η_{int} is remarkably close to 1. The slope efficiency is the derivative of this equation and is strongly related to the losses of the cavity. It should also be noted that the mirror loss, α_{mir}, is calculated strictly from the front facet of the Laser, so that the ratio describes the fraction of useful optical output power to total loss.

2.2.4 Calculate the slope efficiency of a laser with properties from the previous questions and operating at 1.55 μm.

2.3 Longitudinal Modes

The rate equations are accurate only if there is a single optical mode for photons to populate. In a more realistic description, the photons can spontaneously emit and couple to different modes. Photons created by stimulated emission will couple to the same mode as the photon that stimulated it and the resultant output spectrum will have one or more frequency peaks. These frequency peaks correspond to the longitudinal modes of a Fabry–Perot cavity.

As optical waves propagate back and forth in a Fabry–Perot cavity their accumulated phase shifts can cause them to interfere constructively or destructively. Wavelengths that interfere constructively are preferred and make up the different longitudinal modes. The spacing between adjacent longitudinal modes can be expressed by:

$$\Delta v = \frac{c}{2 n_g L}, \qquad (8)$$

where c is the speed of light, n_g is the group index and L is the length of the cavity.

For long haul communications a single mode laser is preferred, as adding unwanted frequencies can exacerbate dispersion. The wavelength dependent gain, resulting from the bandgap of the semiconductor, translates to a mode dependent gain. The result is one or two modes are favored over the rest.

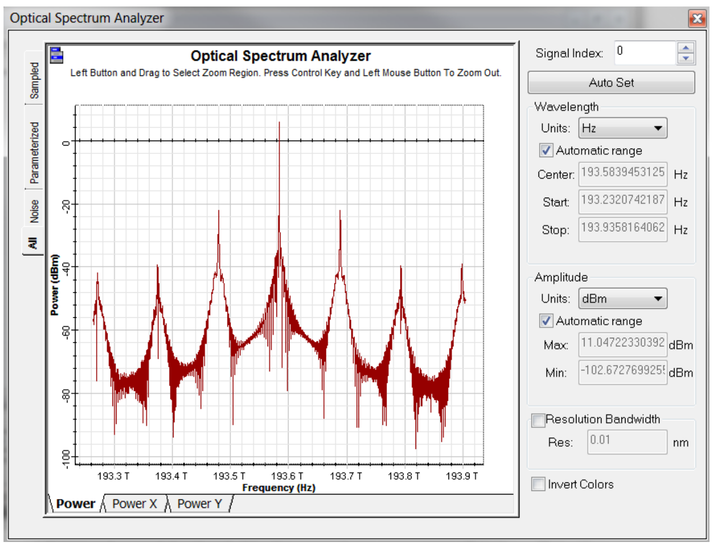

Figure 2: The wavelength dependent gain of the semiconductor favors one of the longitudinal modes over the others.

The side mode suppression ratio (SMSR) is commonly used to quantify the difference in power between the dominant and adjacent mode. It is calculated by comparing the dominant mode's peak power and that of the adjacent mode.

Questions:

2.3.1 Calculate the mode spacing of a 500 μm long cavity with a group index of 3.5.

3 Measuring Threshold Current and SMSR

Once the injection current has increased passed the threshold value, a very large percentage of carriers efficiently recombine to create photons and the output optical power to current graphs becomes linear. To measure the threshold current of a laser, increasing the current bias slowly and recording the optical power is straightforward method that is used experimentally and can also be simulated with OptiSystem.

3.1 OPTISYSTEM PROJECT FILE

Start a new project in OptiSystem and place the following components in the same fashion as the layout below:

- Bias Generator — Transmitters Library/Pulse Generators/Electrical
- Fabry Perot Laser — Transmitters Library/Optical Sources
- Optical Time Domain Visualizer — Visualizer Library/Optical
- Optical Spectrum Analyzer — Visualizer Library/Optical
- Optical Null — Tools Library

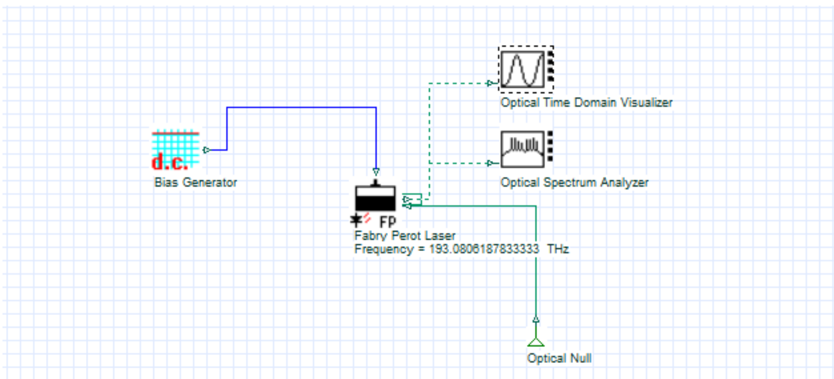

Figure 3: Simulation layout of a Fabry–Perot Laser

Testing the steady state operation of the Fabry Perot Laser requires a constant electrical signal, in OptiSystem a Bias Generator can be used. To locate the threshold current the electrical bias needs to be swept through a linear range, while the output optical power is monitored.

In OptiSystem, electrical pulse generators are measured in arbitrary units, which then can be interpreted as either current or voltage by the driven electrical component. In this case, the Fabry Perot Laser interprets it as a current and scales it according to:

$$\mathrm{I(t) = I_{DC} + I_{in}(t) \times I_{pk}(t),} \tag{9}$$

where I_{DC} and I_{pk} are the Fabry Perot Laser parameters “Bias current” and “Modulation peak current”. The Bias Generator creates the I_{in} value, which in this case is 1. For this simple DC signal, the “Bias current” parameter can be set to 0 and the output of the Bias generator can be directly controlled by the “Modulation peak current”.

3.2 SETTING UP AND RUNNING PARAMETER SWEEP

Perform a parameter sweep of the “Modulation peak current” parameter by first opening the Fabry Perot Laser component properties and changing the “Modulation peak current” mode to sweep. Clicking on the table icon will allow you to set the total number of iterations, which should be set to 10. Make sure to also change the “Laser model” to Transmission Line.

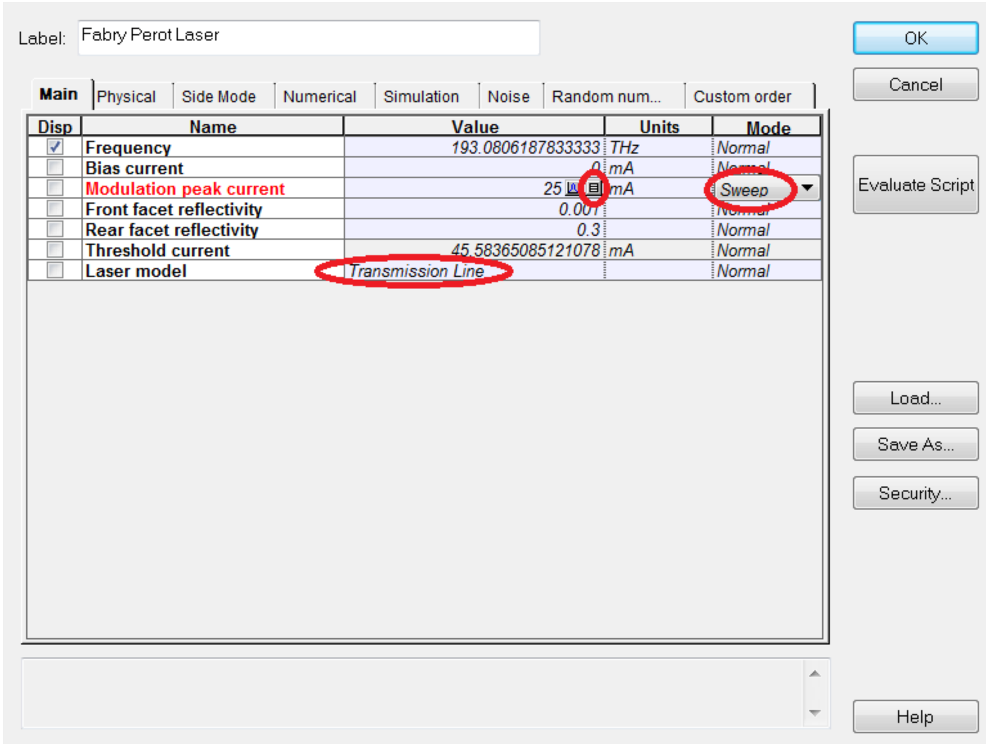

Figure 4: Component Properties window

Click on the "Modulation peak current" column and choose a linear distribution from the spread tools and choose a start and end value of 25 and 70.

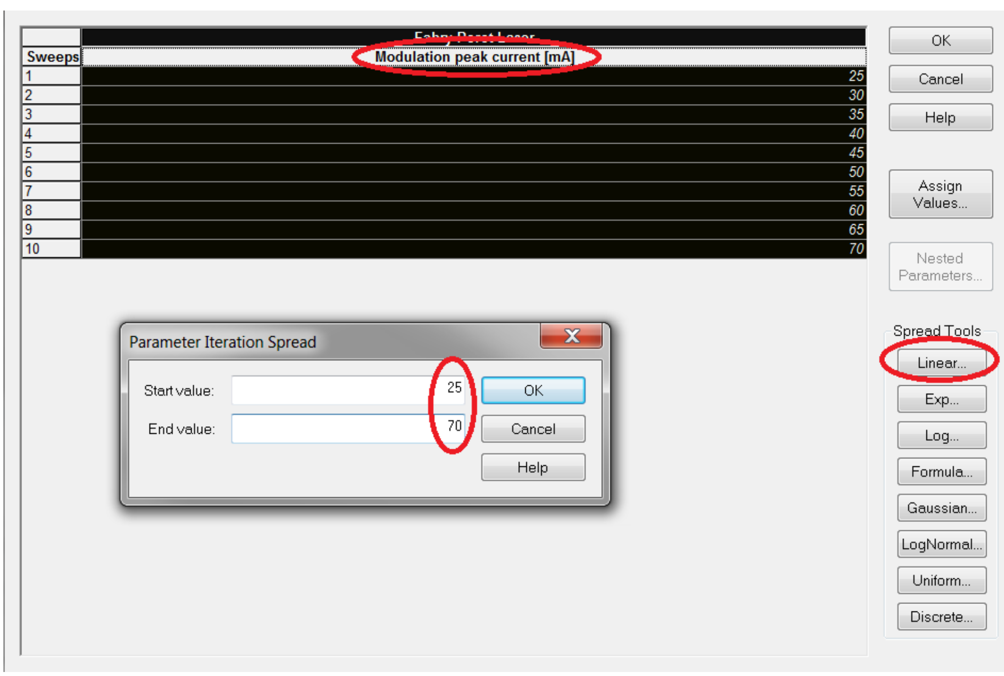

Figure 5: Parameter sweep window

Open the calculation window (Ctrl + F5) and run the simulation, using multithreading if you desire.

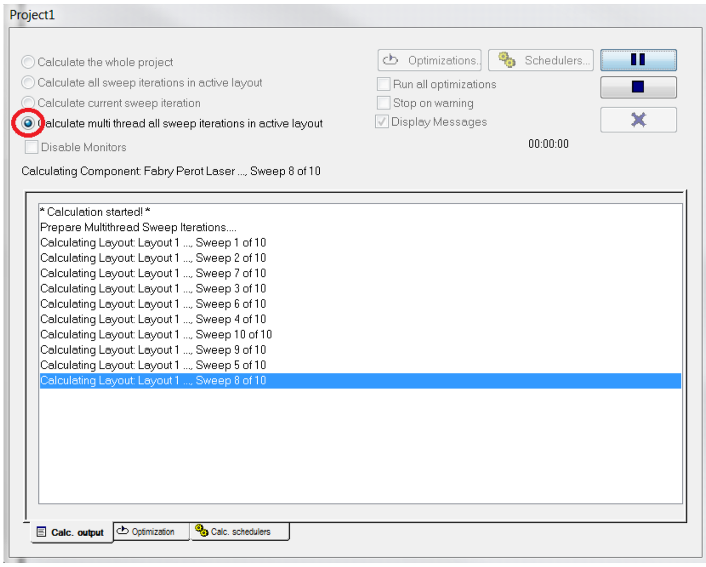

Figure 6: Calculation window

3.3 Results

The threshold current will be clear once the optical power is compared to the injection current. Head to the report page and choose the Opti2DGraph. Dragging a box creates a graph to your desired dimensions

In the project browser on the left locate the “Modulation peak current” parameter and drag it to the *x* axis.

Finally drag the “Signal Power (Mean)” optical time domain visualizer result to the *y* axis.

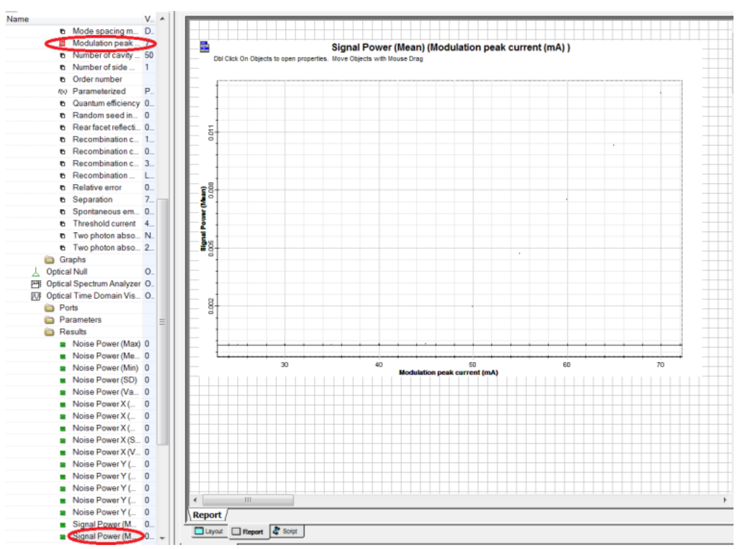

Figure 7: Report page

Using this feature the threshold current can be found graphically. Right-clicking the plot and activating it will allow the placement of Markers, which then can be used to accurately measure the current.

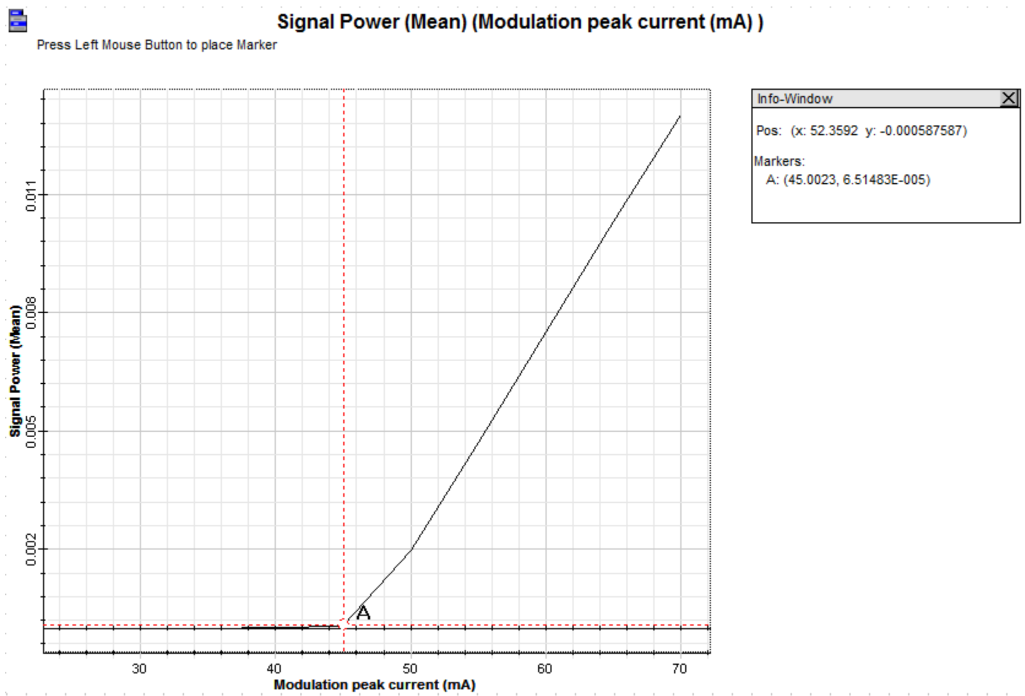

Figure 8: Plot of optical power as a function of the injection current.

For this laser the threshold current is estimated to be 45 mA.

3.4 Characterization of an InGaAsP Laser

Using the previous section as a guide and using the same project layout find the threshold current of a Laser with the following parameters:

Wavelength	1.55 µm
Front facet reflectivity	0.178
Rear facet reflectivity	0.9
Active length	0.01 cm
Active layer width	1.5 µm
Active layer depth	0.2 µm
Group Index	3.5
Quantum efficiency	0.45
Differential gain coefficient	0.4×10^{-15} cm^2
Carrier density at transparency	1e18 cm^{-3}
Mode confinement factor	0.4
Carrier lifetime	1.5 ns
Spontaneous emission factor	0.001
Loss	35 cm^{-1}
Laser model	Transmission Line

Keep all other parameters their default value.

Questions:

3.4.1 Using the graphical method demonstrated plot the P – I curve of this Laser and determine its threshold current.

3.4.2 Find the slope efficiency graphically.

3.4.3 Using a spectrum analyzer determine whether the laser is operating in a single mode manner.

3.4.4 Change the length of the cavity to 500 µm and determine the mode spacing and SMSR at approximately double the new threshold current. Hint: The larger cavity means that the number of cavity sections used in the numerical method must be increased. In the numerical tab of the FP Laser try 100 sections.

4 Report

In your lab report include the following:

- Brief overview of the background and theory.
- Answers to all pre lab questions, clearly showing your work.
- Brief description of the simulation method and setup, including screenshots.
- Final results including figures and discussion.

5 References

[1] Agrawal, G. P. *Fiber-optic Communication Systems*. New York: Wiley, 1997. Print.

[2] Saleh, Bahaa E. A., and Malvin Carl. Teich. *Fundamentals of Photonics*. New York: Wiley, 1991. Print.