

Overview of Modulated and Pulsed Diode Laser Systems

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1 Introduction

In this paper we explore the differences between modulation modes and pulsed modes of laser diode modules and the resulting performance of the lasers. While some applications only require a laser diode to be run in continuous wave (CW) mode, some applications require the laser diode to either be pulsed or modulated. The laser diode modules we will review are typically single mode Fabry-Perot also known as FP lasers in the visible to NIR wavelength range (405nm-1550nm). Although other types of laser structures such as DFB or DBR lasers are also capable of the range of performance detailed in this paper.

2 Pulsed Lasers

A pulsed laser is a system which will emit light in the form of optical pulses, rather than a continuous wave (CW). There are numerous methods to achieve laser pulsing, but the end result follows the same principles. A pulsed laser periodically emits pulses of energy in an ultra-short time duration. These periodic pulses, or pulse train, can be seen in Figure 1. The duration, or pulse width (τ_L) for laser diodes can range from 10's of nanoseconds (10^{-9} seconds) to 10's of picoseconds (10^{-12} seconds). There are several things to consider with the properties and characteristics of pulsed lasers, such as peak power, average power, pulse width, and pulse energy.

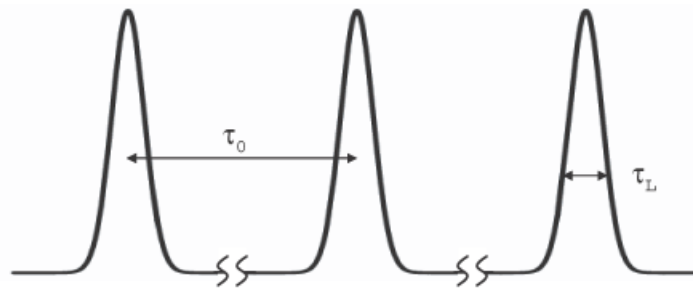


Figure 1: Pulses emitted by a pulsed laser.

2.1 Peak Power

To get a better understanding of the pulses emitted from these lasers we can refer to Figure 1. Here we have a pulse train with a period τ_0 , and a pulse width (or time duration) τ_L ¹. One of the important aspects of these pulses is how much power is delivered with each pulse. This is what is referred to as peak power P_{peak} , which is the maximum amount of power a pulse delivers. Generally, power is defined as the amount of energy with respect to the time it takes to release the energy. We can define peak power as

$$P_{peak} = \frac{Energy}{\tau_L}$$

From this equation, the peak power is dependent upon the pulse width. For a given pulse energy it applies that the shorter the pulse width the greater the peak power. For most diode lasers, the pulse widths can range from nanoseconds (10^{-9} seconds) to picoseconds (10^{-12} seconds). The amount of energy released is very small, ranging from few nanojoules (10^{-9} Joules) to picojoules (10^{-12} Joules).

¹Another term more often used for pulse width is "Full Width at Half Maximum" (FWHM) of optical power versus time. The pulse width τ_L is measured at half of the maximum amplitude of the pulse

2.2 Average Power

An important item to contrast with peak power is average power. The average power of a pulsed laser is defined as the amount of energy released over the period of the cycle. This is expressed as

$$P_{avg} = \frac{Energy}{\tau_0}$$

$$= Energy \times frequency$$

where $frequency = 1/\tau_0$. From this equation it reveals that the shorter the period (or more frequent the pulse) the average power increases.

2.3 Gain Switched Diode Lasers

Many are familiar with traditional Q-switched lasers that allow the production of light pulses with extremely high peak power, much higher than would be produced by the same laser if it were operating in a continuous wave (i.e. constant output) mode.

Gain-switching is a technique similar to Q-switching, which a laser can be made to produce pulses of light of extremely short duration much like a Q-switched laser, of the order of picoseconds (10^{-12} s). The term gain-switching derives from the fact that the optical gain is negative when carrier density or pump intensity in the active region of the device is below threshold, and switches to a positive value when carrier density or the pump intensity exceeds the lasing threshold.

The resulting performance of gain switched laser diodes using either Fabry-Perot or distributed feedback type cavities is a short pulse of 50-100 picoseconds up to 10 times to that of the possible average power for a given diode. However, the average power of such systems is a factor of 100 lower than what is possible running the same diode in CW mode.

In summary gain switched laser diodes produce high peak powers with low average powers at high repetition rates up to 100MHz.

2.4 Gain Switched Diode Laser Manufacturer and Model Example

In this section we will examine a laser from Advanced Laser Diode System, a manufacturer of gain switched diode laser systems. We will use data taken from ALS PiLas040. The system encompasses a laser head which includes a collimator and a laser driver and controller unit that provide the drive current and triggering function for pulsing the diode. This laser emits 408nm pulses with a pulse repetition frequency (PRF) of 1MHz. The laser can be triggered internally (via its own controller) or externally. To control the peak power for every pulse, the PiLas040 is equipped with a "Tune" feature. This feature allows the electrical pumping energy to be adjusted from 0% to 100%.

Example

The following data in Table 1 are actual measurements of a PiLas040.

	Frequency	Tune Value	FWHM(ps)	Avg. Power(μ W)	Pulse Energy(pJ)	Peak Power(mW)
1	100kHz	30%	32.4	0.934	9	278
2	100kHz	60%	24.3	1.558	15	617
3	100kHz	90%	24.4	2.415	24	984

Table 1: Actual test data from a PiLas040

Using the equations from Sections 2.1 & 2.2 we can verify all of the given data within reasonable approximation. Taking the data from row 1 the peak power is calculated as

$$P_{peak} = \frac{9 \times 10^{-12} J}{32.4 \times 10^{-12} s} = .278 W$$

$$P_{peak} = 278mW$$

The average power can be calculated as

$$P_{avg} = (9 \times 10^{-12}J) \times (100 \times 10^3Hz) = 9 \times 10^{-7}W$$

$$P_{avg} = 0.9\mu W$$

The following figure is an actual measurement of the pulses in Table1. As the data indicates, as the peak power increases the pulse width decreases. This observation is concomitant with the equations.

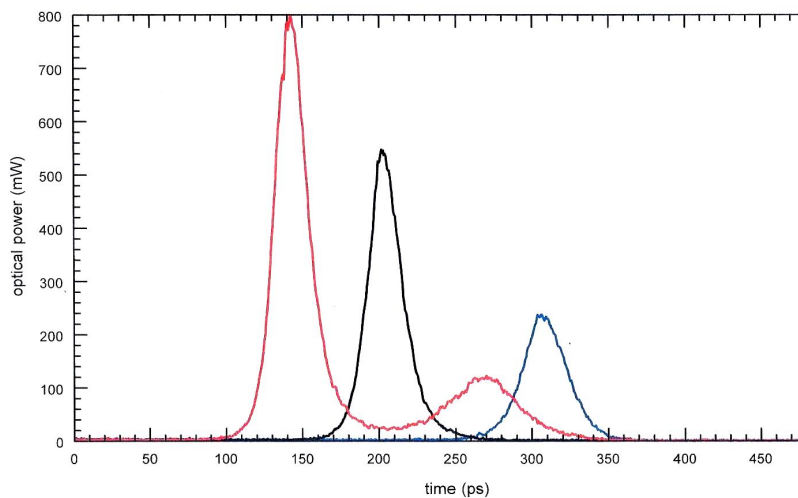


Figure 2: Scan measurements at 100kHz. Tune 30%: 32ps-235mW (blue); Tune 60%: 24ps-540mW (black); Tune 90%: 24ps-795mW (red).

3 Modulated Lasers

A modulated diode laser is a CW laser system in which its output power can be manipulated in accordance to an input signal triggering it. One of the most common application for a modulated diode laser is to input a periodic analog or digital signal, such that it will be modulated between an "on" state and "off" state, as seen in Figure 3. Because the pulse train in Figure 3 has similar qualities as in Figure 1, there is a common misconception that a modulated laser is the same as a pulsed laser. This is not the case. In this particular application the main difference between the modulated laser and pulsed laser is the modulated laser is simply turning on and off periodically. Whereas, a pulsed laser will release burst of energy periodically. The modulated laser will only turn on to a set maximum output power, regardless how quickly or slowly the laser is modulating between the on and off states. We will discuss in the later sections the unique features the modulated diode laser can offer, in regards to pulse shaping.

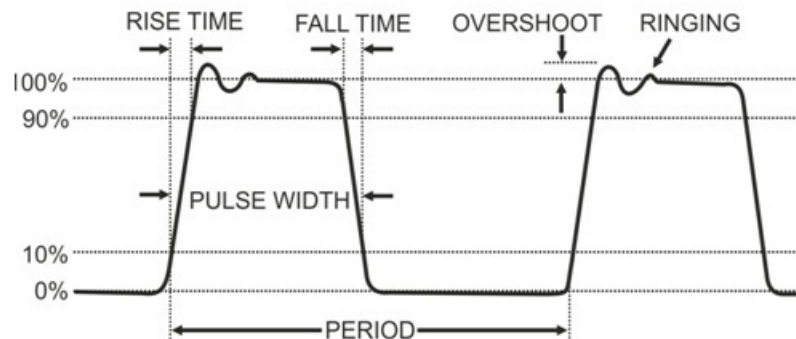


Figure 3: Pulse train emitted from a modulated laser.

3.1 Modulation Properties

In this section we will discuss the properties of the modulated diode laser, and get a better contrast from the pulsed laser systems. Comparing Figure 3 to Figure 1, we see that there are distinct differences between the pulse trains. Although the period and pulse width can be measured in the exact same way as you would for a pulsed laser, the overshoot, ringing, rise time, and fall time are other factors that must be considered.

3.1.1 Rise and Fall Time

Even with more advanced electronic switching system, an instantaneous transition from on→off & off→on is impossible. A short duration of time, also known as rise and fall time, is required for the laser to turn “on” and “off”. Rise time refers to the time required for a signal to change from a specified low value to a specified high value. Fall time is just the opposite, as it is the time required for a signal to change from a specified high value to a specified low value.

3.1.2 Overshoot and Ringing

Overshoot and ringing in a pulse train are due to the electronics of the laser system and the natural behavior of semiconductor materials. In a laser diode, there is always a delay in the development of laser radiation with respect to the pump. Whenever pump is above the threshold requirement, the population inversion also develops above the threshold followed by delayed spiking at regular intervals in laser output, the amplitude of which decays exponentially until the laser attains the steady state mode.

Overshoot and ringing can be compensated with more sophisticated laser diode drivers.

3.1.3 Extinction Ratio

The extinction ratio, also known as the depth of modulation, is a ratio between the power levels of the on state, P_{on} , and the off state, P_{off} .

$$\text{Extinction Ratio} = \frac{P_{on}}{P_{off}}$$

For example, if a laser is at 100mW in the on state and 0.1mW in the off state, the extinction ratio will be 1000:1. The depth of modulation increase as the P_{off} approaches 0. The extinction ratio can be a very important factor for applications that require a high modulation rate and low light leakage in the off state.

3.1.4 Duty Cycle

The duty cycle is the percentage of how long the laser is in the “on” state in the given modulated period. For instance, a laser with a 70% duty cycle is in the “on” state 70% of the period and off 30%. The duty cycle can be defined as

$$Duty\ Cycle = \frac{Pulse\ Width}{Period}$$

Another important aspect to understand about the duty cycle is the pulse repetition rate. This rate is a useful reference as to how frequently the laser is externally controlled. The pulse repetition rate is defined as the inverse of the period

$$Pulse\ Repetition\ Rate = \frac{1}{Period}$$

3.2 Average Power

Because the peak power of a modulated diode laser's pulse train is set to a fixed value, the average power is very simple to calculate. We will use the equations from Section 2.1 and solve for *Energy*, which gives us

$$Energy = P_{peak}\tau_L = P_{avg}\tau_0$$

where τ_0 and τ_L are the period and pulse width, respectively. Using the equation from Section 3.1.4 we have the following relationship

$$Duty\ Cycle = \frac{Pulse\ Width}{Period}$$

$$Duty\ Cycle = \frac{\tau_L}{\tau_0} = \frac{P_{avg}}{P_{peak}}$$

Therefore our average power is

$$P_{avg} = P_{peak} \times Duty\ Cycle$$

3.3 Analog and Digital Input Signals for Modulated Diode Lasers

An analog signal is a continuous signal which gives you the capability to modulate the laser at a given frequency with a varying amplitude, as seen in Figure 4(a). Whereas, a digital signal is a discontinuous signal with a discrete maximum (on state) and minimum (off state), which gives you the capability to modulate between on and off states, as seen in Figure 4(b). When combining the two signals you are able to shape the pulses, as seen in Figure 4(c). The digital signal can be used to cut portions of the analog signal.

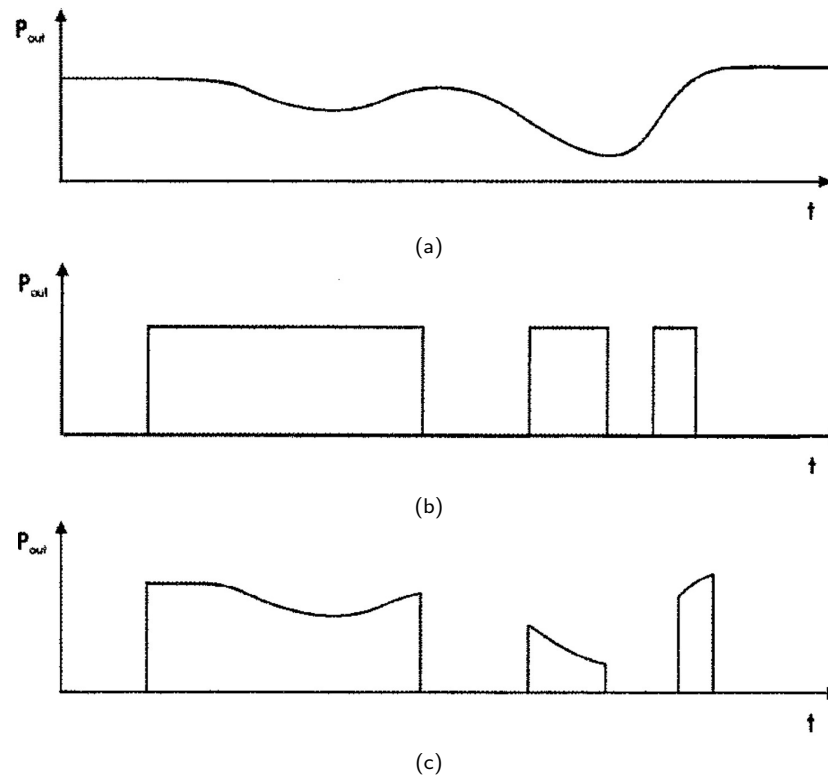


Figure 4: (a) Analog signal (b) Digital signal (c) Combined digital and analog signals

3.3.1 TTL and Other Differential Signal

The qualitative factors for a high frequency response in driving diode lasers are the digital input signals themselves. Single ended signaling such as TTL (Transistor-Transistor Logic) and 0 to 1V/50Ω, have short rise and fall times and are found to be very useful for digital modulation in frequency ranges of DC to 150MHz. Differential signaling like PECL (Positive Emitter Coupled Logic), LV-PECL (Low-Voltage Positive Emitter Coupled Logic) and LVDS (Low-Voltage Differential Signaling) are ultra-high speed digital logic technologies, and are able to modulate at higher frequencies with minimal noise, up to 500MHz or higher.

3.3.2 Diode Laser Manufacturer and Model Example

Omicron-Laserage is a manufacturer of high depth modulated diode laser systems. For this example we will examine a PhoxX 405 (405nm wavelength) diode laser module. The system encompasses a laser head that includes the diode, thermoelectric cooler, collimator and beam circularization and laser controller including the diode and TEC drivers. This module includes five modes of operation: CW operation, analog modulation, digital modulation, Laser Enable modulation, and mixed analog and digital modulation. The modulation modes are triggered by an external signal generator. The output power and operation modes can be changed and configured through Omicron's user-friendly laser communication software. For this example we will examine the PhoxX's modulation modes.

In the analog modulation mode, the PhoxX 405 is able to modulate up to 3MHz with a signal voltage amplitude range of 0-5 volts. As discussed in Section 3.3, the laser's output power will alter in accordance to the input analog signal. In the digital mode, the PhoxX 405 can be modulated (between on and off states) up to 180MHz by either a TTL signal or other ultra-high speed differential signals discussed in Section 3.3.1. The laser enable mode is similar to the digital modulation mode. The only difference is that this feature is able to modulate the laser "completely" on and off. It has

a much higher depth of modulation than the digital mode, but it is only able to operate up to 250kHz by a TTL signal. Finally, the mixed analog and digital modulation combines both the modes together and shape the laser's pulses, as seen in Figure 5.

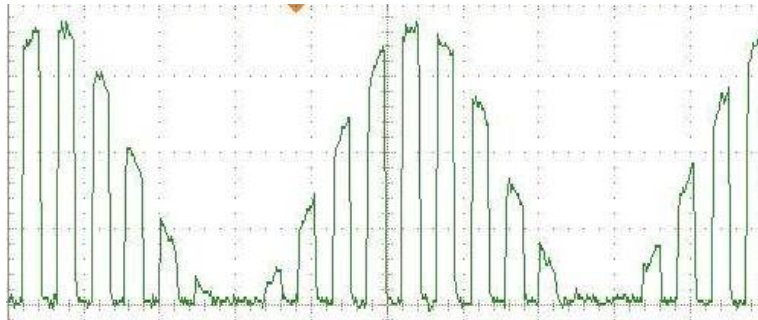


Figure 5: Measurement of the optical output of an Omicron PhoxX 405. A sine wave analog modulation at 1MHz mixed with a PECL differential digital modulation at 11MHz with a 50:50 duty cycle.

Example

In an exemplary application, a PhoxX 405-60 is being used to expose a sample. For this application the PhoxX 405 needs to be digitally modulated at 150kHz, must have low light leakage in the off state, and needs to be in the off state for 1 microsecond in each cycle of modulation. Furthermore, sample cannot be exposed to anything greater than 35mW on average. (a)What is the best operation mode for this experiment? (b) What will the duty cycle of the signal generator need to be set to in order to accommodate the 1μs off state? (c) What is the maximum power level setting on the PhoxX 405?

(a) Laser Enable mode will be the best operating mode for the experiment. Because this experiment require low light leakage and is modulating under 250kHz, the Laser Enable mode offers complete on and off states and high extinction ratio.

(b)In order to determine the duty cycle we must determine the period of the signal. We know that the frequency or pulse repetition rate needs to be 150kHz, so using the equation from Section 3.1.3 we get

$$150\text{kHz} = \frac{1}{\text{Period}}$$

$$\text{Period} = 6.67 \times 10^{-6}\text{s}$$

$$\text{Period} = 6.67\mu\text{s}$$

Out of the 6.67μs we need 1μs to be in the off state, leaving us with 5.67 μs in the on state. Therefore our pulse width is 5.67 μs, and the duty cycle can be calculated as

$$\text{Duty Cycle} = \frac{5.67 \times 10^{-6}\text{s}}{6.67 \times 10^{-6}\text{s}}$$

$$\boxed{\text{Duty Cycle} = .85 \Rightarrow 85\%}$$

(c) Finally, we can use the equation in Section 3.2 to find our maximum power setting for the PhoxX 405.

$$P_{peak} = \frac{P_{avg}}{Duty\ Cycle}$$

$$P_{peak} = \frac{35mW}{.85}$$

$$P_{peak} = 41.2mW$$

So 41.2mW is the maximum power level setting for the PhoxX 405.

4 Summary

While the performance of individual systems can vary based on the specific wavelength and laser structure of the diode used in the system, we have shown the basic differences in operational modes of gain switched (pulsed) and modulated FP based diode laser systems. We trust this will provide a better understanding of the features and benefits of using such systems in your application.