

## **Selection and Construction of an RF-modulated Laser Diode System for Frequency Domain Photon Migration (FDPM)**

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Special thanks to Siavash Yazdanfar, Ph.D. (Applied Optics Lab, GE Global Research, Niskayuna, NY) for many helpful discussions.

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## Step 1. Laser Diode (LD) Selection

To select an appropriate laser diode one needs to know the required

1. output power range,
2. wavelength range,
3. desired rise-time/frequency response, and
4. packaging for the system.

Once these parameters are known, one can pick a laser diode from any vendor.

We have used Thorlabs (Newton, NJ) photonics devices for our system. Thorlabs offers an extensive selection of discreet laser diodes with wavelengths ranging from 405 nm to 2004 nm, 3 different types of packaging, i.e., 5.6 mm, 9 mm, and VCSEL packages, and output power ranges from 5 mW to 2 W.

For our application, we are interested in NIR wavelengths (770-790 nm excitation) and an output power of ~50 mW or higher. We do not have a packaging preference. Based on the given specifications we picked the following two laser diodes:

Part Number	Wavelength (nm)	Power (mW)	Package (mm)	Threshold Current (mA)	Mode
GH0781JA2C	781.00	120.00	5.6	30	Single Mode
HL7851G	785.00	50.00	9.0	45	Single Mode

**Note:**

- If you already have a mount for the laser diode, make sure your mount supports the packing and pin configuration of the selected laser diode.
- Although many laser diodes can be modulated, it is always advisable to check the specification of the laser diode to verify it can be modulated. Usually the ones that can be modulated include pulsed optical power output in the specifications.

## Step 2. Laser Diode Mount

Because we would like to modulate the laser with an external RF source, we need an interface between the RF source, the DC power, and the laser. We have chosen a diode mount from Thorlabs to facilitate this interface. While one could build such an interface using a Bias-Tee, etc., we chose to use the TCLDM9 mount from Thorlabs due to its unique features. TCLDM9 is a Temperature Controlled Laser Diode Mount and has an RF input for modulating the laser with an external RF source from 200 KHz up to 500 MHz (see Table 2). The RF input is AC-coupled directly to the laser diode via a Bias-Tee network. Additionally, it supports all 3-pin and 4-pin laser diodes with 9 mm and 5.6 mm packages. Our selected diodes, GH0781JA2C and HL7851G, have different packages (5.6 mm vs 9.0 mm), so this is an ideal choice for us.

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### Note:

- When selecting a diode mount, in addition to the package sizes, one needs to make sure that the mount's power and maximum laser current are compatible with those of the selected laser diodes. Make sure the diode's maximum current is less than what the mount device can handle.

Our selected laser mount is a high power Butterfly Laser Diode Mount, and its characteristics are given in Table 2.

<b>Part Number</b>
<b>TCLDM9 - TE-Cooled Mount For 5.6 &amp; 9mm Lasers</b>

TABLE 2. TCLDM9 SPECIFICATIONS	
Laser Diode Package:	5.6mm & 9mm
Maximum Laser Current:	2A
Polarity of Laser Diode:	Selectable
Polarity of Monitor Diode:	Selectable
Maximum RF Power:	200mW, RMS
RF Input Impedance:	50 Ohm
Modulation Frequency (Bias-T):	0.2 to 500 MHz
Maximum TEC Current:	5A
Maximum TEC Voltage:	4V
TEC Heating/ Cooling Capacity:	20W
TEC Interface:	DB9 Male
Temperature Sensor:	AD592, 10k Thermistor
Temperature Range (@25°C with 2A TEC Current):	+5 to 70°C
<i>Source: Thorlabs data sheet.</i>	



Another nice feature of the TCLDM9 device is that its front plate is equipped with tapped holes to mount extension rods (#4-40 threaded holes on 30 mm centers), and its bottom surface provides #8-32 and M4 mounting holes. All the required screws and parts for mounting are provided by Thorlabs as well. For more information please see the operating manual.

### Step 3. Laser Controller

After the laser diode is mounted, we need a way of controlling the injection current and/or the optical power output of the diode before it can be operated. We have chosen Thorlabs LDC220 Laser Diode Current Controller. This is a high power controller and is compatible with all laser diode and photo diode polarities. Additionally, it has built-in protection features to ensure that the maximum allowed laser current cannot be exceeded. Any time the laser current reaches the pre-set current limit, an LED lights up and a short warning beep goes off. The protection feature also works when one is using the external modulation feature, i.e., the current cannot exceed the current limit.

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The LDC220 allows us to drive the laser diodes in either Constant Current (CC) or Constant Power (CP) modes (provided that the laser diode can be driven in constant power mode). In the CC mode, the user sets a current level and the current to the laser is held precisely at this level. CC mode is used when the lowest noise and highest response speed is required. In CP mode, a photodiode and a feedback circuit is used to actively stabilize and adjust the output power of the laser.

The LDC220 additionally provides an analog modulation input and analog monitor output for the laser current. For more information please see the operating manual.

Part Number
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LDC220 - Benchtop Laser Diode Current Controller, $\pm 2A$
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FIGURE 1. LDC220 controller

### Step 4. Thermo-Electric Cooler (TEC) Controller

The optical properties of a laser diode are a function of its laser chip temperature and thus it is very important to maintain the laser diode's temperature at its typical operating temperature for wavelength stability. For example, the wavelength of a typical GaAlAs diode increases by nearly 0.25 nm for each 1°C temperature increase. Undesirable mode hopping that results in frequency and intensity noise is another side effect of wavelength change in single mode laser diodes. The output power of the laser is also adversely affected if the temperature fluctuates; if the laser is running near its maximum rated power, such fluctuations can lead to premature failure.

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We have chosen the TED200 thermoelectric temperature controller from Thorlabs. A variety of temperature sensors are supported by this controller including the thermistor and the temperature-IC installed in the TCLDM9. TCLDM9 is specifically designed to interface easily with the TED controllers.

<b>Part Number</b>
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<b>TED200</b> – Benchtop Temperature Controller, $\pm 2A/12W$
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The TED200 device uses a Proportional-Integral-Derivative (PID) controller to adjust the actual temperature to the desired temperature level. This controller is a feedback-loop controller that operates based on the idea of minimizing the error (i.e., the difference between the actual temperature measurement and the desired set-point) by three different manipulations, including error multiplication by a gain, P (proportional); multiplication of the integral of the error over a period of time by a gain, I (integral); and finally, multiplication of the error change rate (or the first derivative) by a gain, D (derivative). Setting these three parameters correctly is the key to reaching the desired set-point in a short time, with minimal overshoot and little error. A proportional controller (P) reduces the rise time and the steady-state error (it cannot eliminate the error). An integral control (I) eliminates the steady-state error, but it can potentially worsen the transient response. A derivative control (D) increases the stability of the system, reduces the overshoot, and improves the transient response. It is important to note that these three parameters are dependent on each other and changing any one of them will affect the other two.

Effects of each of P, D, and I on a closed-loop system are summarized in the table shown below.

Gain	Rise Time	Overshoot	Settling time	Steady-State Error
<b>P</b>	Decrease	Increase	Small Change	Decrease
<b>I</b>	Decrease	Increase	Increase	Eliminate
<b>D</b>	Small Change	Decrease	Decrease	Small Change

Instructions on how to set and fine tune these parameters are given in the TED200 instruction manual.

<b>TABLE 3. TED200 SPECIFICATIONS</b>	
<b>TEC Current Output</b>	
Control Range:	-2A to +2A
Compliance Voltage:	>6V
Maximum Output Power:	12W
Measurement Resolution:	1mA
Control Range:	-2A to +2A
Accuracy:	$\pm 20mA$
Noise and Ripple (typ.):	<1mA
<b>Thermistor Sensors</b>	
Control Range	10 $\Omega$ to 19.99k $\Omega$ / 100 $\Omega$ to 199.90k $\Omega$ (2 Ranges)
<b>IC Sensors</b>	
Supported Sensors	AD590, AD592, LM335
Control Range with AD590	-25 $^{\circ}C$ to 105 $^{\circ}C$
<i>Source: Thorlabs data sheet.</i>	



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## Step 5. Collimator Lens

Many laser diodes (including the ones we selected) have a wide beam divergence (perpendicular axis), and we need to use a collimating or focusing lens to collect and re-focus the beam. It is very important to use the right lens with a large enough numerical aperture (NA) to efficiently collect the laser beam.

The NA value for the GH0781JA2C (using the formulas in Appendix C) is approximately 0.4, and a lens with NA greater than or equal to 0.4 will effectively collimate the beams. We have used the C110TME-B aspheric lens from Thorlabs for collimation.

<b>Part Number</b>
<b>C110TME-B</b> - f=6.24mm 0.40NA Mounted Geltech™ Aspheric Lens, AR Coating: 600-1050nm

<b>TABLE 4. C110TME LENS CHARACTERISTICS</b>							
Item Number	f (mm)	NA	Clear Aperture (mm)	Working Distance (mm)	Housing Diameter (mm)	Center Thickness (mm)	Design Wavelength (nm)
<b>C110TME</b>	6.24	.40	5.00	3.44	9.24	5.36	780

Source: Thorlabs data sheet.

### Note:

- It is better to buy Mounted Glass Aspheric Lenses (as opposed to unmounted ones) since they are easier to handle and are ready to use. (They do not require additional mounting to an adapter, etc.)

## Step 6. Lens Mount/Adapter

To attach a collimator lens (or any other lens) we need a lens mount or an adapter. The aspheric lens adapters for 1.0" threads from Thorlabs provide an easy method for integrating the mounted aspheric lens into the TCLDM9. The threaded lens cells thread into the center of the adapter ring. The adapter rings are all 0.275" thick and contain a rubber friction ring to prevent movement once set.



<b>Part Number</b>
<b>S1TM09</b> - SM1 to M9 aspheric lens cell adapter

S1TM09 is compatible with: C110TME, C220TME, C230TM, C260TM, C280TM, C230220P, C230260P, C330TM, C340TM, C560TME, and C671TM.

## Step 7. Stand-Alone High-Speed Photodetector (i.e., Photoreceiver)

To view and measure the optical output of a laser diode requires a stand-alone photodetector, i.e., photoreceiver. We routinely use a high speed (125 MHz) photoreceiver manufactured by New Focus (San Jose, CA). This photoreceiver contains a photodiode that is followed by a low-noise amplifier acting as a pre-amp with a compensating amplifier circuit as the output stage. This model offers a unique combination of low-noise, bandwidth, and gain over the DC to 125 MHz frequency range. This photoreceiver provides great sensitivity for




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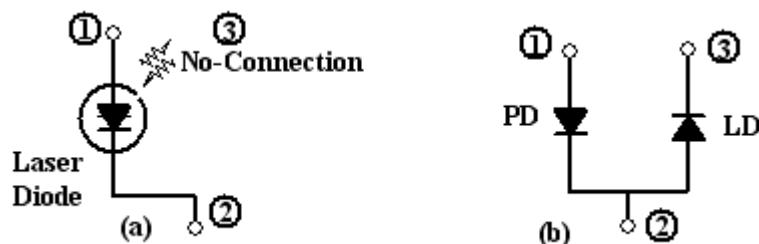
very short rise and fall time signals, due to their low NEP and high trans-impedance. The wavelength range for this model is 300-1000 nm.

Wavelength Range	320-1000 nm	
3-dB Bandwidth (DC versions)	125 MHz	
3-dB Bandwidth (AC versions)	25 kHz-125 MHz	
Rise Time	3 ns	
Maximum Conversion Gain	$2 \times 10^4$ V/W	
Typical Maximum Responsivity	0.5 A/W @ 800 nm	
Transimpedance Gain	$4 \times 10^4$ V/A	
Output Impedance	50 $\Omega$	
Minimum NEP	3.3 pW/ $\sqrt{\text{Hz}}$	
cw Saturation Power	110 $\mu\text{W}$ @ 800 nm	
Maximum Pulse Power	10 mW	
Detector Material/Type	Si/PIN	
Detector Diameter	0.4 mm	
Power Requirements	$\pm 15$ V DC, < 250 mA	
Optical Output	Free Space	
Electrical Output	SMA	

Source: New Focus data sheet.

### Step 8. System Operation

The GH0781JA2C diode does not have an internal photodiode for feedback (see Terminal Connection in Figure 2(a)) and cannot be operated in constant-power mode. Pin configuration for HL7851G is shown in Figure 2(b). This diode has an internal photodiode.



**FIGURE 2.** Terminal connections (a) GH0781JA2C; (b) HL7851G.

The diode mount comes with two thermoelectric coolers (TEC) and two temperature sensors; i) an AD592 Temperature Transducer, and ii) a 10K $\Omega$  NTC thermistor. The Thorlabs TED200 supports both sensors; however, only one of them can be used as a temperature sensor. In principal, there is no difference between the two (thermistors are slightly faster than temperature-ICs). However, if the temperature controller (TED200) is operated with the thermistor as the temperature sensor, the thermistor resistance at set temperature “TSET” must be in K $\Omega$ . If the TED200 is operated with a temperature-IC (i.e., AD592) the temperature is shown in  $^{\circ}\text{C}$ .

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(The dependency of resistance on temperature and vice-versa of an NTC thermistor is described by a formula given in Appendix B. The values for TH10KΩ thermistor used in TCLDM9 are also given in this appendix.)

### **Note:**

One should not use the AD590 temperature sensor together with the Bias-T (i.e., during RF modulation) because the sensor produces current drifts through the RF and therefore causes temperature drifts of the diode. With the thermistor as sensor the temperature controller works fine. (Source: Thorlabs' technical notes.)

### **Additional notes:**

Be careful of the maximum operation current when working with diodes, especially with external modulation since there is no protection circuit for the diode when working with an external source that is connected to the TCLDM9 mount.

To modulate the laser diode with an external RF source, one needs to consider the following:

Although you are using an external signal generator to drive the RF as input to the TCLDM9, you still need to use the laser diode driver (LDC) to set the DC level. You are basically using the LDC to bias the laser diode on. It is recommended to use the driver in the constant current mode for best results.

Before setting the signal values note that when one applies a signal to the Bias-Tee input, that signal will be superimposed on the DC operating level set by the LDC driver. If you apply a 20 mA p-p signal to a 40 mA DC bias current, **and** your threshold current is 20 mA, your laser diode will "see" a drive current ranging from 30 mA to 50 mA (20 mA centered on the 40mA bias current).

Be careful to set the LDC drive value such that the negative cycle of the modulation signal does not drive the laser below its threshold level or the output from the laser diode will be clipped on the bottom. At all times the following three relations should hold:

$$\text{i) } I_{LDC} > I_{th}, \quad \text{ii) } I_{LDC} + \frac{I_{p-p}}{2} \leq I_{typ}, \quad \text{iii) } I_{LDC} - \frac{I_{p-p}}{2} \geq I_{th},$$

where  $I_{LDC}$  is the LDC driver's current,  $I_{th}$  is the LD's threshold current,  $I_{typ}$  is the LD's typical operating current, and  $I_{p-p}$  is the peak-to-peak value of the RF signal applied.

The best approach to using the Bias-Tee input is to do the following:

1. Disconnect the RF signal generator completely from the TCLDM9,
2. Apply a current from the LDC driver while monitoring the output of the LD on an oscilloscope. The best way to observe the LD output is to use a high-speed photodiode as described in Step 7. These devices should be fast enough for the frequency modulation that you will be working with and also be appropriate for the wavelength of the laser diode.
3. Increase the current until you are at the maximum level you wish to operate the laser. Note the level on the scope (cursors are handy for this).
4. Reduce the LDC current to 1/2 of the operating current range. This should be the maximum current you just were at **minus** the threshold current ( $I_{typ} - I_{th}$ ).



$$I_{LDC} = I_{typ} - [(I_{typ} - I_{th})/2]$$

This is the DC operating current that will let you ideally modulate the LD with full depth of modulation from  $I_{th}$  to  $I_{typ}$ .

5. Set your signal generator output to zero and connect it to the RF input of the TCLDM9.
6. Slowly increase the RF voltage while observing the LD output on the scope.
7. You should start to see the output modulate in response to your input signal.
8. Continue to increase your RF voltage until the peak level reaches the level observed in Step 3 above, OR your RF voltage has reached 4V (see calculation below). This is the maximum depth of modulation that you can achieve from this set-up.

You can also reduce your RF level and increase your bias current from the LDC, just be careful not to exceed the limit you measured in Step 3.

**Note:**

The Max RF power of the TCLDM9 is 200 mW, which means the maximum contribution of the RF to the current is calculated as follows:

$$p = RI^2 \rightarrow I_{RMS} = \sqrt{\frac{p}{R}} = \sqrt{\frac{200 \times 10^{-3}}{50}} = 63.25 \text{ mA and } I_{p-p} = 89.4 \text{ mA}$$

$$V = RI = 50 \times 84.9 = 4.245 \text{ v}$$

Also note that the frequency response of the bias-T is 200 kHz to 500 MHz. The Bias-Tee will not conduct below this frequency.

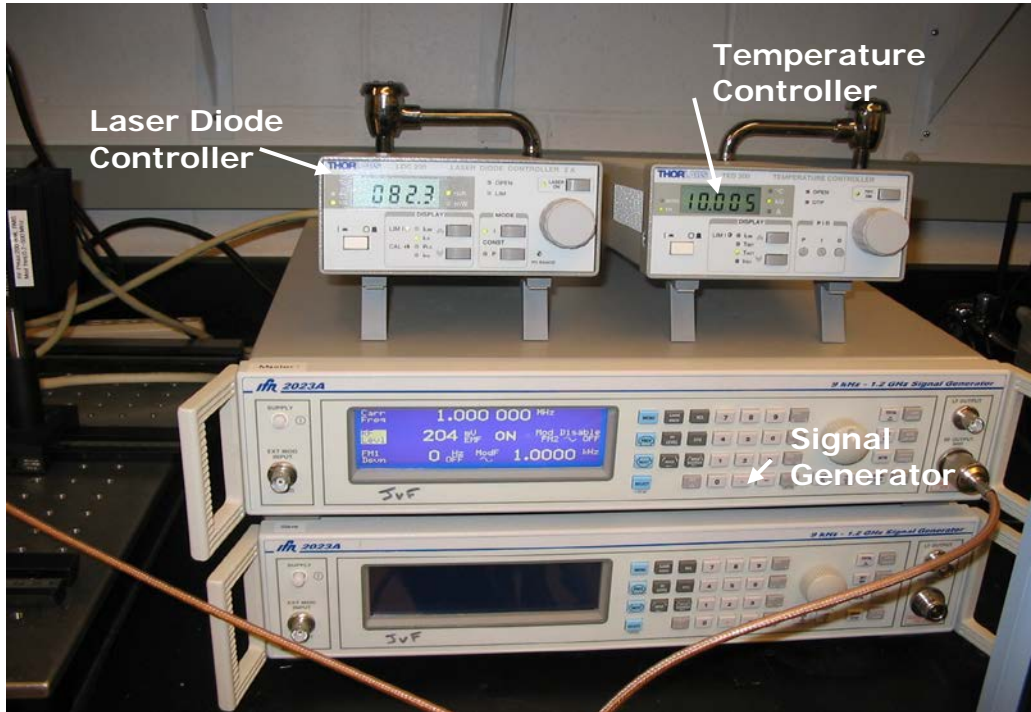
It is recommended that one starts with low modulation signals first to get a sense of how the circuit is working (practice). It is also recommended that one use an inexpensive test laser diode to set this up.

Figure 3 through Figure 6 show the images of the system setup for RF modulation. The system includes the following devices: TED200, LDC220, TCLDM9, photo-receiver, a signal generator, an RF amplifier, and an oscilloscope.

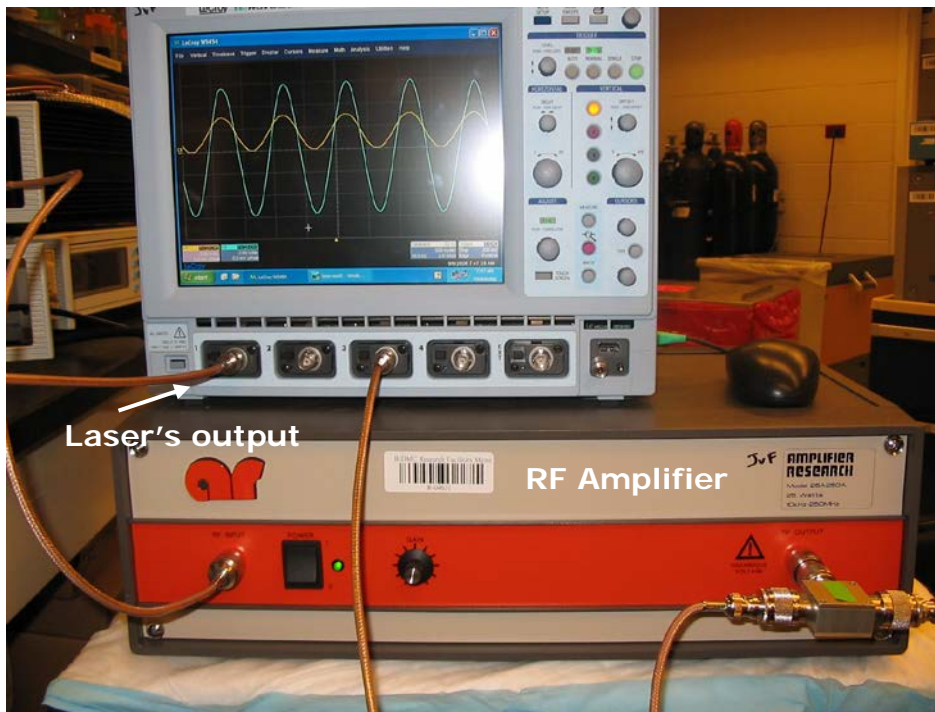
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**FIGURE 3.** Thorlabs Temperature Controller (TED200), Laser Diode Controller (LDC 220), and Aeroflex 2023A signal generator. The output of the signal generator is fed into an RF amplifier shown in Figure 4.

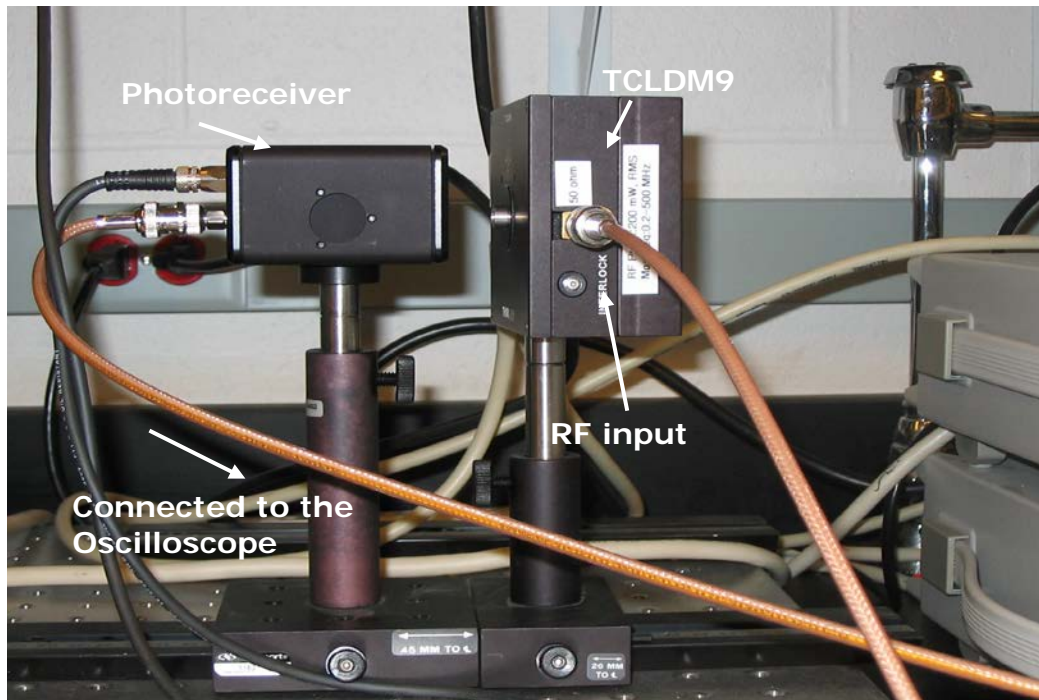


**FIGURE 4.** RF amplifier and the oscilloscope. Signals shown on the oscilloscope are i) the RF amplifier output that is also the RF input to the TCLDM9 mount and ii) the laser diode modulated output captured by the photo-receiver.

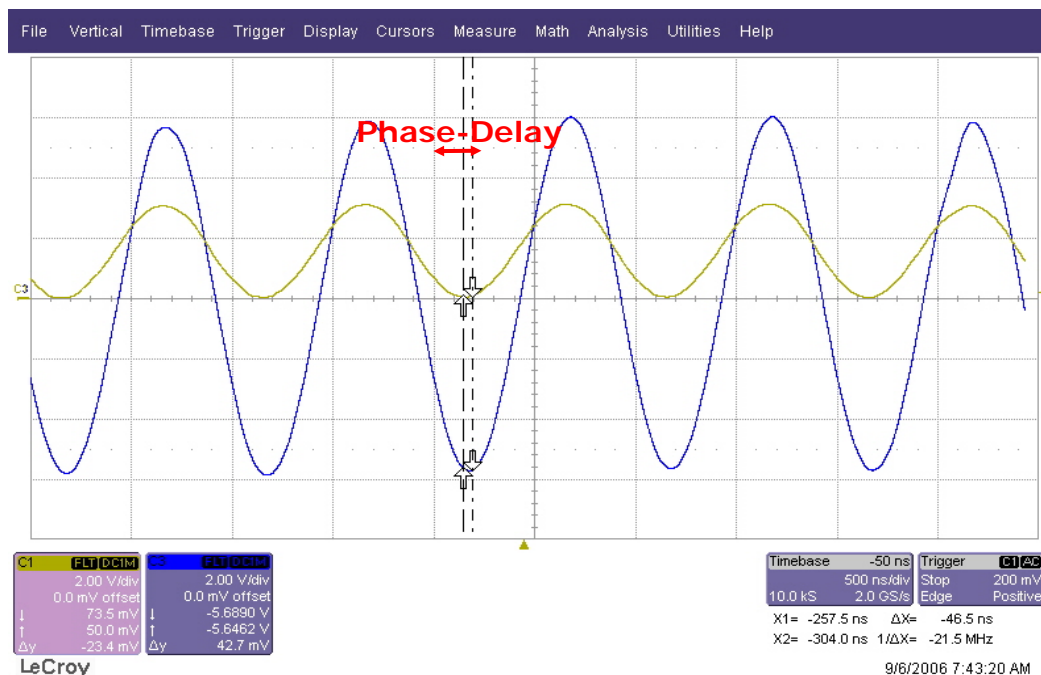
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**FIGURE 5.** TCLDM9 that is connected to the Temperature controller, LD controller and RF output of the RF amplifier. The output of the TCLDM9 is received by the photo-receiver on the left.



**FIGURE 6.** Modulated laser signal (yellow signal) and RF input (Blue signal). As it can be observed from this picture there is a phase difference between the two signals that is due to inherent delay in the system.

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## A Few Safety Recommendations

It is strongly recommended that the following items are used to ensure safe handling of the laser system.

### 1. Protective eyewear

To minimize the risk of exposing your eyes to the laser beam, you must use laser protective eyewear. Such protective eyewear is available in different shapes and styles, but the most important parameter in selecting an eyewear is the optical density (OD) for the specific wavelength range. Kentek Corporation (Pittsfield, NH) is a company that offers a wide range of laser protective eyewears.

### 2. IR viewing card

When working with a laser diode, **you must never look into the beam under any circumstances**. IR and UV wavelength are invisible to the human eye, so there is no perception of actual intensity. Hence, use of an IR viewing card is strongly recommended to help detect the beam.

We have used Thorlabs IRC3 card. This is a small card (2.4" x 1.79") and is designed for the 700-1400 nm wavelength range. This card requires room light charging. Its 1.5" x 0.75" sensor area is encapsulated between durable clear plastic. After charging, invisible light appears as a yellow glow on the card, which can be seen even when wearing safety goggles.



<b>Part Number</b>
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<b>IRC3</b> - Viewing Card for IR Band (700-1400nm)
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### 3. Grounding wrist strap

When dealing with static sensitive devices (such as laser diodes) it is recommended that a device to eliminate static charges be used. We have used Thorlabs' Grounding Wrist Strap. This wrist strap is a 6-foot coiled cord and is equipped with alligator clips for ground connection. The ground cord has a built-in 1 M $\Omega$  resistor for user safety.



<b>Part Number</b>
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<b>GWS02</b> - Grounding Wrist Strap w/ Coiled Cord One Size
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**How to Fiber Couple the Laser**

Some biomedical applications will require coupling of the laser diode to an optical fiber. To fiber couple the laser we need to collimate and focus the laser beam. The fiber we use routinely has a 300  $\mu\text{m}$  core, with  $\text{NA}=0.22$ , and the connection is provided via an SMA-905 connector. Depending on the number of paths (single vs. multiple) on which the light signal is propagated through the fiber core, fibers are considered multi-mode or single mode. Multi-mode fibers usually have a larger diameter core (62.5  $\mu\text{m}$  or larger) that is much larger than the wavelength of the light transmitted. Multi-mode fibers are used for most general fiber applications and short distance transmission. The fiber we are using is also a multi-mode fiber.

Step 1. Use a fiber coupling lens pair:

One easy and effective solution to connect a laser diode and a fiber is to use a fiber coupling lens pair. The lens pair consists of a collimating lens and refocusing lens. To pick a correct lens pair we need to calculate a few parameters including the required NA of the collimating lens. On the fiber side, since we know the fiber has an  $\text{NA} = 0.22$  we need to have a lens that has an NA smaller than 0.22. Using the formula given in Appendix C (repeated below for convenience), the NA values are calculated as follows:

$G_1 :=$  Divergence x-axis Half-Width Half-Max (HWHM) (deg)

$G_2 :=$  Divergence y-axis Half-Width Half-Max (HWHM) (deg)

$E_1 := \text{atan} \left( 1.699 \times \tan \left( G_1 \times \frac{\pi}{180} \right) \right)$  Divergence of  $1/e^2$  (half angle to x-axis) (rad)

$E_2 := \text{atan} \left( 1.699 \times \tan \left( G_2 \times \frac{\pi}{180} \right) \right)$  Divergence of  $1/e^2$  (half angle to y-axis) (rad)

$\text{NA of the Optic} > \sin(E_2)$

For our first laser diode, GH0781JA2C we have:

$$G_1 = 8.7$$

$$G_2 = 16$$

$$E_1 = 0.2544$$

$$E_2 = 0.4533$$

$$\sin(E_2) = 0.4380$$

$$\text{NA}_{O_1} = \sin(E_2) = 0.4380$$

For our second laser diode, HL7851G we have:

$$G_1 = 9.5$$

$$G_2 = 23$$

$$E_1 = 0.2770$$

$$E_2 = 0.6248$$

$$\text{NA}_{O_2} = \sin(E_2) = 0.5849$$



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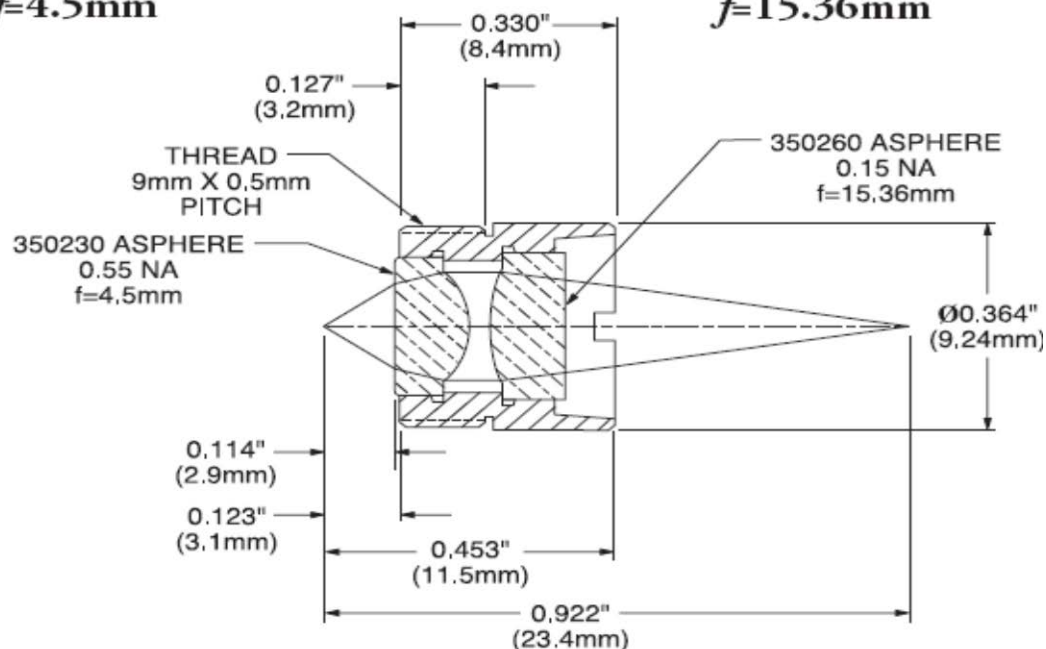
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The NA of the collimating lens should be greater than the NA of the LDs. Based on this conclusion (and the N.A. of the fiber) the C230260P-B lens pair from Thorlabs is a good candidate for our application. This lens pair is capable of coupling the LD to fibers with an NA above 0.16. This mounted lens pair consists of two lenses, one with a numerical aperture of 0.55, for the laser side, and the other with a numerical aperture of 0.15, for the fiber side. This high NA at the LD side enables us to easily launch the light from the divergent output of a diode into a multimode fiber. The combination of the high NA, short focal length (on the LD side) and the lower NA, longer focal length (on the fiber side) reduces the NA of the emitter by the ratio of the focal lengths. This lens pair has an anti-reflection coating that makes it suitable for the 600-1050 nm range.



**Laser Side:**  
**0.55NA**  
 **$f=4.5\text{mm}$**

**Fiber Side:**  
**0.16NA**  
 **$f=15.36\text{mm}$**



**FIGURE 7.** C230260P-B lens.

The C230260P-B lens pair is pre-aligned and mounted in a metal housing with an external 9 mm x 0.5 mm thread on the side designed to face the laser diode.

Part Number
C230260P-B - Mounted Pair of Aspheric Lenses 0.55NA/0.15NA for 600-1050nm

Although our employed fiber has a relatively large core, we need to calculate the final spot-size to make sure the lens we have picked provides the right spot size for our fiber.

We use the equations given in Appendix C as follows:



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### Beam Diameter:

$f := 4.5$  focal length of the optic

#### Note:

The emitter sizes are not given in the LDs' specification sheets; however, Thorlabs has provided us with the following typical values to be used in our calculations.

$L_1 := 3 \times 10^{-3}$  emitter size x-axis (mm)

$L_2 := 1 \times 10^{-3}$  emitter size y-axis (mm)

For our first laser diode, GH0781JA2C we have:

$E_1 = .2544$

$E_2 = 0.4533$

$$D_1 := 2 \times f \times \tan(E_1) + L_1 = 2 \times 4.5 \times \tan(E_1) + 0.003 = 2.3433$$

$$D_2 := 2 \times f \times \tan(E_2) + L_2 = 2 \times 4.5 \times \tan(E_2) + 0.001 = 4.3852$$

$\lambda = 785$  nm

$$F_1 := 2.44\lambda \times \frac{f_2}{D_1} \times 1000 = 2.44 \times 785 \times 10^{-6} \times \frac{15.36}{2.3433} \times 1000 = 12.5551 \quad \text{spot size } (\mu\text{m})$$

$$F_2 := 2.44\lambda \times \frac{f_2}{D_2} \times 1000 = 2.44 \times 785 \times 10^{-6} \times \frac{15.36}{4.3852} \times 1000 = 6.7091 \quad \text{spot size } (\mu\text{m})$$

For our second laser diode, HL7851G we have:

$E_1 = 0.2770$

$E_2 = 0.6248$

$$D_1 := 2 \times f \times \tan(E_1) + L_1 = 2 \times 4.5 \times \tan(E_1) + 0.003 = 2.5588 + 0.003 = 2.5618$$

$$D_2 := 2 \times f \times \tan(E_2) + L_2 = 2 \times 4.5 \times \tan(E_2) + 0.001 = 6.4906 + 0.001 = 6.4916$$

$\lambda = 785$  nm

$$F_1 := 2.44\lambda \times \frac{f_2}{D_1} \times 1000 = 2.44 \times 785 \times 10^{-6} \times \frac{15.36}{2.5618} \times 1000 = 11.4843 \quad \text{spot size } (\mu\text{m})$$

$$F_2 := 2.44\lambda \times \frac{f_2}{D_2} \times 1000 = 2.44 \times 785 \times 10^{-6} \times \frac{15.36}{6.4916} \times 1000 = 4.5321 \quad \text{spot size } (\mu\text{m})$$

As we can see from these calculations even our largest spot size is smaller than the fiber core and hence the lens pair seems to be a good match for our system.

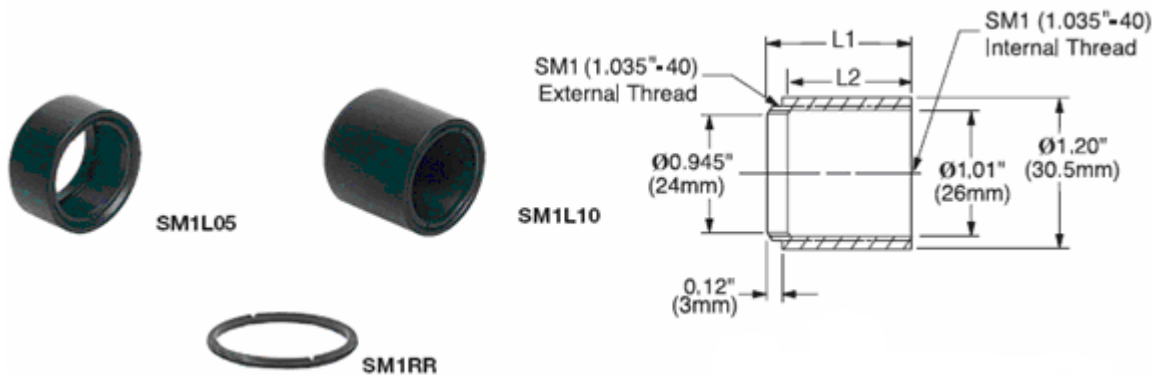
Step 2. To mount the lens pair onto the TCLDM0 we need an adapter. We use catalog # S1TM09.

Step 3. Next we need to adjust the LD's focused beam to get as much light as we can into the fiber. This can be done in several different ways. Three approaches (relatively low budget solutions) are given below:

**Approach 1:**

1. Stackable Lens Tubes

One can use this approach if the exact alignment of optical axes and focusing is not important. In this simple and easy approach lens tubes can be used to mount the lens. The stackable Ø1" Lens Tubes from Thorlabs provide a fast and easy means for building the required optical assemblies. There is no precision placement in these tubes but we can use retaining rings for small depth adjustments, i.e., insert the first ring at the depth required and then add the optic, and then a second retaining ring to lock the optic in place.



**FIGURE 8.** Stackable lens tubes and a retaining ring (from Thorlabs' catalog page)

Part Number
<b>SM1L10</b> - SM1 Lens Tube, 1.00" (25.4mm) Bore Depth, One SM1RR Included
<b>SM1L05</b> - SM1 Lens Tube, 0.50" (12.7mm) Bore Depth, One SM1RR Included
<b>SM1RR</b> - SM1 Retaining Ring, 1.035"-40 Thread x 0.08" (2mm) Thick
<b>SPW602</b> - SM1RR Spanner Wrench with Clear Aperture
<b>SPW301</b> - Spanner Wrench for a 9mm Optics Housing

We can use the lens tubes for more flexibility with the following two approaches as well.

**Approach 2:**

1. Use a Kinematic Mount (the fiber will be mounted on this mount by means of an SM1SMA adapter, see **Step 4**).

The KC1-T offers three lockable adjusters in combination with a rugged mechanical design. The Flexure locking mechanism allows independent locking of all three adjusters. Both the front and rear plates have been machined with four clearance holes designed for direct compatibility with 30-mm cage rod spacing. The rear plate provides locking setscrews to clamp to cage rods for secure positioning. The cage rod holes in the front plate are sufficiently oversized to allow  $\pm 4^\circ$  tip and tilt without interference with the rods ( $\pm 4^\circ$  angular rotation,  $\pm 3$ mm linear translation). The KC1-T provides an SM1 (1.035"-40) center tap for compatibility with SM1-series lens tubes and related accessories. It is also post mountable via #8-32 (M4) tapped hole



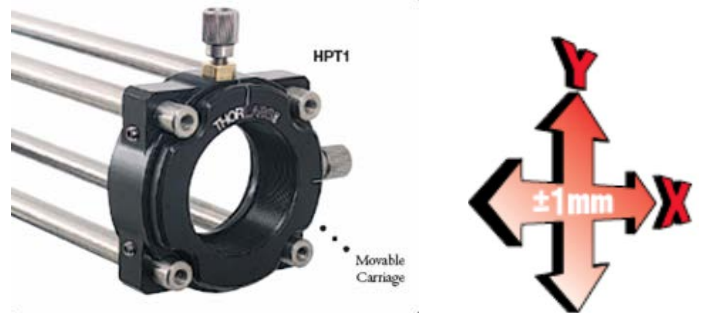
2. Assembly Rods

Similar to Approach 2, assembly rods can be used to mount the KC1-T on the TCLDM9.

**Approach 3:**

1. Use an XY translator (the fiber will be mounted on this translator by means of an SM1SMA adapter, see **Step 4**).

The HPT1 XY Translator provides  $\pm 1$  m of travel perpendicular to the optical axis of a cage system. The movable carriage is threaded and directly accepts  $\text{Ø}1$ " optics (up to 8 mm thick). The back side, which is fixed, is also threaded to allow additional attachments (e.g. lens) if necessary. The alignment along the Z axis can be done by moving the translator along this axis and also adjust the distance between the lens and fiber.



**FIGURE 9.** XY Translator (Picture from Thorlabs' catalogue.)

Part Number
HPT1 - 30mm Cage Assembly, XY Translating Lens Mount

## 2. Assembly Rods

The TCLDM9 has 4-40 tapped holes on 30 mm centers that facilitate mounting of cage assemblies. We can use Thorlabs' precision ground cage assembly rods to mount the XY translator on the TCLDM9.

We have used the second approach for our fiber coupling application.

Step 4. Finally, we need an SM1SMA adapter to integrate the fiber with the SMA-905 connector with the SM1 (1.035"-40) mount.

This adapter is easily mounted on the devices described in **Step 3**.



**FIGURE 10.** 2" Assembly rods.



**FIGURE 11.** SM1SMA adapter.

## **References**

1. Operational Manual, Thorlabs Blueline series, Laser Diode Controller LDC2xx, 2006.
2. TCLDM9 5.6mm/9mm Laser Diode Mount Operating Manual.
3. Operation Manual: Thorlabs Blueline Series, Thermoelectric Temperature Controller, TED200, 2006.
4. Thorlabs Catalog: Tools of the Trade, Volume 18.
5. [www.thorlabs.com](http://www.thorlabs.com)
6. 125-MHz Photoreceivers, Models 1801 and 1811 User's Guide, 2001

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**Appendix A**

Details of parts used in the described laser system are provided in this Appendix.

<b>TABLE A.1. PARTS REQUIRED FOR THE LASER DIODE SYSTEM</b>							
<b>Qty</b>	<b>Unit</b>	<b>Description</b>	<b>Supplier</b>	<b>Supplier. Catalog#</b>	<b>Manufac. Catalog #</b>	<b>Unit Cost (\$)</b>	<b>Total Cost (\$)</b>
2	ea	784nm, 120mW, Sharp Laser Diode	Thorlabs	GH0781JA2C		33.64	67.28
2	ea	785nm, 50mW Hitachi Diode	Thorlabs	HL7851G		83.33	166.66
1	ea	Benchtop Laser Diode Current Controller, $\pm 2A$	Thorlabs	LDC220		1,194.00	1,194.00
1	ea	TE-Cooled Mount For 5.6 & 9mm Lasers	Thorlabs	TCLDM9		420.00	420.00
1	ea	Benchtop Temperature Controller, $\pm 2A/12W$	Thorlabs	TED200		1068.00	1068.00
1	ea	f=6.24mm 0.40NA Mounted Geltech™ Aspheric Lens, AR Coating: 600-1050nm	Thorlabs	C110TME-B		86.00	86.00
1	ea	SM1 to M9 aspheric lens cell adapter	Thorlabs	S1TM09		19.50	19.50
<b>Total</b>							<b>3021.44</b>



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<b>TABLE A.2. PARTS REQUIRED FOR LASER SAFETY</b>							
<b>Qty</b>	<b>Unit</b>	<b>Description</b>	<b>Supplier</b>	<b>Supplier. Catalog#</b>	<b>Manufac. Catalog#</b>	<b>Unit Cost (\$)</b>	<b>Total Cost (\$)</b>
1	ea	Grounding Wrist Strap w/ Coiled Cord One Size	Thorlabs	WS02		21.00	21.00
1	ea	NIR Laser Viewing Card: 700-1400 nm (10%-800 nm)	Thorlabs	IRC3		110.00	110.00
1	ea	770 nm Laser Goggles w/ KFG- 21 Glass Filter (OD > 7)	Kentek	SEG-21	K-Jet	329.00	329.00
<b>Total</b>							<b>460.00</b>

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<b>TABLE A.3. PARTS REQUIRED FOR FIBER-COUPLING THE LASER</b>							
<b>Qty</b>	<b>Unit</b>	<b>Description</b>	<b>Supplier</b>	<b>Supplier Catalog #</b>	<b>Manufac. Catalog #</b>	<b>Unit Cost (\$)</b>	<b>Total Cost (\$)</b>
1	ea	Mounted Pair of Aspheric Lenses 0.55NA/0.15 NA for 600-1050nm	Thorlabs	C230260P-B		167.00	167.00
1	ea	SM1 (1.035"-40) to SMA Fiber Connector Adapter Plate	Thorlabs	SM1SMA		26.00	26.00
1	ea	Spanner Wrench for a 9mm Optics Housing	Thorlabs	SPW301		13.00	13.00
1	ea	Spanner Wrench for SM1 adapters	Thorlabs	SPW909		27.00	27.00
<b>Total</b>							<b>233.00</b>

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<b>TABLE A.4. PARTS REQUIRED FOR MONITORING THE LASER OUTPUT</b>							
<b>Qty</b>	<b>Unit</b>	<b>Description</b>	<b>Supplier</b>	<b>Supplier Catalog #</b>	<b>Manufac. Catalog #</b>	<b>Unit Cost (\$)</b>	<b>Total Cost (\$)</b>
1	ea	125 MHz amplified photodiode, DC (required power supply)	New Focus	1801-FS		732.78	732.78
1	ea	Power Supply for 1801-FS amplified photocathode ( $\pm 15V$ )	New Focus	0901		510.16	510.16
<b>Total</b>							<b>1242.94</b>

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<b>TABLE A.5. LASER DIODE TO FIBER COUPLING APPROACH 1</b>							
<b>Qty</b>	<b>Unit</b>	<b>Description</b>	<b>Supplier</b>	<b>Supplier Catalog #</b>	<b>Manufac. Catalog #</b>	<b>Unit Cost (\$)</b>	<b>Total Cost (\$)</b>
2	ea	SM1 Lens Tube, 1.00" (25.4mm) Bore Depth, One SM1RR Included	Thorlabs	SM1L10		15.00	30.00
2	ea	SM1 Lens Tube, 0.50" (12.7mm) Bore Depth, One SM1RR Included	Thorlabs	SM1L05		13.25	16.50
2	ea	SM1 Retaining Ring, 1.035"-40 Thread x 0.08" (2mm) Thick	Thorlabs	SM1RR		5.00	10.00
1	ea	SM1RR Spanner Wrench with Clear Aperture	Thorlabs	SPW602		27.00	27.00
<b>Total</b>							<b>83.50</b>

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<b>TABLE A.6. LASER DIODE TO FIBER COUPLING APPROACH 2</b>							
<b>Qty</b>	<b>Unit</b>	<b>Description</b>	<b>Supplier</b>	<b>Supplier Catalog #</b>	<b>Manufac. Catalog #</b>	<b>Unit Cost (\$)</b>	<b>Total Cost (\$)</b>
1	1	Threaded Kinematic Mount for Ø1" Optics	Thorlabs	KC1-T		86.00	86.00
4	ea	Cage Assembly Rod - 2", 6mm Diameter	Thorlabs	ER2		6.20	24.80
2	ea	SM1 Retaining Ring, 1.035"-40 Thread x 0.08" (2mm) Thick	Thorlabs	SM1RR		5.00	10.00
1	ea	SM1RR Spanner Wrench with Clear Aperture	Thorlabs	SPW602		27.00	27.00
<b>Total</b>							<b>147.80</b>

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<b>TABLE A.7. LASER DIODE TO FIBER COUPLING APPROACH 3</b>							
<b>Qty</b>	<b>Unit</b>	<b>Description</b>	<b>Supplier</b>	<b>Supplier Catalog #</b>	<b>Manufac. Catalog #</b>	<b>Unit Cost (\$)</b>	<b>Total Cost (\$)</b>
1	ea	30mm Cage Assembly, XY Translating Lens Mount	Thorlabs	HPT1		156	156.00
4	ea	Cage Assembly Rod-2", 6mm Diameter	Thorlabs	ER2		6.20	24.80
<b>Total Sum</b>							<b>180.80</b>



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## Appendix B

This appendix provides the resistance to temperature conversion table. Room temperature is in **red**.

$$R(T) = R_0 \times e^{\beta \left( \frac{1}{T} - \frac{1}{T_0} \right)} \Leftrightarrow T(R) = \frac{\beta \times T_0}{T_0 \times \ln\left(\frac{R}{R_0}\right) + \beta}, \quad \beta = 3977K, \quad R_0 = 10K\Omega, \quad T_0 = 298.15K$$

Kelvin	Resistance	Celsius	Kelvin	Resistance	Celsius
274	32186	1	317	4494	44
275	30532	2	318	4320	45
276	28973	3	319	4154	46
277	27504	4	320	3995	47
278	26120	5	321	3843	48
279	24814	6	322	3698	49
280	23583	7	323	3560	50
281	22420	8	324	3427	51
282	21323	9	325	3300	52
283	20286	10	326	3178	53
284	19307	11	327	3062	54
285	18381	12	328	2950	55
286	17506	13	329	2844	56
287	16678	14	330	2741	57
288	15895	15	331	2643	58
289	15153	16	332	2549	59
290	14451	17	333	2459	60
291	13785	18	334	2373	61
292	13155	19	335	2290	62
293	12558	20	336	2211	63
294	11991	21	337	2134	64
295	11454	22	338	2061	65
296	10944	23	339	1991	66
297	10460	24	340	1923	67
<b>298</b>	<b>10000</b>	<b>25</b>	341	1858	68
299	9563	26	342	1796	69
300	9149	27	343	1736	70
301	8755	28	344	1679	71
302	8380	29	345	1623	72
303	8023	30	346	1570	73
304	7684	31	347	1519	74
305	7362	32	348	1470	75
306	7055	33	349	1422	76
307	6762	34	350	1377	77
308	6484	35	351	1333	78
309	6218	36	352	1291	79
310	5965	37	353	1250	80
311	5724	38	354	1211	81
312	5494	39	355	1173	82
313	5275	40	356	1137	83
314	5066	41	357	1102	84
315	4866	42	358	1068	85
316	4676	43			

## **Appendix C\***

In this appendix collimation of diode laser using diffractive limited performance with several examples is described.

### **Specification of the laser diode:**

Example: **DL7032-001 – 830 nm, 100 mW Sanyo Laser Diode**

$G_1 := 3.5$       Divergence x-axis HWHM (deg)

$G_2 := 9$       Divergence y-axis HWHM (deg)

$$E_1 := a \tan\left(1.699 \tan\left(G_1 \times \frac{\pi}{180}\right)\right) \quad \text{Divergence of } 1/e^2 \text{ (half angle to x-axis) (rad)}$$

$$E_2 := a \tan\left(1.699 \tan\left(G_2 \times \frac{\pi}{180}\right)\right) \quad \text{Divergence of } 1/e^2 \text{ (half angle to y-axis) (rad)}$$

N.A. of the Optic  $> \sin(E_2)$

$$\therefore E_2 = 0.263 \rightarrow NA_o := \sin(E_2) = 0.26$$

### **Beam diameter for a particular optic:**

Example: **LT230P-B - Collimation Tube W/Optic, 9 mm & 5.6 mm Laser, NA: 0.55**

$f := 4.5$       focal length of the optic

$L_1 := 3 \times 10^{-3}$       emitter size x-axis (mm)

$L_2 := 1 \times 10^{-3}$       emitter size y-axis (mm)

$$D_1 := 2 \times f \times \tan(E_1) + L_1 \quad \therefore D_1 = 0.938 \text{ (mm)}$$

$$D_2 := 2 \times f \times \tan(E_2) + L_2 \quad \therefore D_2 = 2.423 \text{ (mm)}$$

### **Beam divergence behind optic:**

$$E_3 := a \tan\left(\frac{L_1}{2f}\right) \times 1000 \quad \therefore E_3 = 0.3 \quad \text{Divergence to x-axis (mrad)}$$

$$E_4 := a \tan\left(\frac{L_2}{2f}\right) \times 1000 \quad \therefore E_4 = 0.1 \quad \text{Divergence to y-axis (mrad)}$$

---

\* These formulas and examples are provided by Thorlabs.

**Diameter at a distance of (m):**

Example: **d = 0.5 m**

$$D_3 := d \times 2000 \times \tan\left(\frac{E_3}{1000}\right) + D_1 \quad \therefore D_3 = 1.272 \quad \text{Diameter (mm)}$$

$$D_4 := d \times 2000 \times \tan\left(\frac{E_4}{1000}\right) + D_2 \quad \therefore D_4 = 2.534 \quad \text{Diameter (mm)}$$

**Fiber-coupling (collimated beam):**

Example: **f<sub>2</sub> = 4.5**    **Focus length of coupling optic**

$$NA_1 := \sin\left(a \tan\left(\frac{D_1}{2 \times f_2}\right)\right) \quad \therefore NA_1 = 0.104 \quad \text{Should be 80% of recommended fiber}$$

$$NA_2 := \sin\left(a \tan\left(\frac{D_2}{2 \times f_2}\right)\right) \quad \therefore NA_2 = 0.26$$

**Focus-spot size:**

Example: **λ = 670 × 10<sup>-6</sup>**    **Operation wavelength**

$$F_1 := 2.44 \lambda \times \frac{f_2}{D_1} \times 1000 \quad \therefore F_1 = 7.841 \quad \text{spot size (μm)}$$

$$F_2 := 2.44 \lambda \times \frac{f_2}{D_2} \times 1000 \quad \therefore F_2 = 3.036 \quad \text{spot size (μm)}$$

**Calculate a coupling optic for a given fiber:**

Example:

**NA<sub>F</sub> := 0.12**            **NA of the Fiber**  
**D<sub>F</sub> := 4 × 10<sup>-3</sup>**        **Fiber core diameter (mm)**  
**λ<sub>1</sub> := 670 × 10<sup>-6</sup>**      **Wavelength (mm)**  
**D<sub>B1</sub> := 5.56**            **Larger Beam Diameter (mm)**

$$f_{\max} := 0.8 \times D_F \frac{D_{B1}}{\lambda_1 \times 2.44} \quad \therefore f_{\max} = 10.883 \quad \text{Max. focal length (mm)}$$

**Specification of the Thorlabs HL6320G, 635 nm, 10 mW LD:**

Example: **HL6320G – 635 nm, 10 mW Hitachi Diode**

$G_1 = 11$       Divergence x-axis FWHM (deg)

$G_2 = 37$       Divergence y-axis FWHM (deg)

$f_1 = 50.0$  mm

$f_2 = 12.7$  mm

$$d_1 = 2f_1 \tan(G_1) = 19.44 \text{ (mm)}$$

$$d_2 = 2f_2 \tan(G_2) = 19.14 \text{ (mm)}$$