Final Report

Light Detection with Ultra-High Dynamic Range

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BME Senior Design

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1. Need and Specific Design Requirements

Specialized chemical or voltage sensing domains of proteins in cells often respond to specific environmental stimuli. Until recently, it has been difficult to study and observe such proteins in action: the output of their response was typically known, but the processes were ambiguous. When the protein movements and conformational changes occurred in given light excitation, the number of photons of light stimuli through the protein is changed. By observing the amount of photons collected through the protein of interest in the given time of protein conformational change, the protein kinetics of conformational change can be modeled. This technique has been extremely constrained in the time domain. The conformational changes of protein occur in a very short time; they occur on a timescale of microsecond to nanosecond.

Our client Dr. Jon Silva currently studies channel gating via oocytes. The client's experiments involve a specific microscopy technique called fluorescence microscopy in which a floure molecule is attached to a protein molecule under 600nm green L.E.D. light which is used to acquire data on calcium channel protein kinetics. The photons that pass through the protein are focused through a lens and are collected onto the active area of PIN diode. A PIN diode is a specific type of diode that absorbs photons to elicit a current. The PIN diode generated background currents are often on the order of μA in the client's experiments. Frequency information from protein conformation changes is acquired by the change in current over DC offset value recorded in the PIN diode. The currents used in frequency analysis of protein kinase in the client's experiments are relatively small compared to the background signal. The signal of interest is at the level of pA in which the signal to noise ration of the system is approximately

0.1%. By integrating the frequency information, protein kinase conformational models can be developed.

The client requested the design of an integrated system of light focusing, electrical, and cooling system that minimizes the noise and amplifies this 0.1% signal fitting into adaptors of the fluorescence microscopy currently installed in the client's laboratory.

The optical focusing system must be able to focus a beam of light with a 600 nm wavelength to a diffraction limited spot onto the smallest PIN Diode possible, so as to minimize noise. This can be achieved using many different types of lenses. Singlet lenses are simple and easy to use, but their performance is limited by spherical and chromatic aberrations, astigmatism, and other distortions. Thus, multi-element lenses, designed using combinations of singlet elements, are necessary to minimize the number of aberrations during measurement. One excellent solution is an achromatic doublet lens system, which involves two singlet lens elements cemented together to nearly eliminate the spherical and chromatic aberration components. Achromatic lenses exhibit an interesting behavior in that the shorter the back focal length (distance from the second lens to focal point), the tighter the focal spot. Dr. Silva's parallel input ray bundle will pass through a lens having a 25mm diameter, so as to capture the entire beam. Minimizing the focal length is advantageous due to design constraints, and the smallest commercially available achromatic doublet lens with a 25 mm diameter has a focal length of 30mm.

The PIN diode must have a good responsivity at the given stimulus wavelength of 600 nm green L.E.D. beam of the client's fluorescence microscopy. The whole purpose of the design is to reduce noise as much as possible. The PIN diode itself must have the characteristics of low thermal noise and low dark current noise. To lower the thermal noise, the diode will be cooled by the cooler attached to it. The cooling system, however, must not disturb the PIN diode's operation, meaning that the PIN diode should have a wide temperature of operation. The size of the active area is another source of noise generation. While a smaller active area creates a lower noise environment, the PIN diode must still have an active area that is larger than the diffraction limits of the lens.

Since the input of the system is relatively small compared to the background signal (approximately ~ 0.1 %) the signal must be amplified while reducing the noise. An amplifier or a series of amplifiers is required. The output of the entire electrical system is expected to have a gain of 100 or larger.

The output of the PIN Diode is current. The current generated in PIN diode, thus becomes the primary input of the electrical system. Real OP Amps as opposed to ideal, have small current flow inside of the OP Amps; thus, the current input from the PIN diode induces the internal voltage error that can propagate through the whole circuit. To cancel this error, the input current must be properly biased, or be transformed as a voltage input.

The frequency response of interest in the client's experiment is the response of 5 kHz to 10 kHz. Therefore, the electrical circuit designed must have a bandpass filter with a target bandwidth of 5 kHz to 10 kHz. The change of current generation by PIN diode is the primary indication of the protein conformation; thus, the shape of original signal, featuring the protein kinase, holds crucial information for client's experiments. As the shape of the signal is what the client is interested in, the output signal through filters must preserve the shape of the original signal.

The electrical system will be attached next to the SM1 adaptor; however, the adaptor type can be changed if necessary due to the size limitation of the cooling system. Since all electrical components of the design cost around $1 to $60, the client's request of overall budget of $1000 will be easily achieved.

The client requested that the PIN diode be cooled close to its optimal temperature as a means of reducing electrical noise. The client suggested use of a Peltier Cooler towards this end, but was open to any other solutions. There is an inherent size limitation based on fitting the cooling method with the client's SM1 mount together with the PIN diode, though the client is open to custom adaptor designs or other off the shelf adaptors if necessary.

Table 1: Specific Design Requirements

System	*Requirements*

Electrical System	• PIN Diode
	  - Responsivity at 600nm light beam
	  - Low Noise
	  - Wide Operational Temperature range
	  - Minimized Active Area
	• Bandpass Filter of 5 kHz to 10 kHz
	• Amplifier with a gain of 100 or larger
	• Attach the system next to the SM1 adaptor

Peltier Cooling System	• Peltier or other cooling method to cool PIN diode to optimal temperature (typically around -20 degrees Celsius). • Cooling system must fit client's Sm1 Adaptor.

Light Focusing System	• Achromatic doublet lens
	  • Known diameter = 25mm
	  • Minimized focal length
	  • Focus to diffraction limited spot
	• Minimize optical aberrations

Cost	• 1000$

2. Light Focusing System Design

A. Optical Aberrations

Since the lens must be able to focus the LED beam to a diffraction limited spot, the light focusing system's main limitation lies in the significant amount of optical aberrations encountered in attempting to focus a beam to such a small area. Ideally, a perfect lens would be able to focus a parallel input ray bundle on-axis, to an infinitesimal point, free of aberrations, as shown in Figure 1. However, this phenomenon is impossible with a real lens, so first a thorough investigation of the possible aberrations was conducted.

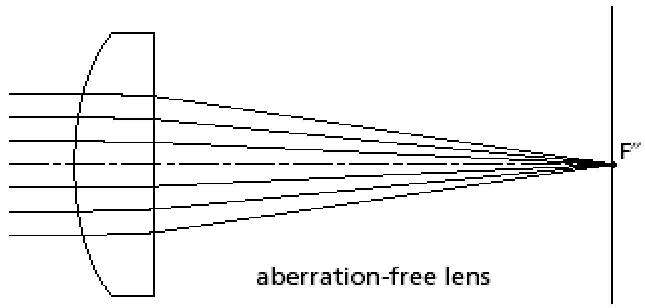


Figure 1: Aberration-Free Lens

Spherical aberration

A lens will focus rays near the edge of the bundle closer to the lens than rays closer to the axis. The distance between the paraxial focal point and the edge ray focal point is the longitudinal spherical aberration. The transverse spherical aberration is the separation between the interception points and the paraxial point, which are displaced when the edge rays intercept the paraxial focal plane. There are two factors that determine the extent of spherical aberration, lens shape and material index. A smaller index of refraction results in less spherical aberration. However, for any given index of refraction, it is possible to design a “best form” singlet lens element free of spherical aberration. Making the surface of the lens aspherical will also eliminate spherical aberration, but the manufacturing of aspherical elements with glass materials is extremely expensive, and for our purposes, an achromatic doublet will be sufficient.

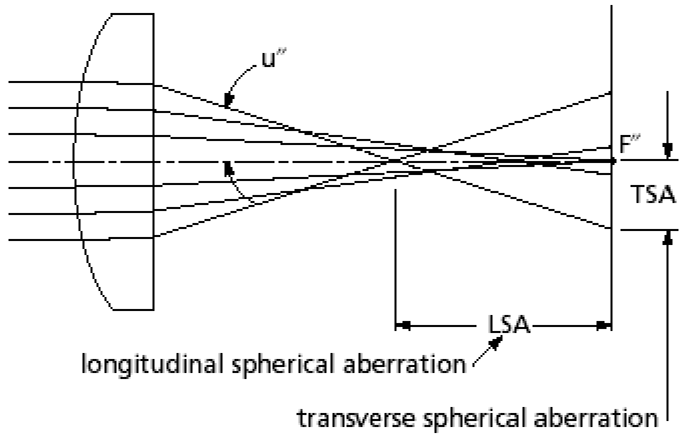


Figure 2: Spherical Aberration

Chromatic aberration

Spherical aberrations are purely a function of the shape of the lens surface, and can be observed with monochromatic light. When attempting to transform light containing multiple wavelengths, additional aberrations can arise. The index of refraction of a material is a function of wavelength, and is represented by the Abbe value of the material. Because the index of refraction is higher for shorter wavelengths, shorter wavelengths are focused closer to the lens than longer ones. Longitudinal chromatic aberration is the axial distance from the nearest to the farthest focal point. Due to the variance in index with wavelength, blue light, for example, is refracted more strongly than red light, and thus their rays will intercept the image plane at different heights. Magnification is dependent on color, and so lateral color is very dependent on the system stop location. In the case of spherical aberration, positive and negative elements have opposite signs of chromatic aberration. Chromatic aberration can be partially corrected by combining elements of nearly opposite aberration to form a doublet. Implementing two pieces of glass with different dispersion characteristics is necessary for the elements to balance each other's aberrations. Achromatic doublets are superior to simple lenses because they correct for both spherical and chromatic aberrations when focusing collimated light or collimating point sources.

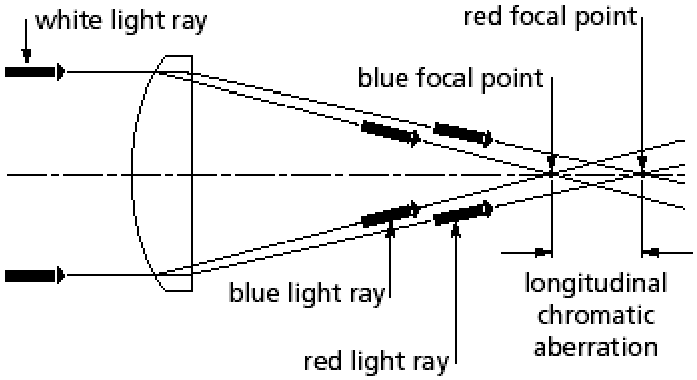


Figure 3: Chromatic Aberration

Astigmatism

When a spherical lens is used to focus an off-axis object, the natural asymmetry leads to astigmatism, and the system appears to have two different focal lengths. The plane containing both optical axis and object point is called the tangential plane, and the tangential rays are those that lie in this plane. Rays outside this plane are called skew rays. The principal ray goes from the object point through the center of the aperture of the lens system. The plane perpendicular to the tangential plane that contains the principal ray is called the sagittal plane. The tangential rays from the object come to a focus closer to the lens than do rays in the sagittal plane. When the image is evaluated at the tangential conjugate, we see a line in the sagittal direction. A line in the tangential direction is formed at the sagittal conjugate. Astigmatism is defined as the separation of these conjugates, where the image is either an elliptical or circular blur. The amount of astigmatism in a lens depends on the shape of the lens shape when there is an aperture in the system that is not in contact with the lens itself. Astigmatism strongly depends on the conjugate ratio.

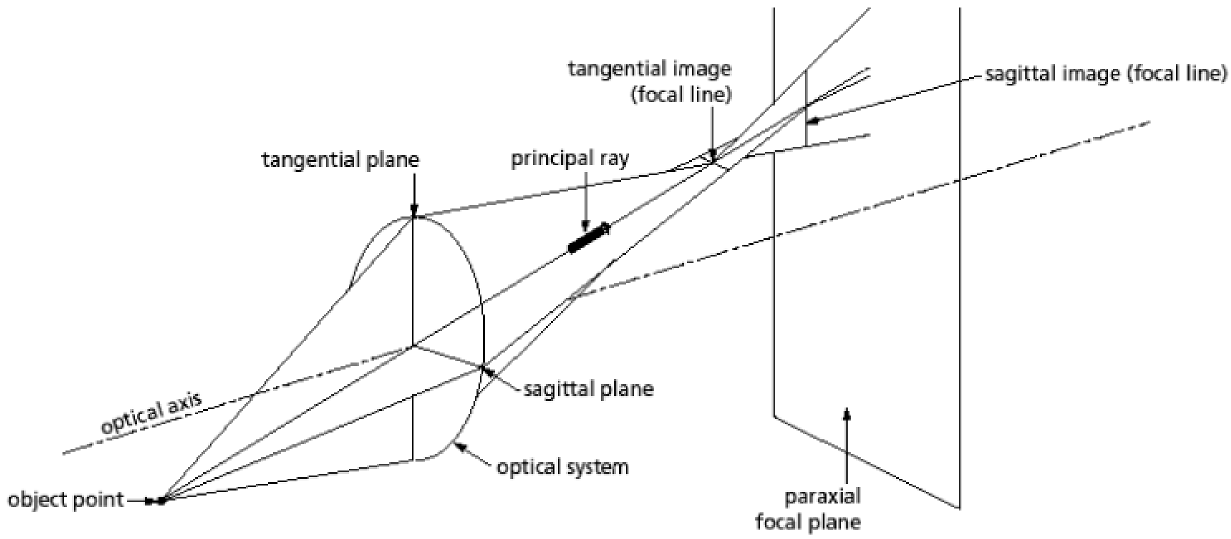


Figure 4: Astigmatism

Field curvature:

There is a tendency of optical systems to image better on curved rather than flat planes, an effect known as field curvature. In the presence of astigmatism, this problem is compounded because there are two separate astigmatic focal surfaces that correspond to the tangential and sagittal conjugates. Field curvature varies with the square of field angle or the square of image height. Therefore, by reducing the field angle by, say one-half, it is possible to reduce the blur from field curvature by a factor of four.

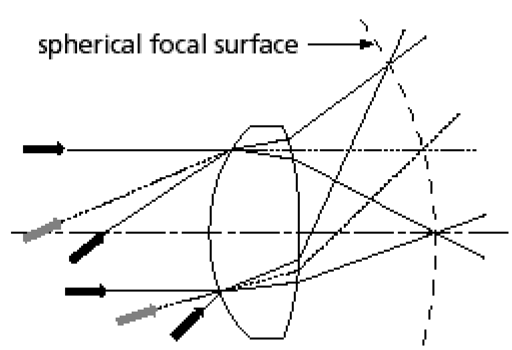


Figure 5: Field Curvature

Coma:

In spherical lenses, different parts of the lens surface exhibit different degrees of magnification, which gives rise to the aberration known as coma. Each concentric zone of a lens forms a comatic circle (ring-shaped image), which causes blurring in the image plane of off-axis object points. Even if spherical aberration is corrected and the lens brings all rays to a sharp focus on axis, a lens can still exhibit coma off-axis. Luckily, this can be corrected by using multiple surfaces or alternatively by placing an aperture, or stop, to eliminate the more marginal rays.

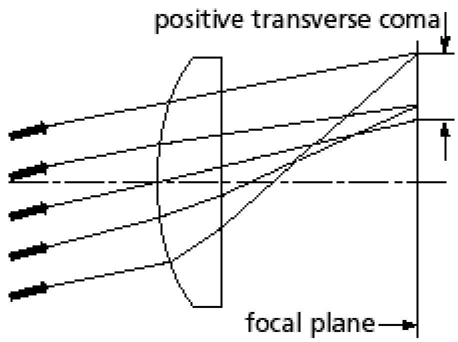


Figure 6: Coma

Geometric distortion:

The image field may also be distorted, which differs from coma. The image of an off-axis point may form at a different location than was predicted by paraxial equations. The amount of distortion increases with increasing image height, and the effect can be categorized as either pincushion or barrel. Distortion does not lower system resolution; it simply means that the image shape does not correspond exactly to the shape of the object. Distortion is the separation of the actual image point from the paraxially predicted location, expressed as either an absolute value or a percentage of the paraxial image height. A lens or lens system has opposite types of distortion depending on whether it is used forward or backward, meaning that if a lens was first used to make a image, and then reversely used to project it, there would be no distortion in the final screen image.

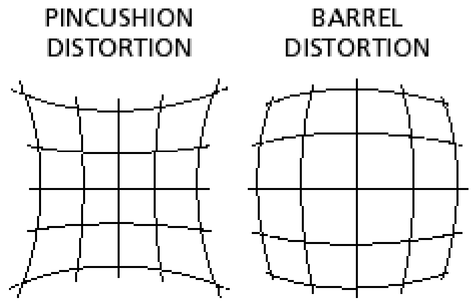


Figure 7: Geometric Distortion Types

B. Lens Alternatives

The first set of lenses is singlet element lenses and generally performs fine for simple tasks. However, for our purposes, considering the requirements of the focusing system, there would be a significant amount of optical aberrations as discussed above.

Plano-convex lens:

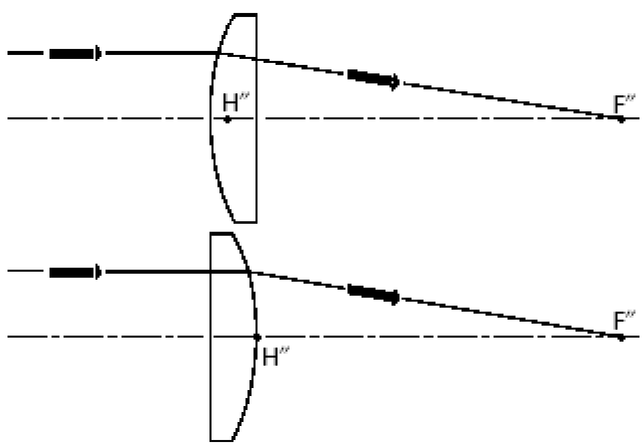


Figure 8: Plano-Convex Lens

Plano-concave lens:

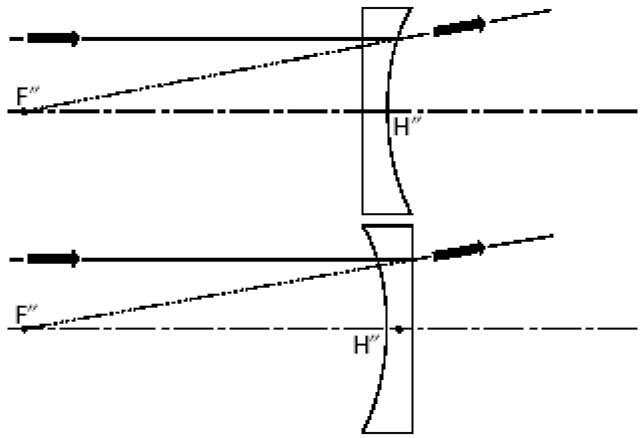


Figure 9: Plano-Concave Lens

Bi-convex lens:

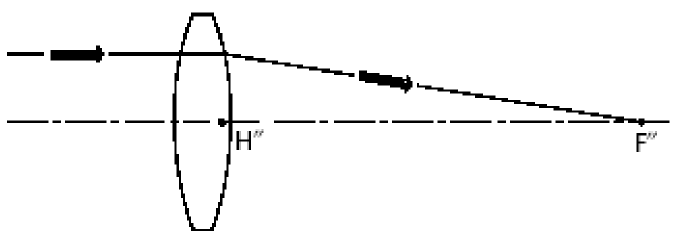


Figure 10: Bi-Convex Lens

Bi-concave lens:

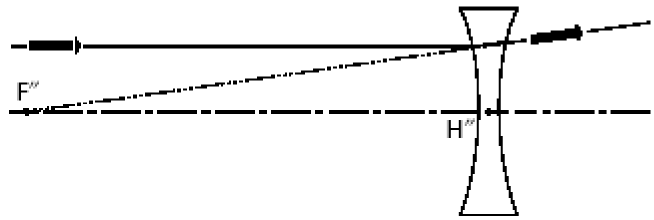


Figure 11: Bi-Concave Lens

Positive meniscus lens:

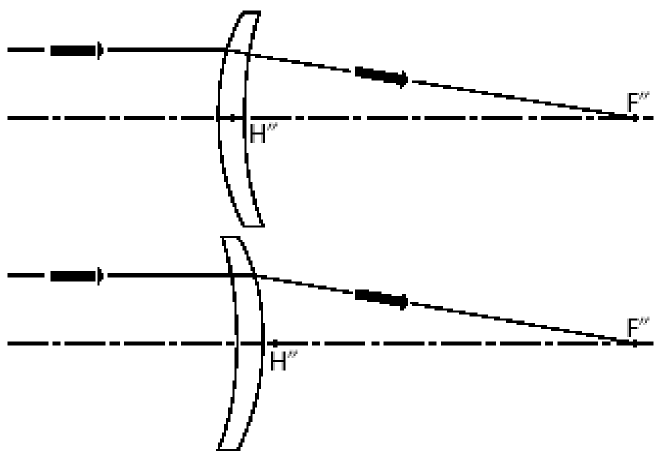


Figure 12: Positive Meniscus Lens

Negative meniscus lens:

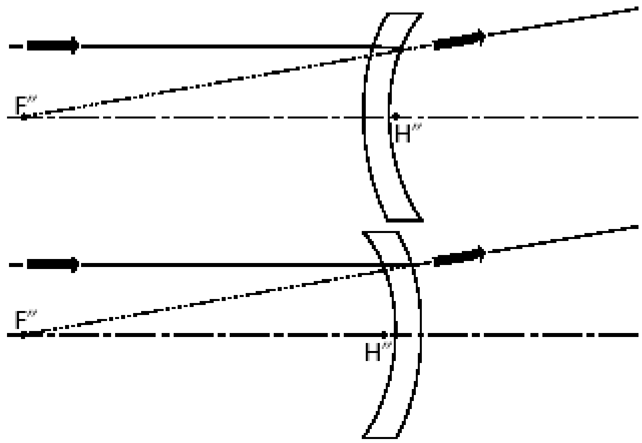


Figure 13: Negative Meniscus Lens

The second sets of lenses are multi-element lenses. Each one has unique characteristics and applications.

Symmetric lens pairs

For finite conjugate applications where both the object and the image are at a finite distance, a pair of identical lenses may be considered. If the configuration is such that the object distance and image distance are nearly equal, lens pairs provide almost perfect performance.

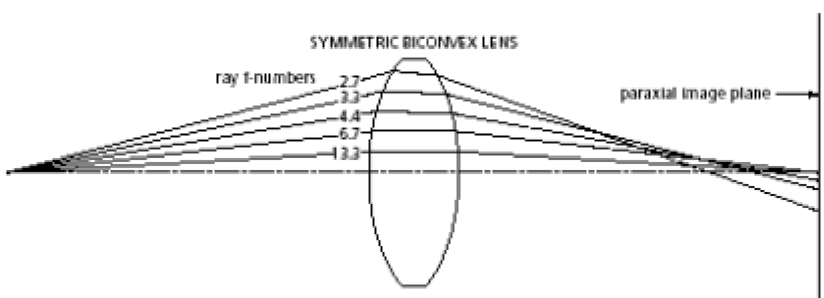


Figure 14: Symmetric Lens Pairs

Cooke Triplet Lenses

The previous lens configurations only provide improved performance on-axis, but for both on and off-axis, more complex lens forms are required. Cooke triplet is a lens form that provides good imaging performance over a field of view of ±20-25 degrees.

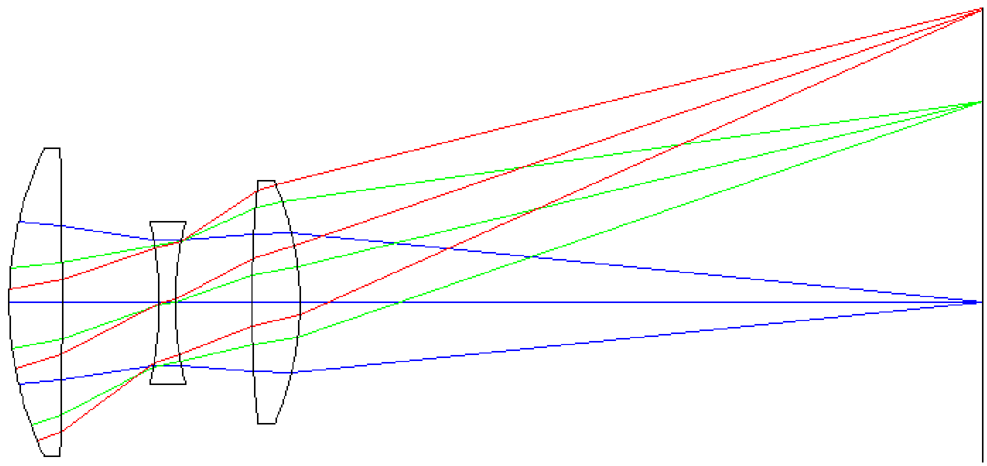


Figure 15: *Cooke Triplet Lenses*

Double Gaussian Lens

To achieve higher image quality and to increase the relative aperture over a Cooke triplet, a Double Gaussian lens can be used. The double Gaussian design uses two cemented doublets and two companion singlet elements. This lens offers excellent performance over a significant field of view.

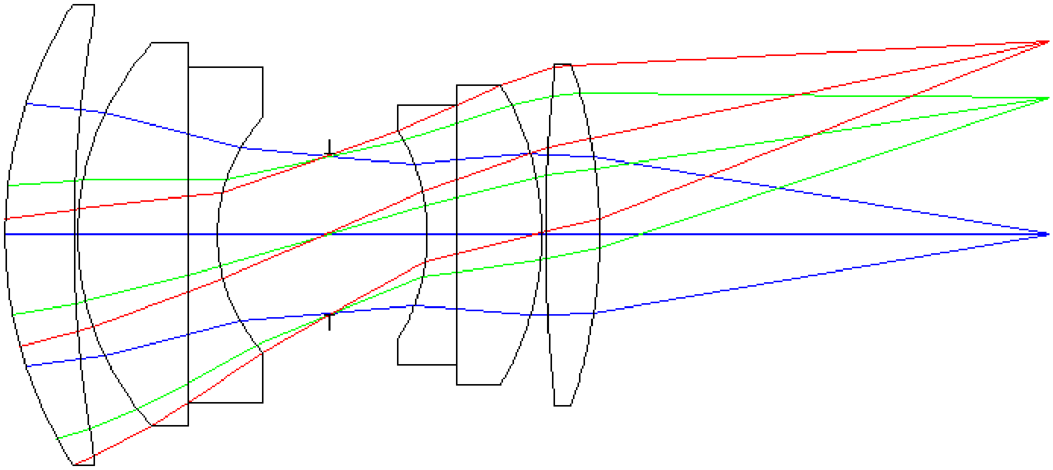


Figure 16: Double Gaussian Lens

Reverse Telephoto Lens

A reverse telephoto lens is used when more field of view coverage is necessary. The front lens group has a negative power while the second is group is positive. This is so that the input field of view is reduced. This configuration allows the field of view to be increased ±35 degrees. An interesting, advantageous quality of this configuration is that the system's back focal length can be longer than the effective focal length, making it very attractive to short focal length lenses.

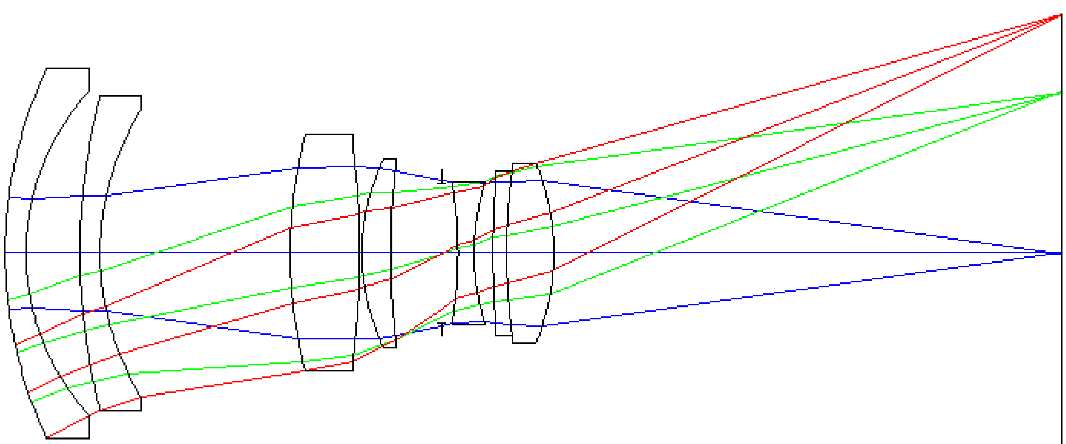


Figure 17: Reverse Telephoto Lens

Wide-angle "Fisheye" Lenses

Wide-angle "fisheye" lenses are typically used in security or surveillance scenarios, requiring a significant number of components. However, there is significant distortion associated with these lenses.

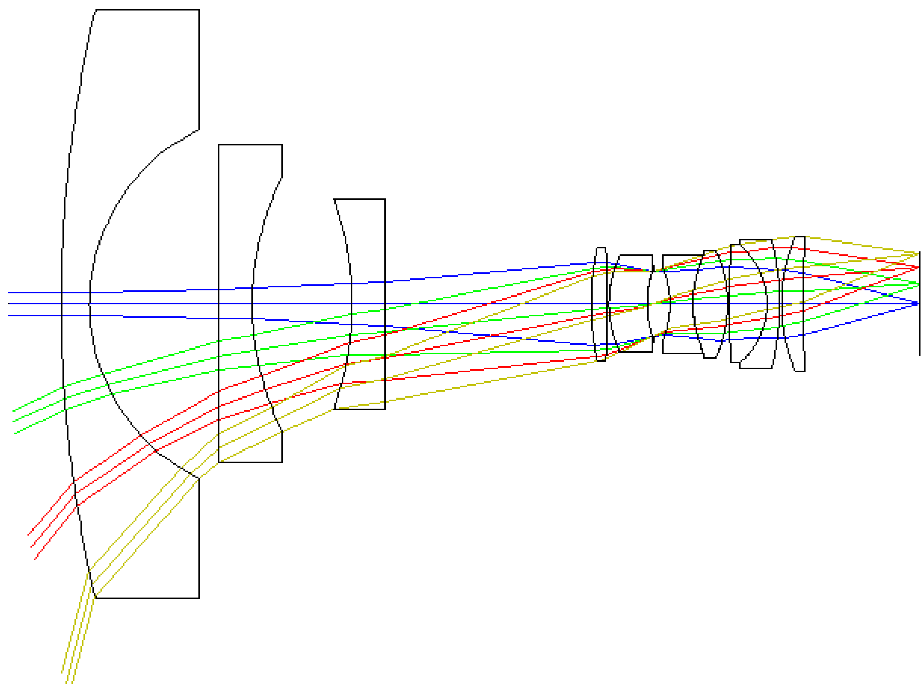


Figure 18: Wide-Angle Lens

C. Actual Design

An achromatic doublet lens will be used in the light focusing system.

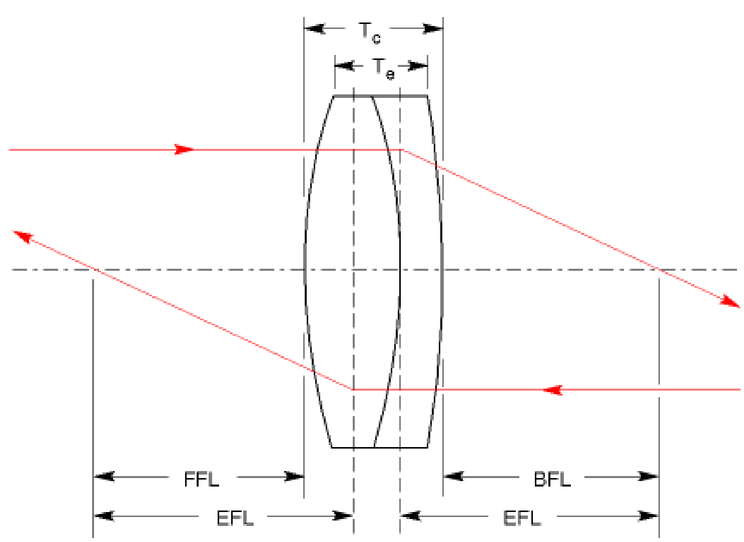


Figure 19: Achromatic Doublet Lens

An achromatic doublet is made of two singlet lens elements combined as one unit. The lens's performance advantage is its ability to completely eliminate the spherical and longitudinal aberration when focusing light to a diffraction limit. They do however, have some major limitations. First, their off-axis performance deteriorates rapidly with the field of view, and secondly, the f/# of achromatic doublet lenses are limited to about f/3 or higher. Luckily these limitations are not detrimental to the performance or design of the optical system in this situation. The specifications of the achromatic doublet lens being implemented in the design can be found in Table 2.

Table 2: AC254-030-A Achromatic Doublet Lens

Product Used in Design	AC254-030-A Achromatic Doublet Lens
Manufacturer	Thor Labs Phone: (973) 579-7227 www.thorlabs.com/
Centration (arcmin)	<3
Clear Aperture (% of diameter)	>90
Design Diameter (mm)	25.4
Design Wavelength (nm)	486.1 587.6 656.3
Diameter Tolerance (mm)	+0.0/-0.1
Focal Length (mm)	30
Surface Quality	40-20 Scratch-Dig
Thickness Tolerance (mm)	±0.15
Weight (kg)	0.04
Cost ($)	77.00
Ground Shipping – 1 week ($)	8.75
Picture of Product	

The diffraction limit equation for calculating the radius of the airy disk formed by an A-sphere lens:

$$r = \frac{2}{\pi}\lambda\frac{f}{D}$$

However, as previously mentioned A-sphere lenses are extremely expensive, and unnecessary for our purposes. A constant is implemented to account for this (achromatic doublet).

$$r = \frac{2}{\pi}\lambda\frac{f}{D} \quad \rightarrow\rightarrow \quad r = \frac{2*C}{\pi}\lambda\frac{f}{D}$$

Using the modified equation, with specifications from Table 2, one arrives at the radius of the airy disk formed, and finally the area of the diffraction limited spot formed on the PIN diode.

$$r = \frac{2*C}{\pi}\lambda\frac{f}{D} = \frac{2*2}{\pi}(0.6\mu\text{m})(\frac{30mm}{25mm})$$

$$r = 0.916\ \mu\text{m}$$

$$A = \pi r^2 = 2.64\ \mu\text{m}^2$$

r: radius of Airy disk formed
λ: wavelength of LED beam
C: constant accounting for non-spherical lens
f: focal length
D: diameter of entrance pupil of imaging lens
A: area of diffraction limit spot

D. Assembly

The assembly of the light focusing system is quite intuitive. Since the apparatus must fit on a microscope the only logical lens mount is a c-mount. The achromatic doublet lens is inserted into the c-mount using a twisting motion, and then the mount along with the lens is properly inserted into the microscope such that the focusing end of the lens is facing toward the diode and away from the eyepiece.

Table 3. C-Mount Lens Holder

Product Used in Design	C-Mount Lens Holder
Manufacturer	Thor Labs Phone: (973) 579-7227 www.thorlabs.com/
Price	$27.60
Shipping	$ 8.75 (6-9 days)
Size	Diameter = 42.164 mm Height = 9.525 mm
Quantity Required	1
Picture of the product	

3. Electrical System Design

A. PIN Diode Selection

Since the L.E.D. light of excitation is 600 nm, the PIN diode must have good responsivity at 600 nm wavelength. As the noise to signal ration of the system is quite high, the noise generation by the PIN diode must be minimized. The thermal noise is another critical source of noise since the signal of interest is the level of pA; therefore, the PIN diode must be able to operate normally in a cooled environment to lower noise. The size of active area of PIN diode must be based on the diffraction limits of the lens for acquiring a maximal signal within minimal size.

A Pugh Chart analysis was performed based on the criteria set above. A smaller active area is required to minimizing noise generation. The focal length calculation performed showed that the focal length of the light focusing system is 30 mm and its matching active area on the PIN diode is 2.64 μm^2. Since the matching active area of PIN diode calculated is much smaller than the active areas of commercially available PIN diodes, PIN diodes with smaller active areas get higher scores.

Table 4: Pugh Chart for PIN Diode

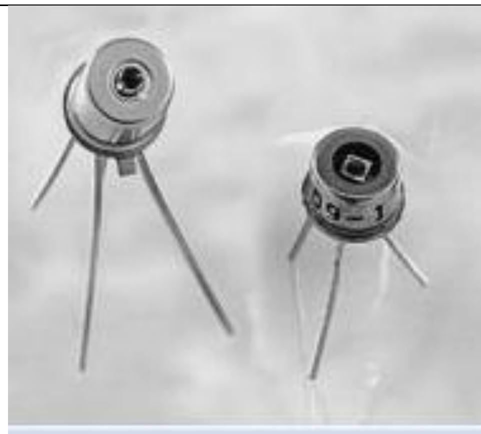
	Weight	PIN_10AP	PIN_10DP(I)/SB	PIN_APD032	PIN_FD07	PIN_FD15	PIN_HR(s)008(L)	PIN-RD100(A)
Ultra Low Noise	10	10	10	10	10	10	10	10
Low Capacitance	8	0	0	10	10	10	10	10
Temperature Range	5	6	6	10	9	9	9	7
Responsivity at 600nm	9	7	8	6	6	6	7	9
Diode Activation Area	8	9	9	5	6	5	9	3
High Speed Circuit	4	0	0	2	2	2	2	2
	Total	265	272	322	335	327	368	320

Table 5: PIN Diode Specifications

PIN Diode Type	Ultra Low Noise	Low Capacitance	Temperature Range (°C)	Responsitivity at 600nm (A/W)	Activation Area (mm^2)	High Speed Circuit
PIN_10AP	✔	X	0 – 70	0.27 - 0.4	100	X
PIN_10DP(I)/SB	✔	X	-10 – 60	0.33 – 0.4	100	X
PIN_APD032	✔	✔	-60 – 100	7.5 @ 850nm	0.5	✔
PIN_FD07	✔	✔	-40 – 100	0.3	7.1	✔
PIN_FD15	✔	✔	-40 – 100	0.3	14.9	✔
PIN_HR(s)008(L)	✔	✔	-40 – 100	0.32	0.04	✔
PIN-RD100(A)	✔	✔	-20 – 60	0.4	100	X

With the highest score of 368 points, PIN-HR(S)008(L) is selected to be used in this project.

Table 6: PIN-HR(S) 008(L) Information

Product Used in Design	PIN-HR(S)008(L)
Manufacturer	UDT Sensor. Inc Phone: (310) 978-0516 http://www.udt.com
Price	$22.00 to $246.00** (Price varies by the additional options)
Shipping	$ 9.28 (6-9 days)
Size	Diameter = 0.4572 ± 0.051 mm Height = 1.5875 mm (Body + Wire) = 0.3175 mm (Body)
Quantity Required	1
Picture of the product	

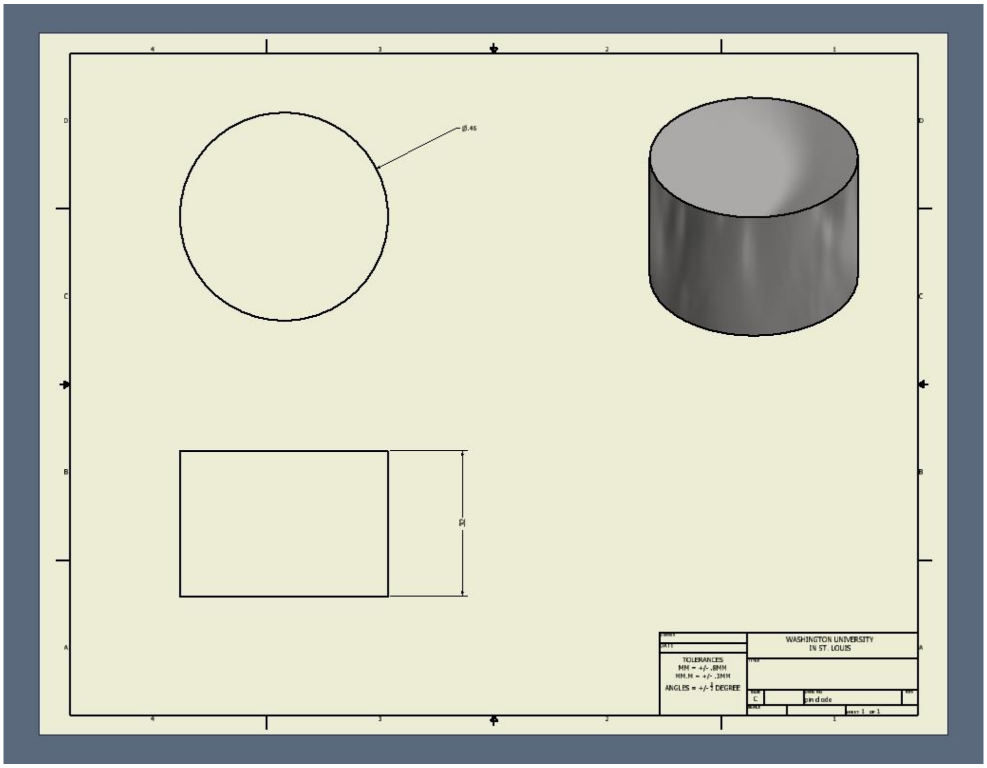


Figure 20 : PIN Diode CAD schematic

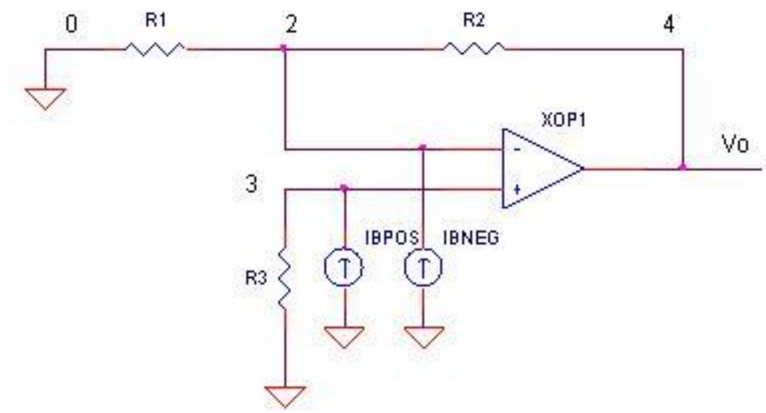
B. Input Constraint Design

Why is Input Constraint Design required?

The source for the electrical system is the current generated in the PIN diode. Since the OP Amp in reality has current flow through the transistors inside of it, the current flowing times the internal impedance of the OP Amp will cause a voltage by Ohm's Law. This is an error voltage between the real signal and what the OP Amp recognizes which becomes an effective offset error which propagates through the circuit. To cancel this error voltage, two techniques can be used: Input Biasing and Current to Voltage Source Converter.

Possible Solution – Input Biasing

Lowering the resistance will generally minimize the error since the current flow of OP Amps is ranged from μA to pA. By installing a bias current, one can find out the resistance values that can cancel the error by following the below calculations. Choosing R3 equal to the parallel combo of R1 and R2, and the bias current errors will be canceled.



$Iboff = Ib^{+} - Ib^{-}$ Ib = Input Biasing Current (μA to pA)

$Vo = Ib^{+} * R3 * (R2/R1 + 1)$

$Vo = -(Ib^{-} * R2)$

$\therefore R3 = (R1 * R2)/(R1 + R2) = R \parallel R2$

However, since the input current of the system is at a level of pA, the current biasing with variable resistance requires the user changing the resistance value for acquiring corresponding input biasing current. This process can be very troublesome for the client. Also as the current becomes the primary input source of the electrical system, all signal responses and outputs must be calculated as current. The current flowing through, however, can be added and subtracted by other power sources, tracking current information will be require extra analysis.

Possible Solution – AC Current to Voltage Converter.

Typical converters use resistances and inductances to transform current to voltage; however, this type of converters usually converts current sources of μA to mA to voltage sources. A literature paper, “A low-noise and wide-band ac boosting current-to-voltage amplifier for scanning tunneling microscopy" written by Dae-Jeong Kim describes the technique of converting pA current to voltage source with unity gain. The designed circuit in literature was used for tunneling microscopy which has a current output level of pA to nA.

By using a converter, a current source can be transformed as a voltage source that has minimized current flow to the electrical system. Minimized current induced lower voltage error generated inside of OP Amps. Also as the primary input of the electrical system becomes voltage, tracking down voltage output values are relatively easy compared to tracking down current outputs. Since the conditions of experiments in literature and of experiments by the client are very similar, the converter design from the literature was adopted.

Actual Design

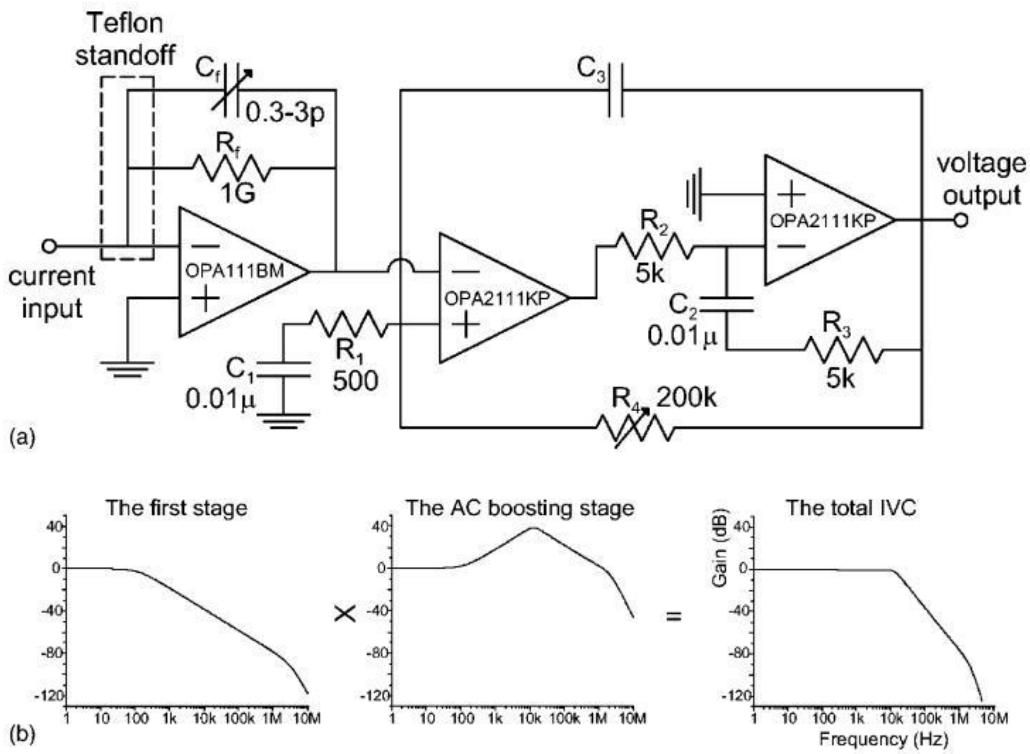


Figure 21: (a) The circuit diagram of two stage ac boosting IVC. (b) The gain response of ac boosting
IVC

Table 7: The bandwidths of the ac boosting IVC tuned by different C3 values, and the corresponding noise characteristics

C3 (pF)	Bandwidth (kHz)	Noise (pA)[a]	Noise (pA)[b]
100	11.3	2.25	4.55
220	5.4	1.29	2.69
470	2.4	0.75	1.37
1000	1.2	0.47	0.73
1500	0.76	0.40	0.58

[a] rms values with the input open.
[b] rms values with the input capacitance of 100 pF.

The design adopted has a unity gain property for the range of 1Hz to 10 kHz (see Figure 21 above). Since the frequency band of interest of client is 5 kHz to 10 kHz, the design adopted didn't distort the signal of interest. For choosing value of C3, since our input is level of pA, noised added by the converter is needed to be minimized. On the other hand, the bandwidth of the system must be wider than 5 kHz. Therefore, a 220 pF capacitor is chosen to be used for C3 of the design adopted.

Table 8: Product Information of Design Requirement

Product Used in Design	OPA111BM	OPA2111KP	Tefalon Standoff – PTFE Insulated Terminal Pins #11067
Manufacturer	Burr Brown Corp. Phone: 520) 746-1111 http://www.burr-brown.com	Burr Brown Corp. Phone: 520) 746-1111 http://www.burr-brown.com	Keystone Electronics. Corp http://www.keyeleco.com
Price	$53.35	$15.23	$0.94
Shipping	$2.95 (4-6 days)	$2.95 (4-6 days)	$4.99 (3-7 days)
Size	9.08 x 9.08 x 4.4 mm^3	9.3 x 6.5 x 6.6 mm^3	4.37 Diameter x 6.35 mm^3
Quantity	1	3	1
Picture of the Product			

C. Amplifier Design

Why is an amplifier required?

Since the input of the system is relatively small compared to the background signal (approximately ~ 0.1 %) the signal must be amplified while reducing the noise. An amplifier or a series of amplifiers is required. The output of the entire electrical system is expected to have a gain of 100 or larger.

Three types of amplifiers are commonly used: OP amps, Diode Amplifier, and Transistor Amplifier. Operational Amplifiers are most commonly used since these are very easy to build and relatively cheap compared to other types of amplifiers. Operational Amplifiers can be enhanced in function by designing Differential Amplifier, Instrument Amplifier, and other else. The diode amplifier is an amplifier that has a diode connected into the amplifier to enforce the input current flow in a certain direction. This is irrelevant to the amplifier design of the client's request. The third type of amplifier is a Transistor Amplifier. In this project, a simple inverted OP Amplifier.

Actual Design

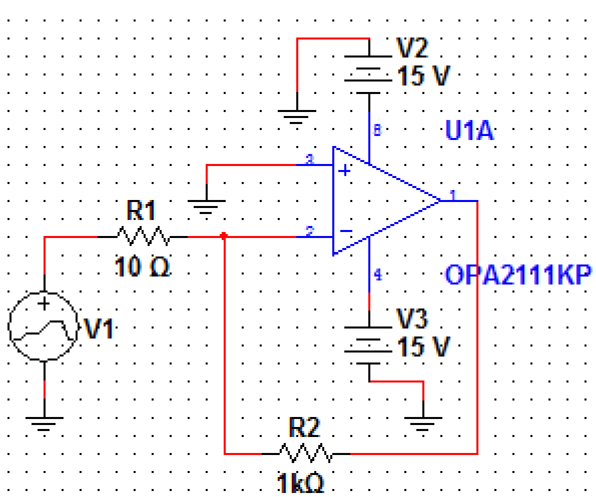


Figure 22: Inverting negative feedback Op Amp

The gain of the system is calculated as

$$G(v) = \frac{\text{Vout}}{\text{Vsig}} = \frac{\text{R2}}{\text{R1}} = \frac{10\text{k}\Omega}{10\Omega} = 100$$

For the operational amplifier of the amplifier, Common mode Rejection Ratio (CMRR) is the most crucial determinant. A pugh chart analysis was performed to choose a proper Op Amp.

Table 9: Pugh Chart Analysis for the Op Amp Selection

	Weight	OPA741	TL072	LM101	OPA111BM	OPA2111KP
Operational Temperature	8	9	9	9	6	8
CMRR	10	9	7	8	9	10
Quiescent Current	7	6	7	7	7	7
Price	6	9	7	6	7	6
	Total	240	233	237	229	249

From the Pugh chart, OPA2111KP was chosen to be used in the amplifier circuit.

D. Bandpass Filter Design

Why is a bandpass filter required?

The client's fluorescence-microscopy research of protein kinases is mostly concerned with the frequency response of 5 kHz to 10 kHz. To maintain the data with minimized noise, a band pass filter with a bandwidth of 5 kHz to 10 kHz is required. Commonly used bandpass filter types are passive, active Bessel filter, active Butterworth filter, active Chebyshev filter, and digital filter. Each type of bandpass filter has its own strengths and weak points.

Since fluorescence-microscopy researches uses the changing of current as the source of protein kinase detection, the shape of the signal observed during protein kinase conformational change is a critical component of such studies. Therefore, signals the original signal structure must be maintained, even after the filtering process.

Passive Bandpass Filter

A Passive Bandpass Filter is the easiest bandpass filter that one can design. The benefit of the passive bandpass filters is that all the components it requires are only simple resistor, inductor, and capacitor. This is very efficient in the sense of production cost. However, its downside is its frequency responses. The cutoff responses of the passive bandpass filters are not acute which means there is a loss of the gain near the cut off frequency. Also the capacitances and inductances of the passive band pass filters will distort the output signal compared to the original input signal. For example, the time constant $\tau = RC$ of the RC bandpass filter, will indicate the delay of the signal by charging and discharging voltage through the capacitors.

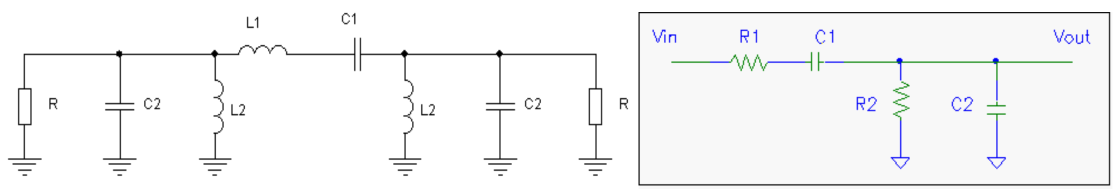


Figure 23: Passive Bandpass Filters (Right: RLC bandpass Filter, Left: RC bandpass Filter)

Digital Filters

Digital Filters are not an actual circuit, but rather a system that performs mathematical operations. To build a digital filter, a professional software developer is required. In this project, client didn't request building a digital filter since the client has an external digital filter connected to fluorescence microscopy. The client stated that he can use the digital filter as an alternative solution if the analog filter design is failed to be achieved.

Active Filters

Active bandpass filters are bandpass filters connected to an amplifier. Amplifiers included in a filter design can be used to improve the performance and predictability of a filter while avoiding the need for inductors. Also an amplifier prevents the load impedance of the following stage from affecting the characteristics of the filter. The most commonly used active filters are Bessel, Butterworth, and Chebyshev Filters. Active filters are commonly used because of the external power source of the OP Amps that supplies power so that the output signal doesn't lose its power, and because of their acute cutoff frequency responses compared to passive filters. Also the decay of the signal outside of the target bandwidth is relatively large. For example, a 4th order Bessel Filter has a slope of -24 dB/dec.

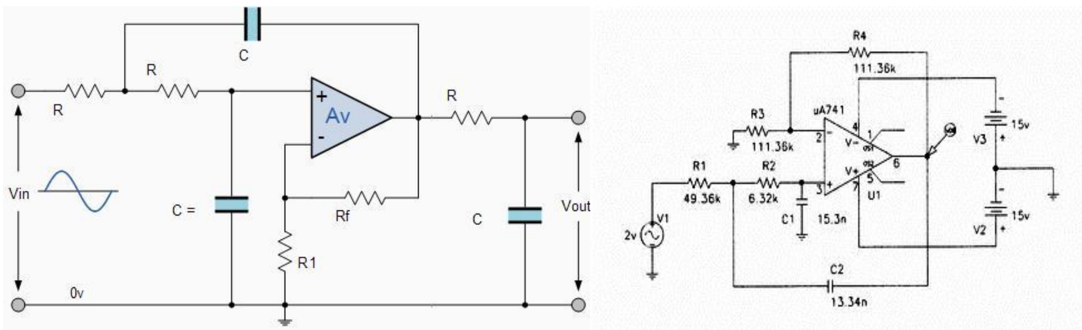


Figure 24: 3rd order Active Butterworth Filter, and 2nd order Active Chebyshev Filter

Sample responses of 8 pole filters, namely the Bessel, Butterworth, and Chebyshev (in this case of 0.5 dB ripple) are compared in the figure below. The responses have been normalized for a cutoff of 1 Hz. Comparing figures below, it is easy to see the trade-offs in the response types.

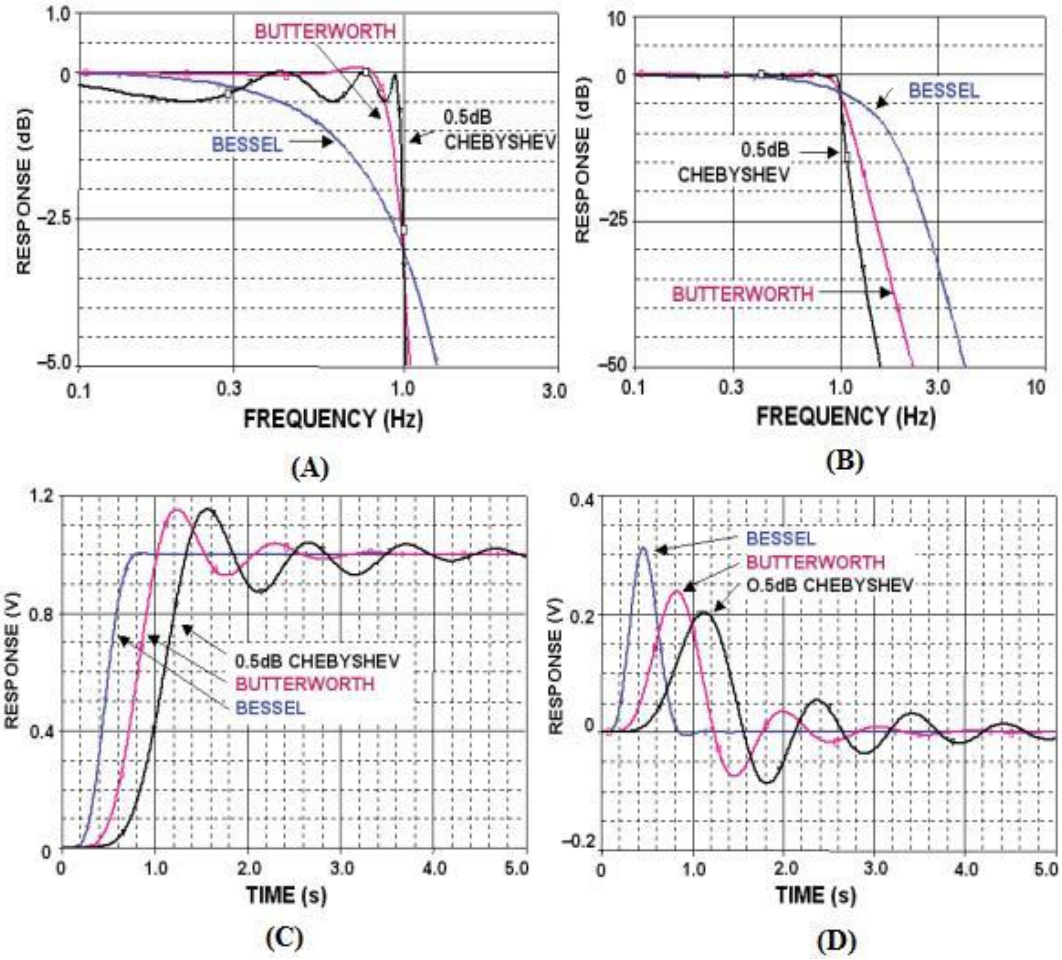


Figure 25: Comparison of Bessel, Butterworth, and Chebyshev Filters:
(A & B) amplitude response (C & D) step and impulse response

Since a Bessel Filter has the characteristic of preserving original signal characteristic as shown in the figure above, it's chosen to be used in the design.

Actual Design

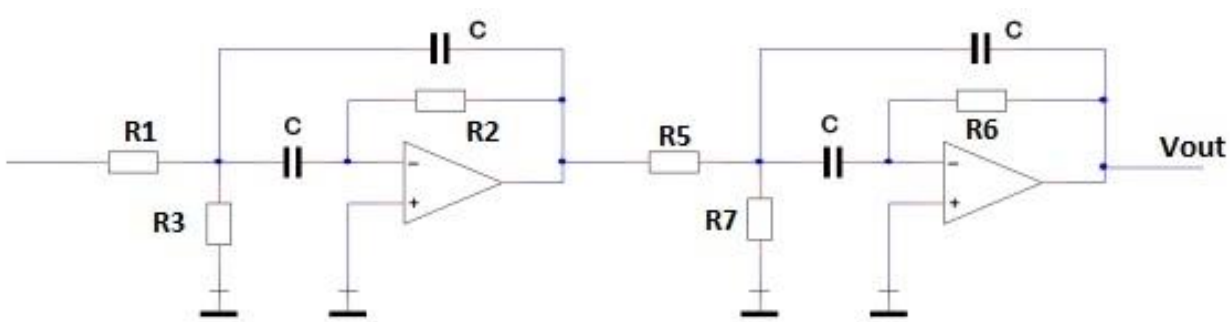


Figure 26: 4th order Bessel Bandpass Filter Schematics

Actual Calculations

- Center Frequency FM= 7.5KHz
- Bandwidth B= 5kHz
- Q= FM/B = 1.5
- Center Gain Km = 1 (absolute value); it is a unity gain filter

- From the Coefficient of the 4th order Filter Table a1 = 1.3617
  b1 = 0.6180
  α = 1.2711 (at Q = 1.5)

- Fm1 = FM/ α = 5900.4 Fm2 = FM* α = 9533.3

- $Q12 = \left(Q(1+\alpha^2)b1 \big/ \alpha a1 \right) = 1.4009 \quad K12 = \left(Q12 \big/ Q \right) \sqrt{Km \big/ b1} = 1.3620$

- C = 10 nF

- $R2 = \left(Q12 \big/ C\pi Fm1 \right) = 7557.5\Omega \quad R1 = \left(R2 \big/ 2 * K12 \right) = 2774.4\Omega$

  $R3 = \left(K12 * R1 \big/ 2 * Q12^2 - K12 \right) = 1474.3\Omega$

- $R6 = \left(Q12 \big/ C\pi Fm2 \right) = 4677.5\Omega \quad R5 = \left(R6 \big/ 2 * K12 \right) = 1717.1\Omega$

  $R3 = \left(K12 * R5 \big/ 2 * Q12^2 - K12 \right) = 912.47\Omega$

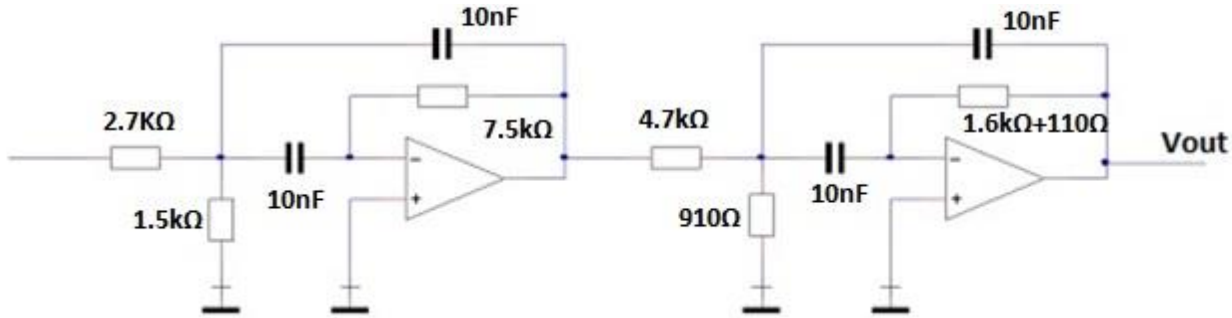


Figure 27: 4th Order Bessel Bandpass Filter Designed with Commercially Available Resistors and Capacitors

For the minimized CMRR, OPA2111KP was chosen to be used in the filter design as it used in amplifier.

Simulation of the Design.

A Multisim simulation for the designed 4th Order Bessel Bandpass Filter was performed. A random noise with a sample rate of 500000 was generated for 10 seconds. This random noise was filtered through the designed 4th Order Bessel Bandpass Filter.

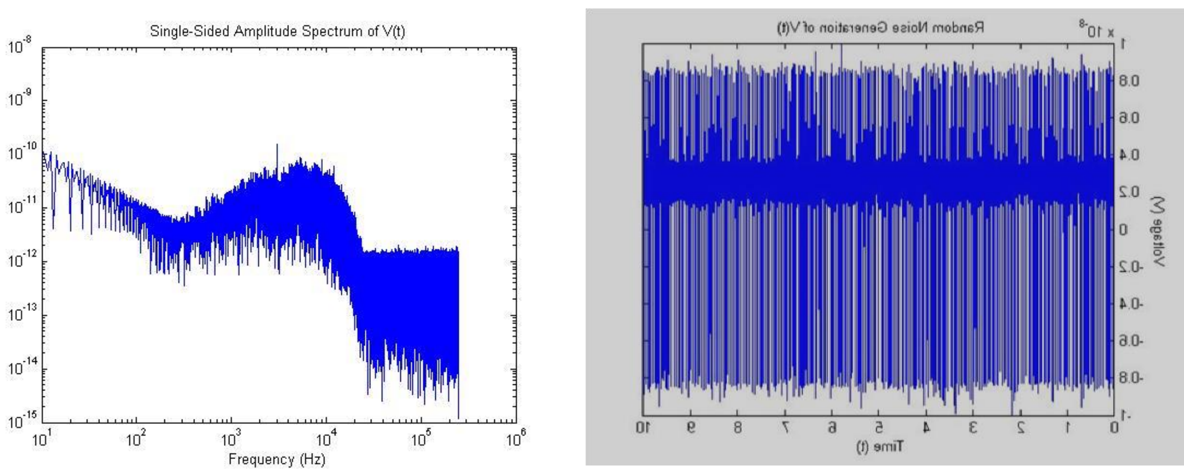


Figure 28: Random Noise Generated

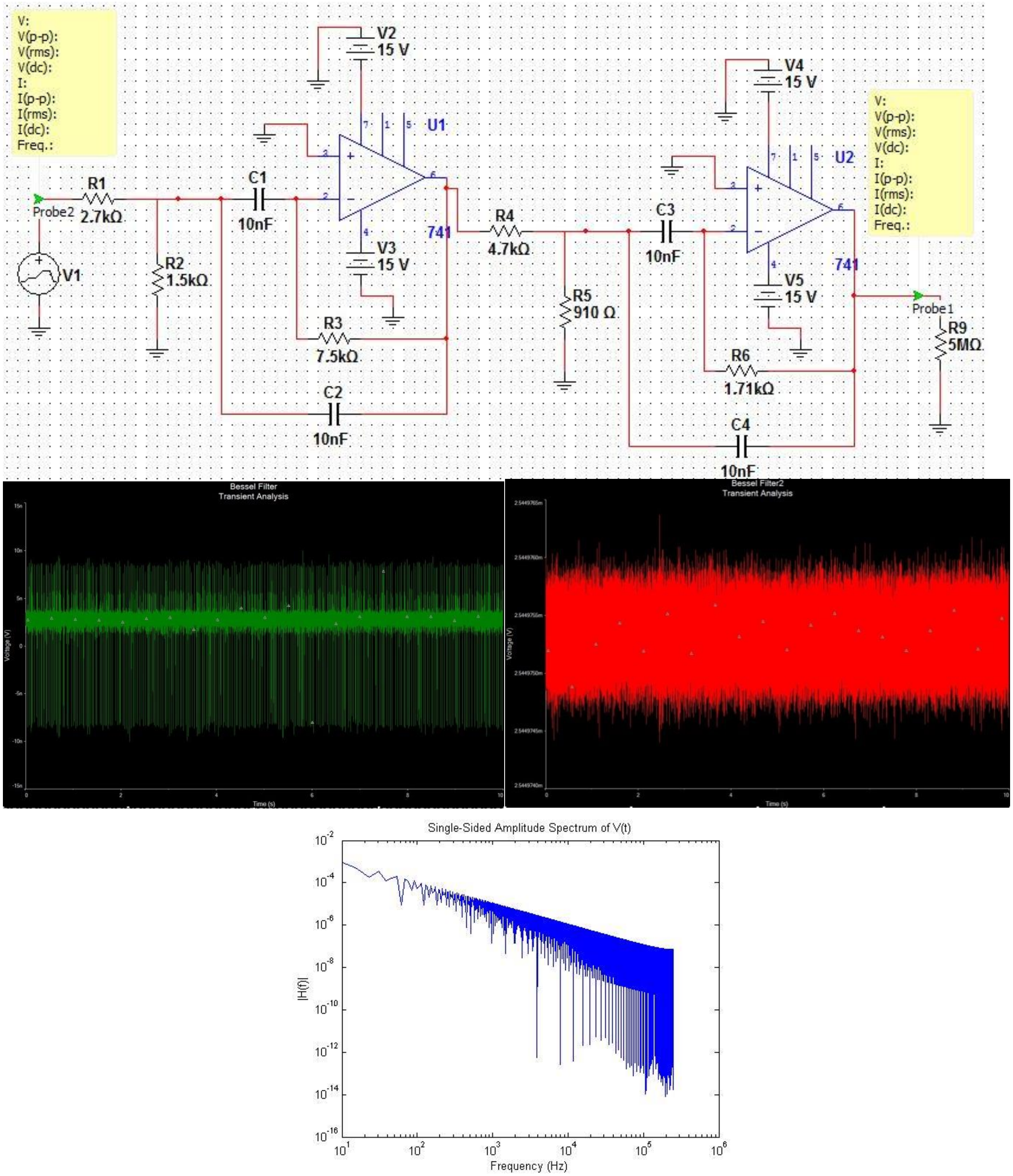


Figure 29: 4th order Bessel Filter Simulations

The Multisim simulation of the designed 4th order Bessel Filter shows the transient response of the filter. Unexpectedly, the gain of the system is 10^6 while the gain of the system was designed to be a unity gain. Also the bandpass filtering with a bandwidth of 5 kHz to 10 kHz function is failed. It instead works as a low pass filter with a cutoff frequency near 10 Hz.

Alternative solution after failure of the designed 4th order Bessel Filter

Since the simulation of the designed filter failed in simulation, our client request not to use the designed filter due to the time constraint. Instead, our client will use an external Digital Filter connected into the microscopy. The digital filter in which client owns is Axon™ Axopatch™ 200B microelectrode Amplifier. This product has a digital filtering software of Bessel and 4-pole Butterworth Filter with a bandwidth of 30Hz to 5kHz. The delay of the system is unknown.

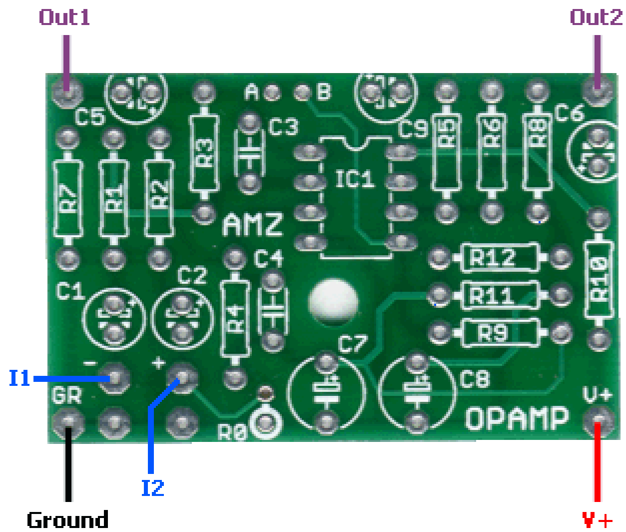
Figure 30: Axon™ Axopatch™ 200B microelectrode Amplifier

E. Assembly of the Circuit Design

All the electrical components will be assembled on the Printed Circuit Board (PCB) by soldering. The proper PCB board must have spaces for the OP Amp, resistors, capacitors, input and output, external power source, and ground. AMZFX® Multi-purpose OP AMP PCB is a PCB with a possible configuration of maximum 1 OP Amp, 12 Resistors, and 8 Possible Capacitors. For the entire circuit assembly, 4 AMZFX® Multi-purpose OP AMP PCBs will be purchased.

Table 10: AMZFX® Multi-purpose OP AMP PCB

Product Used in Design	Multi-purpose OP AMP PCB
Manufacturer	AMZFX® http://www.muzique.com
Price	$10.00

Shipping	$ 2.95 (4-6 days)
Size	31.75 x 48.26 x 4.76 mm^3
Quantity Required	4
Picture of the product	

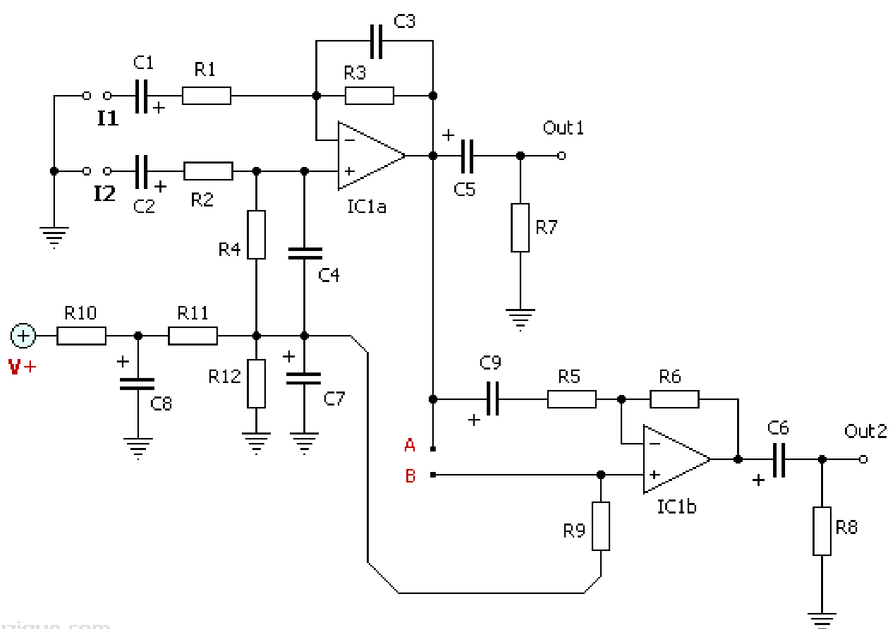


Figure 31: Circuit Schematics for Multi-purpose OP AMP PCB

The various resistors, capacitors, sealed wires, and BNC wire in our design will be obtained from the electrical laboratory in Bryan 306. The PCB boards will be drilled and screwed to the side of the cylinder adopted into the SM1 Adopter of the head-stage.

4. Cooling System Design

A. Survey of Cooling Methods

Several alternatives exist to the thermoelectric cooling suggested by the client, each with their own advantages and disadvantages. Cooling methods primarily rely on fluids (either in enclosures or in open systems) which act to transport heat. More advanced methods utilize thermoelectric effects. The simplest cooling method is open air cooling.

Open Air cooling involves increasing the flow of air in the surrounding region of the circuit to be cooled by employing a fan. Air cooling would not suffice in the light detection system for several reasons. First it is unlikely that sufficient heat dissipation could be achieved due to the small size of the PIN diode to be cooled and the low desired temperature (-20 degrees Celsius) desired. Second, it is unlikely that sufficient air flow could be achieved since the PIN diode will be narrowly embedded within the SM1 adapter. Finally there is the issue of where to place such a fan. Ideally the fan would blow directly through the hole that the PIN diode is located. If placed in front, the L.E.D. is blocked. If placed behind, it would be difficult to fit given the rest of the circuitry. Another popular open cooling design is that of open liquid nitrogen cooling.

Liquid nitrogen can easily provide enough cooling to the PIN diode, since it is capable of achieving temperatures below -100 degrees Celsius. But liquid nitrogen has certain important downsides. First, it is difficult to focus. It would not just cool the circuit, but also the surroundings. In particular it would cool the lens and possibly the specimen being viewed under fluorescence microscopy. In cooling the surroundings, it would cause condensation of water vapor from the air which would prevent the proper functioning of the lens, and potentially damage the electrical filtration system. Finally liquid nitrogen cooling systems have the complication of the Leidenfrost effect, in which the liquid nitrogen would boil upon contact with the system, producing nitrogen vapors which effectively insulate the system, decreasing the efficiency of cooling. Overcoming these downsides requires excessive use of insulation, which is exacerbated by the small area of the SM1 adapter and PIN diode combination. Liquid nitrogen is also a rather expensive cooling solution, requiring continual refills. More complex than liquid nitrogen cooling is refrigeration.

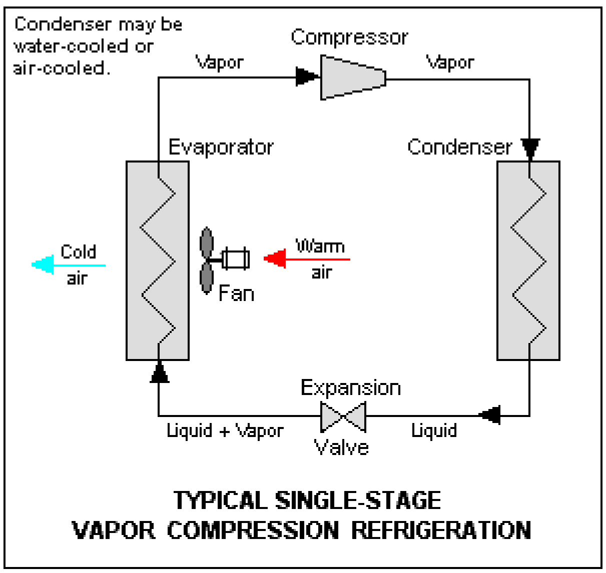


Figure 32: A Typical Refrigeration Cycle

Refrigeration involves cycling a fluid through a circuit involving a compression and an expansion phase. In the compression phase, vapor is condensed to liquid, which then absorbs heat and vaporizes in the expansion phase. Refrigeration can mean placing the entire microscope apparatus in a refrigerator, or it can mean attempting to construct a small refrigeration cycle around the PIN diode. Placing the entire apparatus in a refrigerator is untenable. It makes the microscope difficult to use, it potentially damages the electronics via condensation, and it may damage cold sensitive biological specimens. Constructing a refrigeration cycle around the PIN diode is not really feasible: such an apparatus requires much more space than is available. Even if enough space was available, custom building a refrigeration cycle would be far too costly. Clearly a common problem is size: most cooling methods are designed to cool surface areas far larger than that of a PIN diode.

B. Peltier Cooler Selection

The best method to cool smaller objects is to use a Peltier cooler (also known as a TEC or thermoelectric module). TEC's utilize an effect known as the Peltier effect where the application of a voltage to a thermocouple produces a heat differential dT between the two sides of the thermocouple. One slight problem with Peltier coolers is that their ability to cool is not based on a specific temperature. Their ability to cool is ranked based based off of how much energy per unit time in watts they can transfer from their "hot" side (the side in close proximity to the PIN diode) to their cold side, also known as their Qmax. As such, calculations are usually performed according to a given thermal load, typically that of a computer chip. In this specific case, there is no such load. The PIN diode is only cooled by the ambient temperature of the surroundings. Air currents are variable, so any estimations of the thermal effect of the ambient environment will be inaccurate. The group spoke with an engineer at Tellurex, a firm which specializes in TEC's. The engineer's advice was to use the Peltier cooler with a size that could fit the PIN diode with the highest Qmax that can be found. The DC current powering the cooler could be increased or decreased as necessary to achieve the desired temperature of -20 degrees Celsius. While the client could use multiple DC sources to find the ideal cooling amount, the team designed the Peltier cooler's power supply to be connected in series with a variable resistor for convenience.

The following Pugh Chart analysis was performed based on the parameters detailed above. Since the cooler's activity can be controlled based on the magnitude of its DC power source, the most important parameters are the dimenions A, B, and H of the cooler since the cooler must fit in the SM1 adapter with the PIN diode. In this case, smaller is better. Beyond fitting the enclosure, a high dTmax and Qmax are important as they control the limit of the cooler's cooling capacity.

Table 11: Peltier Cooler Pugh Chart

	Weight	C2-04-0101	C2-06-0902R	00801-9X30-10RU3	C2-06-0402R	C2-04-0102	00301-9X30-10RU2
Qmax	7	5	10	4	8	5.5	3
dTmax	6	8	8	8.5	8	8	8.5
A	10	7	6.5	9	7	8.5	10
B	10	7	3	9	7	8.5	10
H	10	7	7	9	7	8.5	10
	Total	230	283	349	314	341.5	372

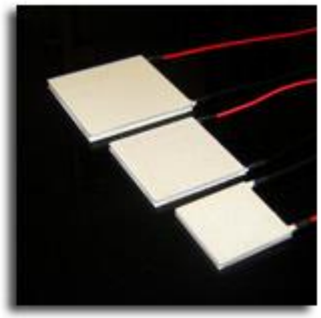
With the highest score of 372 points, the 00301-9X30-10RU2 Single Stage Mini Peltier Cooler from Custom Thermoelectric is selected.

Table 12: Peltier Cooler Specifications

	High Qmax	High dTmax	A dimension (smaller is better)	B dimension (smaller is better)	H dimension (smaller is better)
C2-04-0101	X	✔	4.2mm	4.2mm	2.6mm
C2-06-0902R	✔	✔	6mm	24mm	2.3mm
00801-9X30-10RU3	X	✔	2.5mm	2.5mm	1.8mm
C2-06-0402R	✔	✔	6mm	12mm	2.3mm
C2-04-0102	X	✔	4.2mm	4.2mm	2.3mm
00301-9X30-10RU2	X	✔	1.2mm	1.9mm	1.4mm

Table 13: Product Information of Selected Peltier Cooler

Product Used in Design	00301-9X30-10RU2 Single Stage Mini Peltier Cooler

Manufacturer	- Custom Thermoelectric, Inc. Phone: (443)-926-9135 http://www.customthermoelectric.com/index.htm
Price	$31.50 (includes moisture seal and lead wires)
Quantity	1
Picture of the Product	
Shipping Cost	$8.73
Shipping Time	~5-8 days

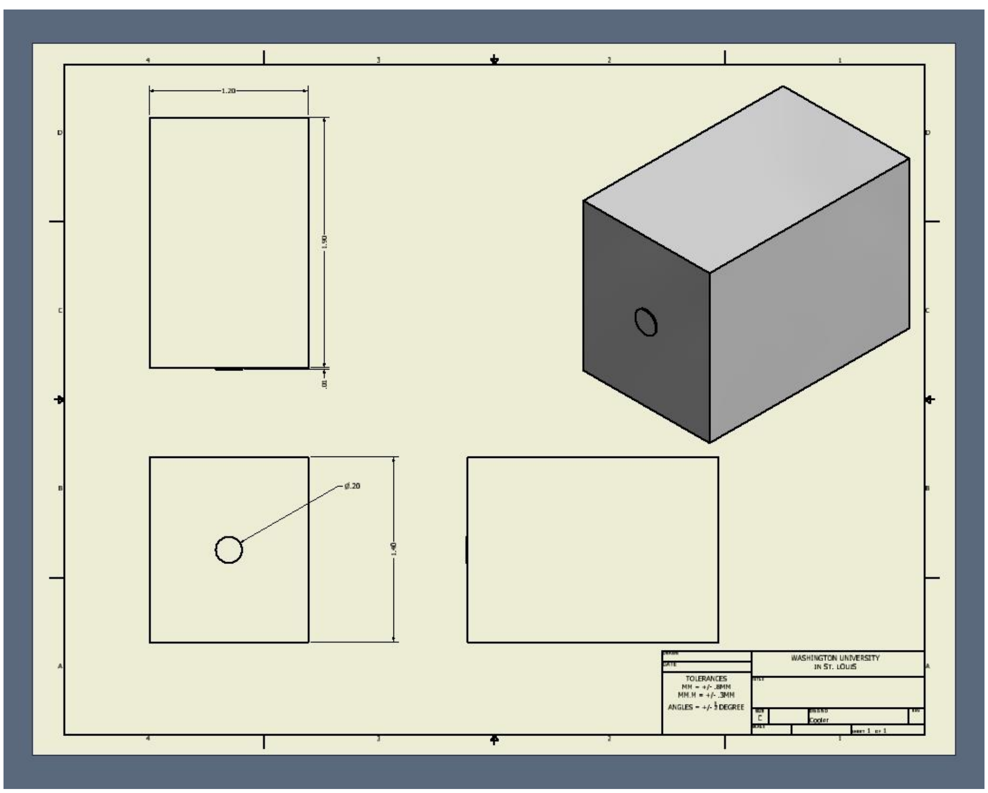


Figure 33: Peltier Cooler CAD drawing

C. Mounting/Heat Sink/Thermal Interface

Peltier coolers require a mounting method, a heat sink, and a thermal interface. Mounting refers to the process of securing the cooler to the device to be cooled. A heat sink serves to collect and dissipate heat that is transferred in the cooling process, and a thermal interface serves to connect the heat sink to the Peltier Cooler. There are three primary mounting methods: 1. Compression, 2. Adhesive bonding, and 3. Soldering.

Compression involves drilling holes through a “Cold Plate.” The cooler is place between the “Cold Plate” and the surface to be cooled. Fasteners are placed through the holes drilled in the “Cold Plate” and used to fasten the cooler to the surface to be cooled in compression. This setup is pictured in figure 34 below. This does not work for the light detection system because the cooler to be secured is rather small (and therefore fragile to compressive forces) and because there is no surface on the PIN diode to be drilled.

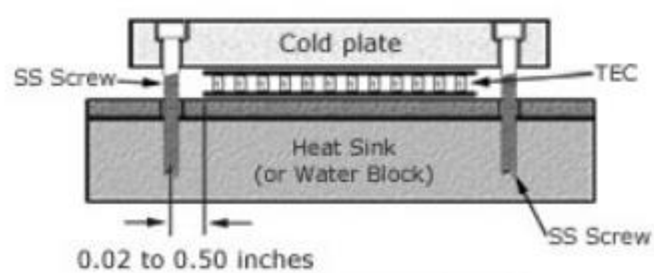


Figure 34: TEC mounted in compression

Adhesive bonding could potentially suffice. It involves “gluing” the cooler to the heat sink with an epoxy. The major downside of adhesive bonding is that it tends to cause outgassing, the release of trapped gas from the epoxy. Outgassing could influence the stability of the temperature and potentially interfere with the operation of the PIN diode. As such, adhesive bonding is a sub-optimal option.

Soldering involves bonding the cooler to the heat sink by utilizing the melting and then solidification of a metal. Soldering provides a very high heat transfer capacity, minimizes outgassing, and is widely regarded as the best solution for TEC's smaller than 23 mm. Soldering also is convenient in that it can act both as a mounting method and as a thermal interface to the heat sink, simplifying the design and providing a net cost savings.

The heat sink functions to collect and dissipate the heat transferred by the Peltier cooler. The heat sink in the team's design shall be the enclosure of the cooler. It shall be a simple hollow cylinder with dimensions detailed in table 14, machined at the machine shop. The Peltier cooler will be soldered to the inner wall of this cylinder. The cylinder can be made from almost any metal since the heat transfer of the system will be constrained by the Peltier cooler. For convenience and cost reasons, the team selected aluminum, though the client may choose another metal at his discretion. The enclosure's outer radius was designed specifically to fit snugly in the client's own SM1ZM adapter tube (see following figure):

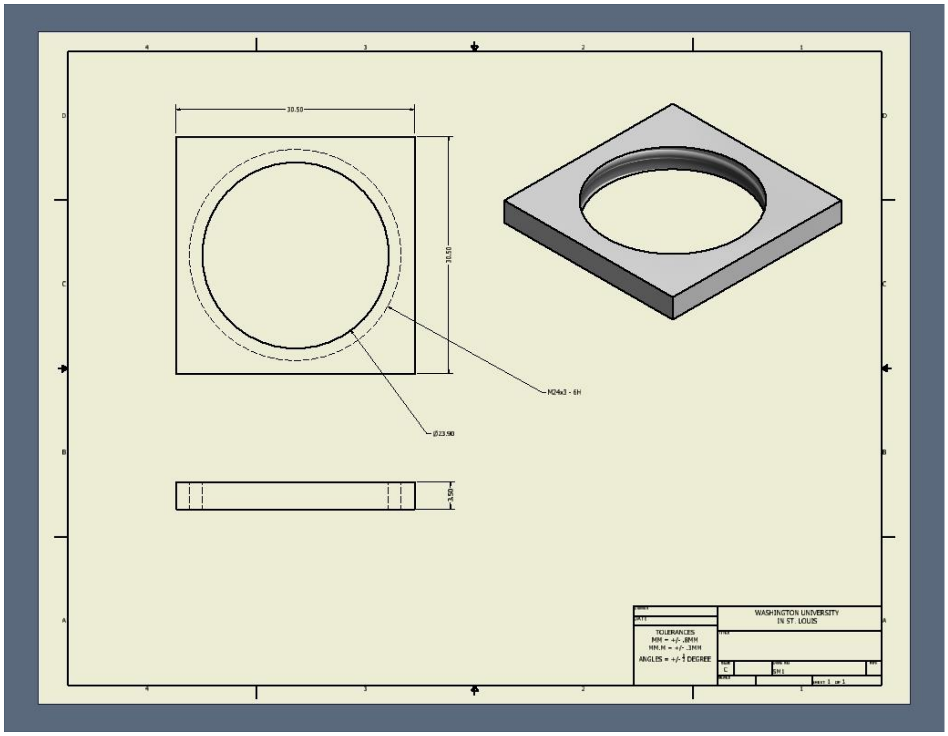


Figure 35: SM1ZM Adapter Tube

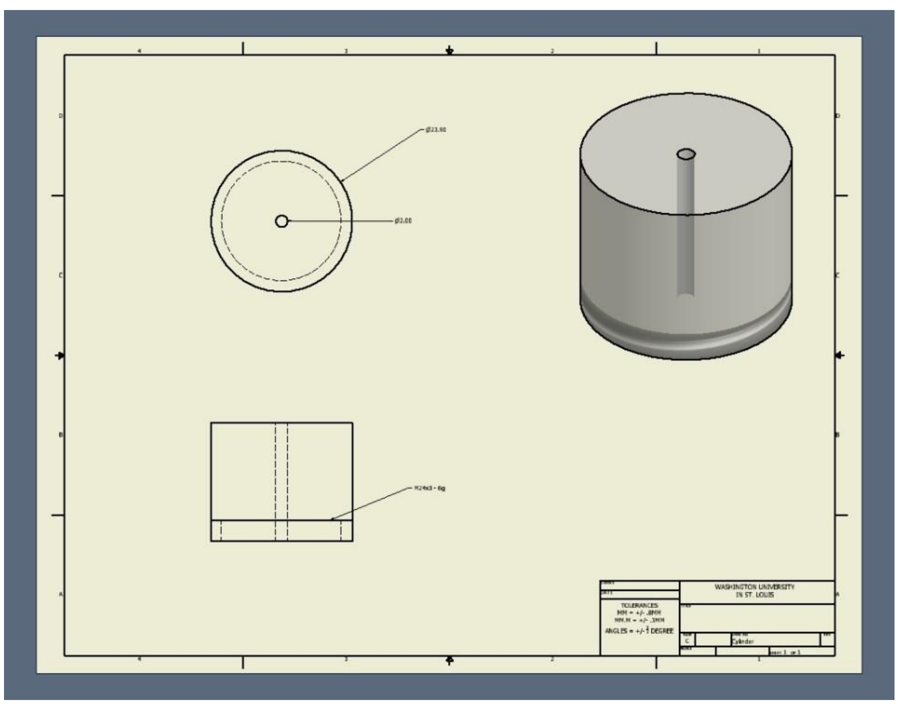


Figure 36: Cylindrical Enclosure

Table 14: Enclosure Dimensions

Outer Diameter	23.90 mm
Inner Diameter	2.00 mm
Height	2 cm
Estimated Cost	$100-300

The Peltier cooler will be powered by a DC supply connected to a variable resistor box so as to allow the client to modulate the cooling as desired. This same power supply will in parallel supply the electrical filtration system. The entire system will be wired through an opening in Dr. Silva's Faraday Cage.

D. Assembly of the Cooling System

The Peltier Cooler will be soldered by the machine shop to the interior of the cylindrical enclosure. Due to the size involved, the machinist at the machine shop recommended forming two separate half cylinders, soldering the Peltier Cooler, merging the two half cylinders, and then slipping the PIN diode into the gap between the cooler and the other wall of the enclosure. Wires could be drawn through one of the large holes in the enclosure (the face opposite where the PIN diode will lie), or a hole could be drilled through the cylinder at the client's discretion. The following DC Power supply and Variable Resistor kit will be used:

Table 15: DC Power Supply

Product Used in Design	Tekpower DC Variable Power Supply, 1.5-15V @ 2A, HY152A

Manufacturer	- Tekpower Phone: 909.628.6088 http://www.tekpower.us/
Price	$39.99
Quantity	1
Picture of the Product	
Shipping Cost	Free
Shipping Time	~5-8 days

Table 16: Variable Resistor

Product Used in Design	Resistor Substitution Box Kit
Manufacturer	- Elenco® Electronics, Inc Phone: (847)541-3800 http://www.elenco.com/
Price	$15.75
Quantity	1
Picture of the Product	
Shipping Cost	Free with DC Power Supply From Above
Shipping Time	~5-8 days

5. Integrated System Design

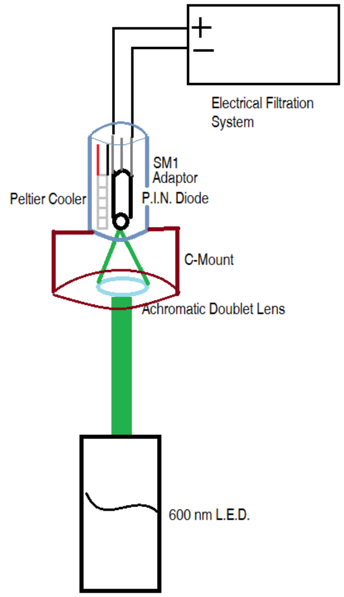


Figure 37: Simplified Schematic of Integrated System

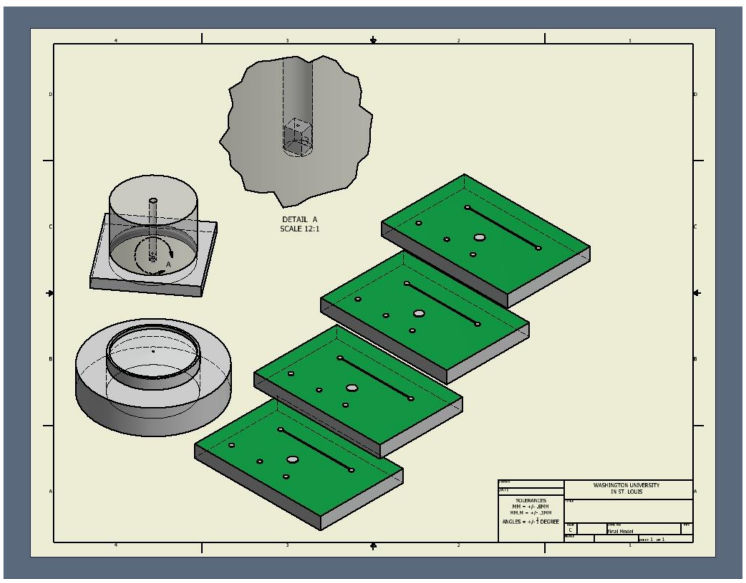


Figure 38: CAD Schematic of Integrated System

The schematics above summarize the overall functioning of the light detection system being developed. The 600 nm L.E.D. fires its light onto the Achromatic Doublet Lens within the

C-Mount. The lens focuses this light onto the small active area of the PIN diode within the SM1 Adapter. The PIN Diode is cooled by the Peltier Cooler so as to reduce electrical noise. The electrical signal generated by the PIN diode is then amplified and filtered by the Electrical Filtration System, and then further interpreted by the client.

System total cost

6. Designsafe Analysis

		Initial Assessment			Final Assessment	
Hazard /		Severity			Severity	
Failure Mode		Probability	Risk Level	Risk Reducti	/Comments	Probability
electrical / electronic : lack of grounding (earthing		Serious	Low	standard procedures		Serious
Improper Assembly		Remote				
electrical / electronic : improper w iring		Moderate	Negligible	standard procedures		Moderate
Improper Assembly		Remote				
heat / temperature : inadequate heating / cooling		Moderate	Low	standard procedures		Moderate
Improper Peltier Cooler Assembly		Unlikely				
w astes (Lean) : correction / defective parts		Moderate	Low			Moderate
Manufacturer's Error		Unlikely				

The Designsafe analysis found only four hazards. The first was the risk of the user not grounding the electronic circuitry properly. Such a mistake would lead to system failure and possible fired since the Operational Amplifier would overheat from excessive currents. Such an error is unlikely since Professor Silva has circuits knowledge and experience, but this hazard should still be mentioned. The next hazard is improper wiring, which is similar to the first hazard in that it would be a consequence of improper assembly by the user Dr. Silva. Improper wiring can lead to a variety of negative consequences, including but not limited to: system overheating, fire, system failure, or electrical shock. The third hazard was that of inadequate cooling by the Peltier cooler. If the cooler is improperly soldered to the enclosure, or if the polarity of the DC voltage is accidently reversed, the cooler would likely overheat, damaging the

PIN diode and leading to system failure. The final hazard is that of a simple manufacturer's defect. A manufacturer's defect can lead to a variety of negative consequences, including but not limited to: system failure, overheating, fire, electrical shock etc..

7. Conclusion

A. Achievement & Problem Solving

The actual design process of the entire electrical circuit with various components is a unique experience. The design of the amplifier, filter, and AC to Voltage converter is a great electrical engineering achievement. Every design targets were achieved except for the design of the 4^{th} order Bessel Bandpass Filter. The simulation of the designed filter proved that the system didn't work as a bandpass filter; rather it works as a low pass filter. The troubleshooting through the simulation didn't solve the problem. Except that, the design requirements of amplifier and input constraint were achieved.

The design of the cooling system was also rather novel for the team. No one on the team had experience with TEC's in the past. The designed cooler is somewhat imprecise, but it should provide more than enough cooling for noise reduction purposes.

B. Future Direction & Improvement.

Due to the time constraint, the design did not achieve the initial requirement of designing a bandpass filter. The 4^{th} order Bessel Filter designed were failed in simulation. The error most likely caused by the faulty calculation. The future of the project if we concede our study will start with the fixing the Bessel Filter designing. Also, the *AC Current to Voltage Converter* is adopted from the literature; therefore, no data is acquired for the actual usage of the fluorescence microscopy. Troubleshooting of possible error of adopted design will be required.

C. Learning from the design process

Basic design of amplifier was not really new; however, the design of the 4th order Bessel Filter and design of the input constraints was totally new subject to learn. By designing theses circuits, understanding of electrical circuits and design skills were improved significantly. Design of the cooling system broadened the team's knowledge, given that the team had never researched or designed cooling methods before.

D. Ethical Considerations

Originally, the fluorescence microscopy techniques were developed for the research of protein kinase. As our design only targeted lowering a signal to noise ratio, there were no significant ethical considerations associated.

E. Intellectual Property (IP)

In the design of the system, no significant innovative ideas or products were developed. The materials and devices were all commercially available, the problem was deciding which ones to implement and why, and how the different components would be assembled together to achieve the goal of the composite device. In essence, there is nothing to protect, thus no intellectual property to be concerned about.

8. Team Responsibilities

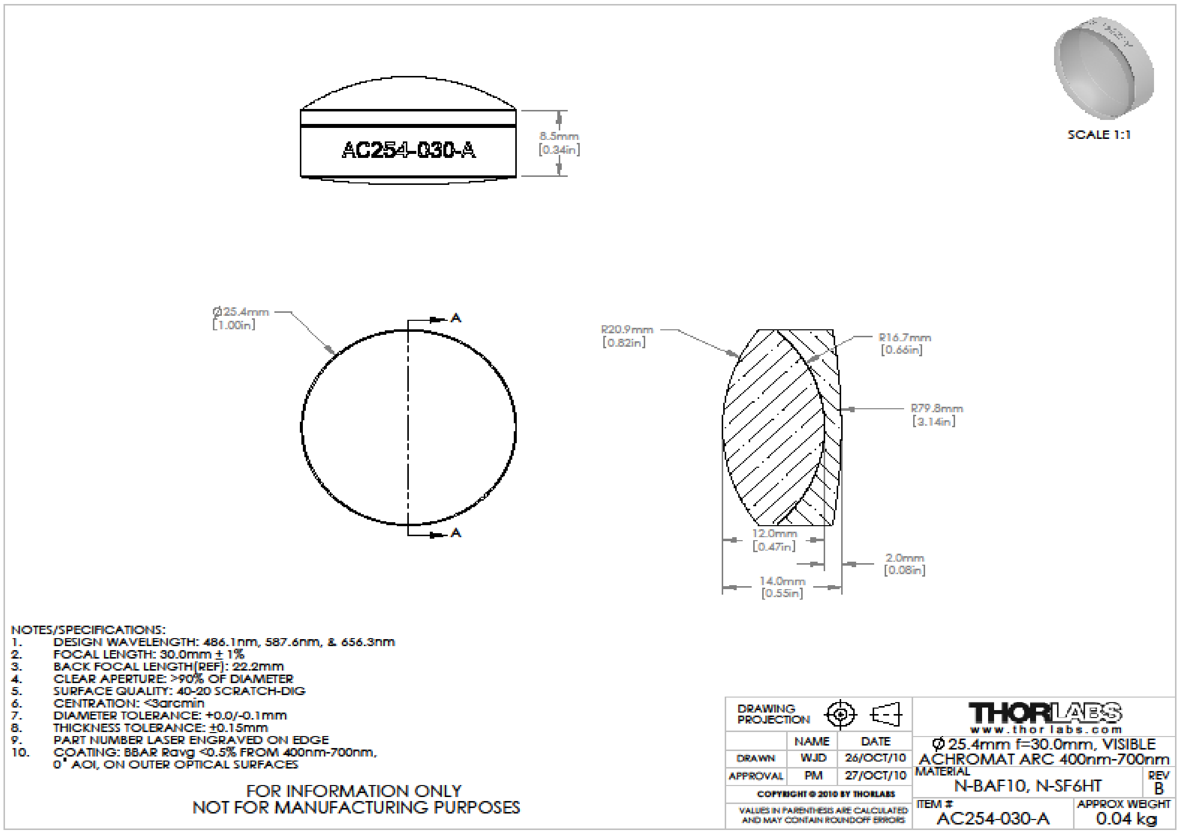
Table 12: Team Responsibilities

Team Member	*Specific Role*
Eric Kleinberg	• Research and Design of Peltier (TEC) Cooling System • Website Development • Schematic Development
Leran Firer	• Research and Design of Optical Focusing System • Lens Selection • Designsafe Analysis
Dohyun Kim	• Research and Design of Electrical Circuitry • PIN Diode Selection • Filter Simulation.

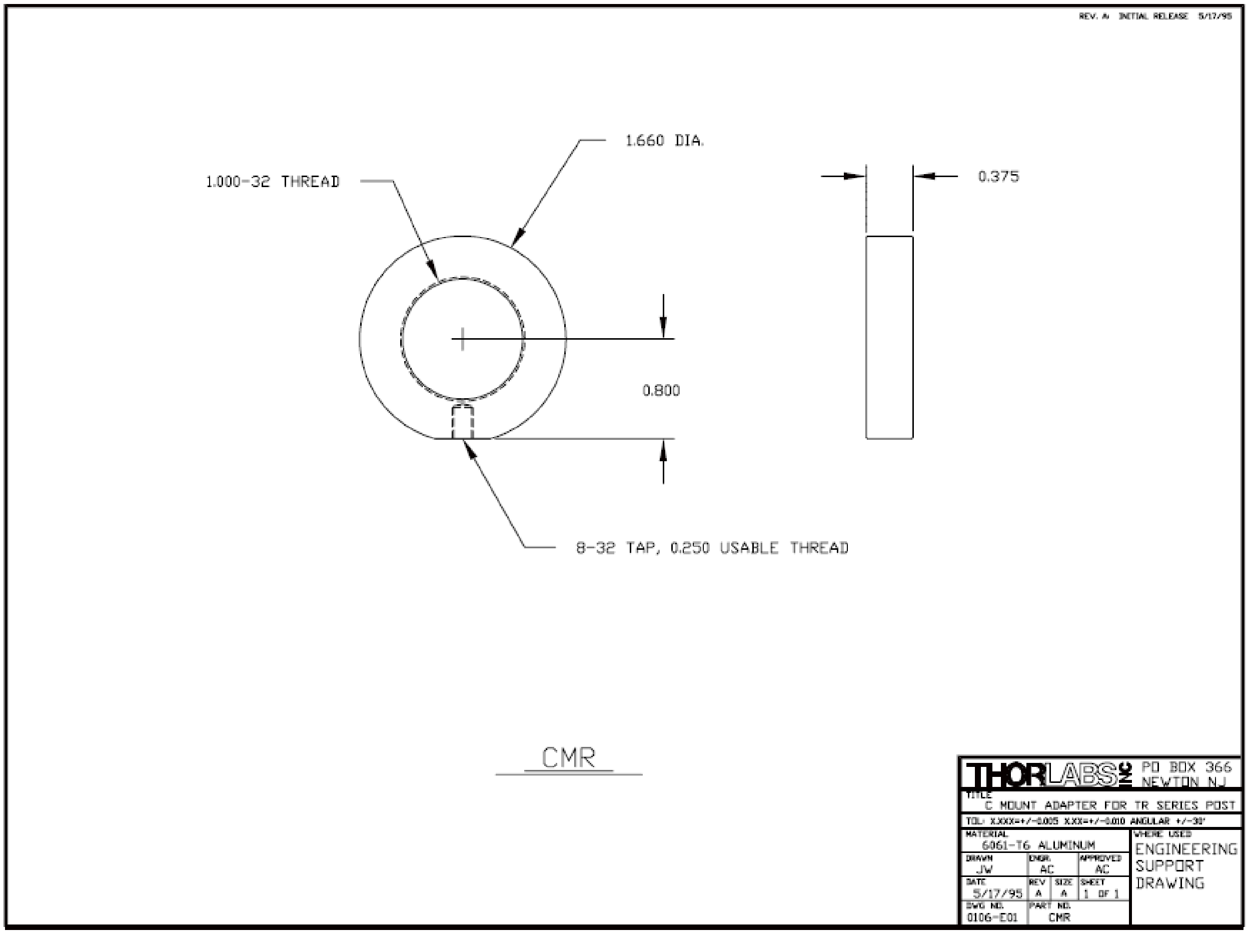
9. APPENDIX

Product Specification Sheet

1. Thor Labs Achromatic Doublet Lens



2. Thor Labs C-Mount Lens Holder



3. Axon™ Axopatch™ 200B microelectrode Amplifier

Molecular Devices

Axon™ Axopatch™ 200B Microelectrode Amplifier Specifications

Unless otherwise noted: T_A = 20°C, 1 hour warm-up time.

CV 203BU Headstage

Construction: All critical components are in a sealed hybrid and cooled with a solid state cooling element.

Configuration: High-speed, low-noise current-to-voltage converter

Cooling: Input circuitry -15°C typical. Headstage cooling should be kept on at all times to ensure proper calibration of offset voltages.

Gain (β): 1 mV/pA (β = 1) Patch or Whole-Cell modes

0.1 mV/pA (β = 0.1) Whole-Cell mode

Feedback element:

Patch	1 pF
Whole Cell	β = 1, 500 MΩ in parallel with 1 pF
Whole Cell	β = 0.1, 50 MΩ in parallel with 1 pF

Tuning (Whole Cell mode only): Tuning circuit to idealize response of the feedback resistor is contained in the main instrument. Tuning is automatically bypassed when the capacitive feedback is selected.

Pipette-capacitance-compensation injection capacitor: 1 pF

Whole-cell-capacitance-compensation injection capacitor:

Patch	none
Whole Cell	β = 1: 5 pF
Whole Cell	β = 0.1: 50 pF

Case: Connected to ground. Case jack mates to 1 mm plugs.

Bandwidth: Test signal applied via Speed Test input

Internal: 140 kHz patch mode
70 kHz whole-cell mode

Max. external: 100 kHz (limited to output filter)

Capacitative load stability: 1000 pF, 0 Ω in series

Maximum instrument noise: Measured with minimal external noise sources (*i.e.*, radiated line-frequency noise, mechanical vibration) 8-pole Bessel filter

Max. Instrument Noise: Without Holder			
	Patch	Whole Cell	Whole Cell
Line Frequency and Harmonics	β = 1 0.005 pA_{P-P}	β = 1 0.005 pA_{P-P}	β = 0.1 0.005 pA_{P-P}
0.1–100 Hz	0.030 pA_{P-P}	0.50 pA_{P-P}	1.6 pA_{P-P}
0.1–1 kHz	0.015 pA_{rms}	0.25 pA_{rms}	0.75 pA_{rms}
0.1–5 kHz	0.060 pA_{rms}	0.65 pA_{rms}	1.65 pA_{rms}
0.1–10 kHz	0.130 pA_{rms}	1.10 pA_{rms}	3.0 pA_{rms}
Max. Instrument Noise: With Holder			
0.1–10 kHz	0.145 pA_{rms}	1.10 pA_{rms}	3.0 pA_{rms}

Reset Characteristics (Patch mode only)

Total reset time: 50 µs ±10%

Time between resets (T_{BR}):

For DC currents: $T_{BR} = 10 / (I_{DC} - I_{BIAS})$ where I_{DC} and I_{BIAS} are in pA and T_{BR} is in seconds.

I_{BIAS} is typically 0.3–1.0 pA.

For transient currents: A reset will occur if the headstage must deliver more than 10 pC of charge to the membrane.

Reset transients in current waveform at Scaled Output (typical):

100 Hz	±0.25 pA
1 kHz	±0.5 pA
10 kHz	±2 pA

Current Clamp

The speed in I=0 mode is the same as in I-Clamp Normal. In addition, Track mode is a slow clamp to zero current. Note that series resistance compensation remains active in current clamp mode, allowing measurement of pipette resistance and (when R_s is compensated) accurate monitoring of cell membrane potential, but the speed setting is still determined by the actual electrode resistance and not only the remaining uncompensated resistance.

The speed of the current clamp depends on the Mode setting (Normal or Fast), the time constant of the cell and the pipette resistance.

			10–90% rise time (overshoot)	10–90% rise time (overshoot)
R_p	R_m	C_m	I-Clamp Normal	I-Clamp Fast
1 MΩ	0 MΩ	0 pF	15 µs (10%)	N/A
1 MΩ	500 MΩ	33 pF	350 µs (0%)	N/A
10 MΩ	0 MΩ	0 pF	200 µs (20%)	20 µs (< 1%)
10 MΩ	500 MΩ	33 pF	250 µs (10%)	10 µs (< 1%)
50 MΩ	500 MΩ	33 pF	500 µs (30%)	150 µs (< 1%)

Capacitance Compensation

Pipette Capacitance	
Fast τ	0.2–2 µs
Fast Magnitude	0–10 pF
Slow τ	0.1–10 ms
Slow Magnitude	0–1 pF

These controls are used to charge pipette capacitance. In I-Clamp modes they act as a negative capacitance.

	β = 1	β = 0.1
Whole-Cell Capacitance	0.3–100 pF	3–1000 pF
Series Resistance	0–100 MΩ	0–100 MΩ

These controls are used to charge membrane capacitance in whole-cell V-Clamp. For Patch mode, whole-cell capacitance is not operative. In I-Clamp modes only the Series Resistance control is operative. The whole-cell capacitance control places an analog voltage proportional to setting on Cell Capacitance Telegraph Output.

Series Resistance Compensation

% Prediction: OFF, 0-100%. Acts with Whole-Cell Parameters to speed up charging of the membrane. Maximum achievable % Prediction is limited by the magnitude of the voltage step.

% Correction: OFF, 0-100%. Acts with Series Resistance setting to reduce series resistance errors and to speed up response to ionic currents.

Lag: 1–100 µs. Cuts high-frequency response of series-resistance correction circuit to enable a higher Correction setting.

Capacitance Dithering

Enabled during a TTL High level signal to Whole Cell Capacitance Dither input.

Effectively increases the observed cell capacitance by 100 fF (β = 1) or 1 pF (β = 0.1). Useful for cell membrane capacitance measurements. May be used in conjunction with the DR-1 Resistance Dither unit.

DR-1 Resistance Dither unit (supplied with the Axopatch 200B amplifier) normally provides a short-circuit link between preparation and ground. Inserts a 500 kΩ resistor in series with bath ground during TTL High signal. Suitable for finding the phase tracking angle in capacitance measurement experiments.

Mode

V-Clamp: Pipette voltage is clamped.

I-Clamp normal or fast: Pipette current is clamped to command current from Holding Command knob or external input. Normal mode is stable for electrode resistances greater than 1 MΩ. Fast mode is stable for electrode resistances greater than 10 MΩ. Series Resistance control is active.

Track: Slow I-Clamp to zero current used to correct pipette offset.

(I=0): I-Clamp to zero current.

Selected mode sets analog voltage on Mode Telegraph Output.

Command Potentials

Seal test: 5 mV (V-Clamp mode), 50 pA (I-Clamp, β = 1) or 500 pA (I-Clamp, β = 0.1) command at line frequency.

External commands: Two separate BNC inputs, one front-switched, one rear-switched

Sensitivity:

	V-Clamp	I-Clamp		Track	I = 0
		β = 1	β = 0.1		
Front input	20 mV/V	2 nA/V	20 nA/V	disabled	disabled
Rear input	100 mV/V	2 nA/V	20 nA/V	disabled	disabled

Input impedance: 10 kΩ. Inputs may be connected in parallel to increase sensitivity.

Holding command: Ten-turn potentiometer with dial. Polarity switch. Value can be previewed on meter.

V-Clamp mode:

	V-Clamp	I-Clamp		Track	I = 0
		β = 1	β = 0.1		
Toggle x1	±200 mV	±2 nA	±20 nA	disabled	disabled
Toggle x5	±1 V	±10 nA	±100 nA	disabled	disabled

Pipette offset:

Manual: ±250 mV. Ten-turn control with uncalibrated dial.

Track, I=0: ±200 mV. Nulling potential automatically adjusts to maintain zero pipette current.

Zap

Amplitude: +1.3 V_{DC} at pipette for chosen duration.

Duration: 0.5–50 ms or Manual. Triggered by front-panel pushbutton. In Manual position Zap amplitude is maintained as long as pushbutton is depressed.

RMS Noise

A 3.5 digit meter displays RMS current noise in pA. Measurement bandwidth is 30 Hz to 5 kHz. Upper -3 dB frequency is set by 4-pole Butterworth filter.

Inputs

Forced resets: Positive edge triggered. Initiates a reset of the integrator; has no control over the duration of reset.

Blank activate: Causes Scaled Output and I Output to hold their initial value for the duration of the blanking pulse. Does not affect 10 V_m output.

Speed test: Injects current into headstage input through a 1 pF capacitor. Injected current waveform is the derivative of the voltage waveform applied at Speed Test input. For example, a 100 Hz 10 V_{P-P} triangle wave will inject a 1 nA_{P-P} square wave into the headstage input.

Signal Outputs

Scaled output: Scaled and filtered by output control settings. Sample and hold pedestal compensation. Output is I (αβ mV/pA) when in V-Clamp or Track modes. Output is V_m (α mV/mV) when in I-Clamp mode. BNCs on front and rear panels are identical.

I: Pipette current. Rear-panel switched gain of either β mV/pA or 100 β mV/pA; fixed filter: 10 kHz 3-pole Bessel. Output does not benefit from sample and hold pedestal compensation.

10 V_m: Membrane potential at x10 gain. Junction potentials removed.

Output Controls

Output gain: 10 values from 0.5-500. Affects Scaled Output only. Selected value sets analog voltage on Gain Telegraph Output for reading by computer.

Lowpass Bessel filter: 4-pole lowpass Bessel filter with five settings; 1, 2, 5, 10 and 100 kHz. Selected value sets an analog voltage on Frequency Telegraph Output.

Leak Subtraction: Causes a signal proportional to the command to be subtracted from current record. Range: 100 β MΩ to 200 GΩ x β.

Telegraph Outputs

Gain: Takes α and β gain factors into account.

I (mV/pA)	0.05‡	0.1‡	0.2‡	0.5	1	2	5	10	20	50	100†	200†	500†
V_m (mV/mV)				0.5	1	2	5	10	20	50	100	200	500
Telegraph Output (V)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5

‡ Applicable for β = 0.1 only. † Applicable for β = 1 only.

Frequency:

Filter Setting (kHz)	1	2	5	10	100
Telegraph Output (V)	2	4	6	8	10

Mode:

	Track	V-Clamp	I=0	I-Clamp Normal	I-Clamp Fast
Scaled Output	I	I	V_m	V_m	V_m
Telegraph (V)	4	6	3	2	1

Cell capacitance (Telegraph output):

0 to +10 V, proportional to setting 0-100 pF (for β = 1; 0-1000 pF for β = 0.1) when WHOLE CELL CAP. switch is in the ON position. 0 to -10 V, when WHOLE CELL CAP. switch is in the OFF position

Data Not Valid: Output goes High during a reset in Patch mode or for the duration of a Blank Activate pulse in either Patch or Whole Cell mode.

Panel Meter

3.5 digit meter displays Track potential (V_{TRACK}) in mV, membrane potential (V_m) in mV, current noise (I_{RMS}) in pA RMS, membrane current (I) in pA or nA, Holding Command (V_{HOLD}/I_{HOLD}) in mV or nA or input circuitry temperature in degrees Celsius (TEMP). Meter has autoranging feature for all settings except TEMP.

Grounding

Signal ground is isolated from chassis and power ground. Signal ground is available on rear panel.

Control Inputs

Above 3 V accepted as logic High. Below 2 V accepted as logic Low. Inputs protected to ±15 V.

Model Cells

Unit is supplied with two model cell assemblies, the PATCH-1U and the MCB-1U model cells.

PATCH-1U model cell emulates three experimental conditions:

BATH: 10 MΩ electrode resistor to ground. 4 pF pipette capacitance.

CELL: 10 MΩ electrode resistor connected to a 500 MΩ//33 pF cell. 4 pF pipette capacitance.

PATCH: 10 GΩ resistor to ground. 5 pF pipette capacitance.

MCB-1U model cell emulates a bilayer membrane. 10 kΩ resistor in series with a 100 pF capacitor.

Pipette Holders

HL-U holders mate to threaded Teflon input connector of the CV headstage. Post for suction tubing is 1 mm OD. HL-U holder accepts glass 1.0–1.7 mm OD. Supplied with silver wire. Optional HLR-U right-angle adapter and HLB-U BNC adapter are available.

General Specifications

Dimensions (in.):	3.5 (H) x 19 (W) x 12.5 (D)
Dimensions (cm):	8.9 (H) x 48.3 (W) x 31.7 (D)
Weight (lbs.):	11.5 (5.1 kg)
Headstage (in.):	0.75 (H) x 0.70 (W) x 4.2 (D)
Headstage (cm):	1.8 (H) x 1.9 (W) x 10.5 (D)
Mounting plate (in.):	0.25 (H) x 2.0 (W) x 2.5 (D)
Mounting plate (cm):	0.6 (H) x 5.0 (W) x 6.2 (D)
Communications:	Analog and digital BNC
Rack use:	Standard 19" rack-mount (2U) with handles
Benchtop use:	Bayonet feet
Power:	85–264 VAC (110–340 VDC) 50–60 Hz, 30 watts (max.)
Fuse:	0.5 A slow (5 x 20 mm)
Line filter:	RFI filter included
Line cord:	Shielded line cord provided
Safety:	CE marking (Conformité Européene)

Contact Us
Phone: +1-800-635-5577
Web: www.moleculardevices.com
Email: info@moldev.com

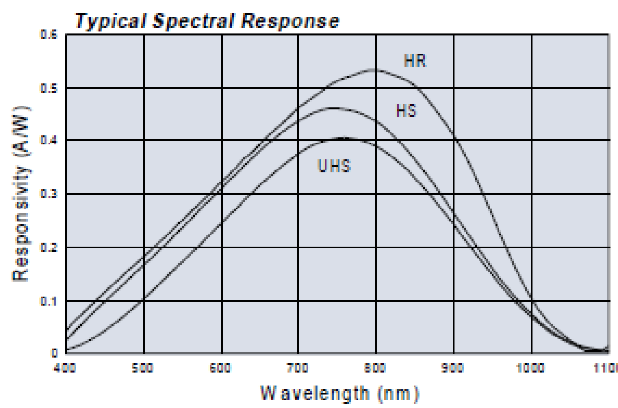
4. UDT Sensor. Inc PIN-HR(S)008(L)

FIBER OPTIC SERIES, SILICON — **TYPICAL ELECTRO-OPTICAL SPECIFICATIONS AT T_A=23°C**

Model No.	Active Area		Peak Wavelength (nm)	Responsivity (A/W)		Capacitance (pF)	Dark Current (nA)		NEP (W/√Hz)	Reverse Voltage (V)	Rise Time § (ns)		Temp Range (°C)		Package Style ¶
	Area (mm²)	Dimension (mm)		830 nm					830 nm		830 nm 50 Ω		Operating	Storage	
				min	typ	typ	typ	max	typ	max	typ	max			
HIGH SPEED SERIES (V_{BIAS}=-3 V)															
PIN-HS005 PIN-HS005L*	.01	0.127 ϕ				1.0	0.01	0.30	4.5 e-15		0.30	0.40			
PIN-HS008 PIN-HS008L*	.04	0.203 sq				1.0	0.01	0.30	4.5 e-15	15	0.30	0.40			
PIN-HS020 PIN-HS020L*	.20	0.508 ϕ	750	.35*	.40*	2.5	0.02	0.50	6.3 e-15		0.40	0.50			
PIN-HS026 PIN-HS026L*	.34	0.660 ϕ				4.0	0.035	0.80	8.4 e-15		0.45	0.65			
PIN-HS040 PIN-HS040L*	.77	0.991 ϕ				5.5	0.05	1.50	1.0 e-14		0.65	0.90			
HIGH RESPONSIVITY SERIES (V_{BIAS}=-5 V)															
PIN-HR005 PIN-HR005L*	.01	0.127 ϕ				0.8	0.03	0.80	1.6 e-14		0.60	1.0	-40 ~ +100	-55 ~ +125	9 / TO-18
PIN-HR008 PIN-HR008L*	.04	0.203 sq				0.8	0.03	0.80	1.6 e-14	15	0.60	1.0			
PIN-HR020 PIN-HR020L*	.20	0.508 ϕ	800	.45*	.50*	2.0	0.06	1.00	8.8 e-15		0.80	1.2			
PIN-HR026 PIN-HR026L*	.34	0.660 ϕ				3.5	0.085	1.50	1.0 e-14		0.90	1.4			
PIN-HR040 PIN-HR040L*	.77	0.991 ϕ				4.5	0.30	2.00	1.9 e-14		1.0	1.6			
ULTRA HIGH SPEED (V_{BIAS}=-3 V)															
PIN-UHS016 PIN-UHS016L*	.13	0.406 ϕ	750	.30*	.35*	2.0	0.020	0.50	7.2 e-15	15	0.25	0.30			

* Responsivity measured with a flat glass window.
§ Refer to the specific family of devices for applied reverse bias.
¶ For mechanical drawings please refer to pages 59 thru 71.

Chip centering within ± 0.005 inches w.r.t. the OD of header.



PRECAUTION: These devices are sensitive to electrostatic discharge (ESD). Use proper handling and testing procedures.

5. Burr Brown Corp, OPA111BM

SPECIFICATIONS

ELECTRICAL

At V_{CC} = ±15VDC and T_A = +25°C unless otherwise noted.

PARAMETER	CONDITION	OPA111AM			OPA111BM			OPA111SM			UNITS
		MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
INPUT											
NOISE											
Voltage, f_O = 10Hz	100% Tested		40	80		30	60		40	80	nV/√Hz
f_O = 100Hz	100% Tested		15	40		11	30		15	40	nV/√Hz
f_O = 1kHz	100% Tested		8	15		7	12		8	15	nV/√Hz
f_O = 10kHz	100% Tested		6	8		6	8		6	8	nV/√Hz
f_B = 10Hz to 10kHz	100% Tested		0.7	1.2		0.6	1		0.7	1.2	μVrms
f_B = 0.1Hz to 10Hz	(1)		1.6	3.3		1.2	2.5		1.6	3.3	μVp-p
Current, f_B = 0.1Hz to 10Hz	(1)		9.5	15		7.5	12		9.5	15	fAp-p
f_O = 0.1Hz thru 20kHz	(1)		0.5	0.8		0.4	0.6		0.5	0.8	fA/√Hz
OFFSET VOLTAGE(2)											
Input Offset Voltage	V_{CM} = 0VDC		±100	±500		±50	±250		±100	±500	μV
Average Drift	T_A = T_{MIN} to T_{MAX}		±2	±5		±0.5	±1		±2	±5	μV/°C
Supply Rejection	V_{CC} = ±10V to ±18V	90	110		100	110		90	110		dB
			±3	±31		±3	±10		±3	±31	μV/V
BIAS CURRENT(2)											
Input Bias Current	V_{CM} = 0VDC		±0.8	±2		±0.5	±1		±0.8	±2	pA
OFFSET CURRENT(2)											
Input Offset Current	V_{CM} = 0VDC		±0.5	±1.5		±0.25	±0.75		±0.5	±1.5	pA
IMPEDANCE											
Differential			10^{13} || 1			10^{13} || 1			10^{13} || 1		Ω || pF
Common-Mode			10^{14} || 3			10^{14} || 3			10^{14} || 3		Ω || pF
VOLTAGE RANGE											
Common-Mode Input Range		±10	±11		±10	±11		±10	±11		V
Common-Mode Rejection	V_{IN} = ±10VDC	90	110		100	110		90	110		dB
OPEN-LOOP GAIN, DC											
Open-Loop Voltage Gain	R_L ≥ 2kΩ	114	125		120	125		114	125		dB
FREQUENCY RESPONSE											
Unity Gain, Small Signal			2			2			2		MHz
Full Power Response	20Vp-p, R_L = 2kΩ	16	32		16	32		16	32		kHz
Slew Rate	V_O = ±10V, R_L = 2kΩ	1	2		1	2		1	2		V/μs
Settling Time, 0.1%	Gain = –1, R_L = 2kΩ		6			6			6		μs
0.01%	10V Step		10			10			10		μs
Overload Recovery, 50% Overdrive(3)	Gain = –1		5			5			5		μs
RATED OUTPUT											
Voltage Output	R_L = 2kΩ	±11	±12		±11	±12		±11	±12		V
Current Output	V_O = ±10VDC	±5.5	±10		±5.5	±10		±5.5	±10		mA
Output Resistance	DC, Open Loop		100			100			100		Ω
Load Capacitance Stability	Gain = +1		1000			1000			1000		pF
Short Circuit Current		10	40		10	40		10	40		mA
POWER SUPPLY											
Rated Voltage			±15			±15			±15		VDC
Voltage Range, Derated Performance		±5		±18	±5		±18	±5		±18	VDC
Current, Quiescent	I_O = 0mADC		2.5	3.5		2.5	3.5		2.5	3.5	mA
TEMPERATURE RANGE											
Specification	Ambient Temp.	–25		+85	–25		+85	–55		+125	°C
Operating	Ambient Temp.	–55		+125	–55		+125	–55		+125	°C
Storage	Ambient Temp.	–65		+150	–65		+150	–65		+150	°C
θ Junction-Ambient			200			200			200		°C/W

NOTES: (1) Sample tested—this parameter is guaranteed. (2) Offset voltage, offset current, and bias current are measured with the units fully warmed up. (3) Overload recovery is defined as the time required for the output to return from saturation to linear operation following the removal of a 50% input overdrive.

6. Burr Brown Corp, OPA2111KP

SPECIFICATIONS

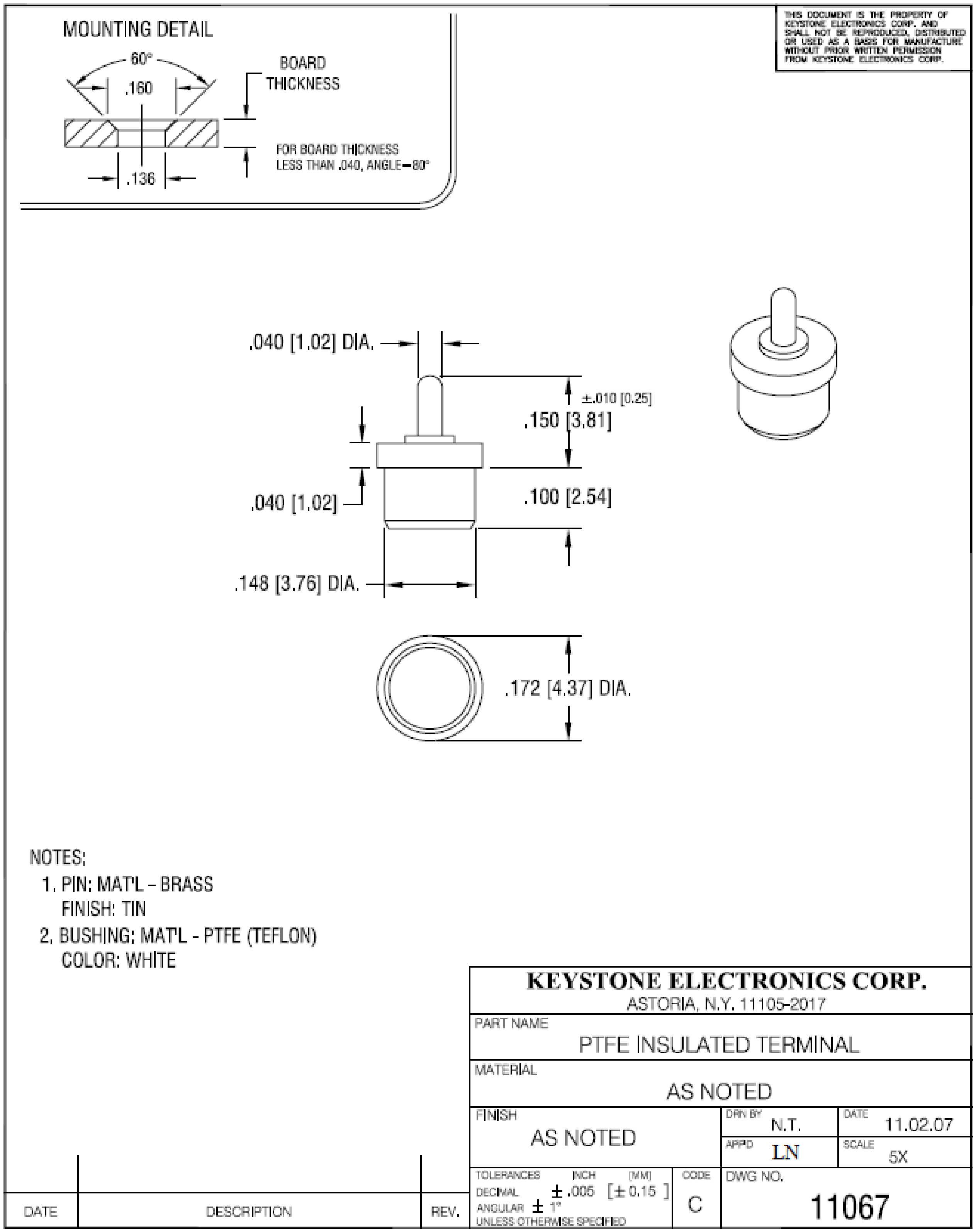
ELECTRICAL

At V_{CC} = ±15VDC and T_A = +25°C unless otherwise noted

PARAMETER	CONDITION	OPA2111AM			OPA2111BM			OPA2111SM			OPA2111KM, KP			UNITS
		MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
INPUT NOISE														
Voltage, f_O = 10Hz	100% Tested		40	80		30	60		40	80		40		nV/√Hz
f_O = 100Hz	100% Tested		15	40		11	30		15	40		15		nV/√Hz
f_O = 1kHz	100% Tested		8	15		7	12		8	15		8		nV/√Hz
f_O = 10kHz	(1)		6	8		6	8		6	8		6		nV/√Hz
f_B = 10Hz to 10kHz	(1)		0.7	1.2		0.6	1		0.7	1.2		0.7		μVrms
f_B = 0.1Hz to 10Hz	(1)		1.6	3.3		1.2	2.5		1.6	3.3		1.6		μVp-p
Current, f_B = 0.1Hz to 10Hz	(1)		15	24		12	19		15	24		15		fAp-p
f_O = 0.1Hz to 20kHz	(1)		0.8	1.3		0.6	1		0.8	1		0.8		fA/√Hz
OFFSET VOLTAGE(2)														
Input Offset Voltage	V_{CM} = 0VDC		±0.1	±0.75		±0.05	±0.5		±0.1	±0.75		±0.3	±2	mV
Average Drift	T_A = T_{MIN} to T_{MAX}		±2	±6		±0.5	±2.8		±2	±6		±8	±15	μV/°C
Match			±1			±0.5			2			2		μV/°C
Supply Rejection		90	110		96	110		90	110		86	110		dB
			±3	±31		±3	±16		±3	±31		±3	±50	μV/V
Channel Separation	100Hz, R_L = 2kΩ		136			136			136			136		dB
BIAS CURRENT(2)														
Input Bias Current	V_{CM} = 0VDC		±2	±8		±1.2	±4		±2	±8		±3	±15	pA
Match			±1			±0.5			±1			2		pA
OFFSET CURRENT(2)														
Input Offset Current	V_{CM} = 0VDC		±1.2	±6		±0.6	±3		±1.2	±6		±3	±12	pA
IMPEDANCE														
Differential			10^{13} ‖ 1			10^{13} ‖ 1			10^{13} ‖ 1			10^{13} ‖ 1		Ω ‖ pF
Common-Mode			10^{14} ‖ 3			10^{14} ‖ 3			10^{14} ‖ 3			10^{14} ‖ 3		Ω ‖ pF
VOLTAGE RANGE														
Common-Mode Input Range		±10	±11		±10	±11		±10	±11		±10	±11		V
Common-Mode Rejection	V_{IN} = ±10VDC	90	110		96	110		90	110		82	110		dB
OPEN-LOOP GAIN, DC														
Open-Loop Voltage Gain	R_L ≥ 2kΩ	110	125		114	125		110	125		106	125		dB
Match			3			2			3			3		dB
FREQUENCY RESPONSE														
Unity Gain, Small Signal			2			2			2			2		MHz
Full Power Response	20Vp-p, R_L = 2kΩ	16	32		16	32		16	32			32		kHz
Slew Rate	V_O = ±10V, R_L = 2kΩ	1	2		1	2		1	2			2		V/μs
Settling Time, 0.1%	Gain = –1, R_L = 2kΩ		6			6			6			6		μs
0.01%	10V Step		10			10			10			10		μs
Overload Recovery, 50% Overdrive(3)	Gain = –1		5			5			5			5		μs
RATED OUTPUT														
Voltage Output	R_L = 2kΩ	±10	±11		±10	±11		±10	±11		±10	±11		V
Current Output	V_O = ±10VDC	±5	±10		±5	±10		±5	±10		±5	±10		mA
Output Resistance	DC, Open-Loop		100			100			100			100		Ω
Load Capacitance Stability	Gain = +1		1000			1000			1000			1000		pF
Short Circuit Current		10	40		10	40		10	40		10	40		mA
POWER SUPPLY														
Rated Voltage			±15			±15			±15			±15		VDC
Voltage Range, Derated Performance		±5		±18	±5		±18	±5		±18	±5		±18	VDC
Current, Quiescent	I_O = 0mADC		5	7		5	7		5	7		5	9	mA
TEMPERATURE RANGE														
Specification	Ambient Temp.	–25		+85	–25		+85	–55		+125	0		+70	°C
Operating "M" Package	Ambient Temp.	–55		+125	–55		+125	–55		+125	–55		+125	°C
"P" Package											–40		+85	°C
Storage "M" Package	Ambient Temp.	–65		+150	–65		+150	–65		+150	–65		+150	°C
"P" Package											–40		+85	°C
θ Junction-Ambient			200			200			200			200(4)		°C/W

NOTES: (1) Sample tested—this parameter is guaranteed. (2) Offset voltage, offset current, and bias current are measured with the units fully warmed up. (3) Overload recovery is defined as the time required for the output to return from saturation to linear operation following the removal of a 50% input overdrive. (4) Typical θ_{JA} = 150°C/W for plastic DIP.

7. Keystone Electronics. Corp, Tefalon Standoff – PTFE Insulated Terminal Pins

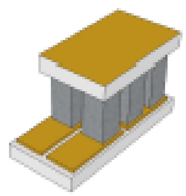


8. Custom Thermoelectric Peltier Cooler (00301-9X30-10RU2)

TEC Specification Sheet

CUSTOM THERMOELECTRIC
Your Thermoelectric Partner

Part #	I_{max} (Amps)	Q_{max} (Watts)	V_{max} (Volts)	DT_{max} (°C)	T_{max} (°C)
00301-9X30-10RU2	1.0	0.20	0.35	70°C	200°C



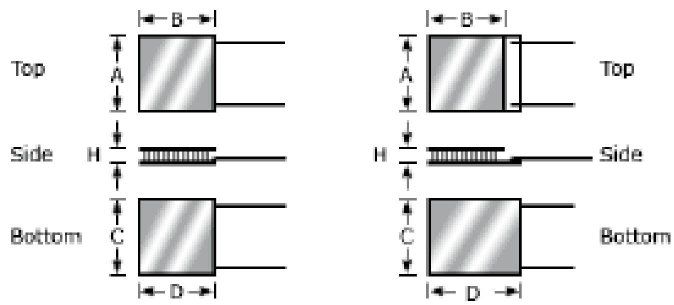
Metallized surfaces

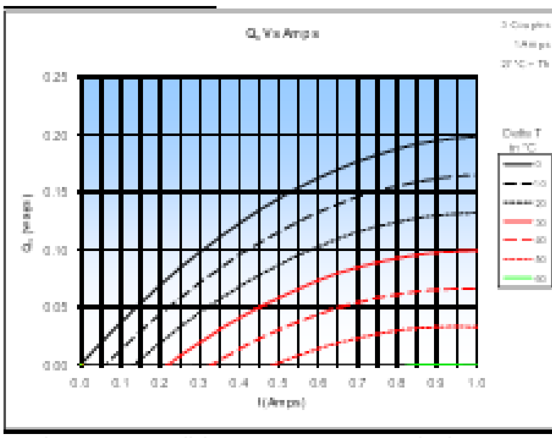
Options:

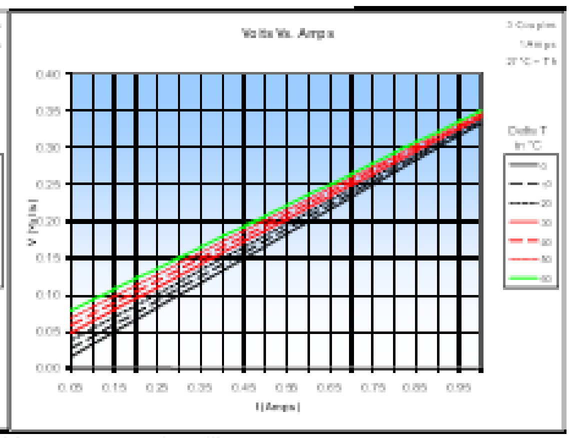
*** This device is normally supplied without lead wires. ***

AWG 30 Stranded Teflon insulated lead wires are available as an option

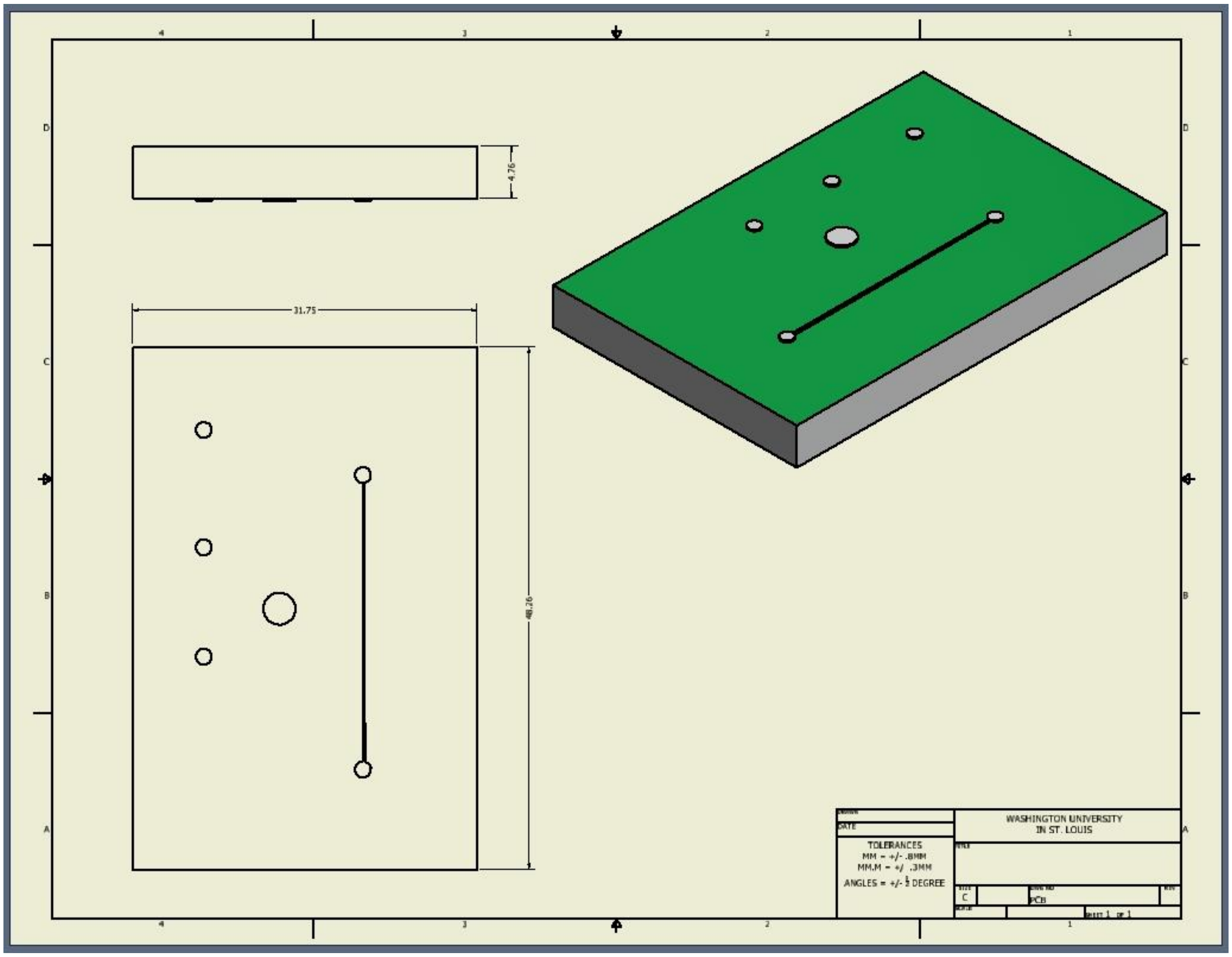
Top Plate				Bottom Plate				Metallized Height		Lapped Height	
A		B		C		D		H		H	
mm	in	mm	in	mm	in	mm	in	mm	in	mm	in
1.2	0.047	1.9	0.075	1.2	0.047	2.6	0.102	1.4	0.055	-	-







9. PCB board


4.76
31.75
48.26
DATE
TOLERANCES
MM = +/- .8MM
MM.M = +/ .3MM
ANGLES = +/- ½ DEGREE
WASHINGTON UNIVERSITY
IN ST. LOUIS
C
PCB
SHEET 1 OF 1

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