

Cyclops LED/Laser Diode Driver User Manual

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Cyclops is a high-power LED/laser diode driver that enables precise control of light power. The circuit was developed by Jon Newman while in Steve Potter's lab at Georgia Tech in order to complete his thesis work, which required the delivery of ultra-precise, continuously time-varying light waveforms for optogenetic stimulation [1,2]. This was, and still is, not possible with commercial hardware for optogenetic stimulation. Since its first use, the circuit has been improved in terms of speed, precision, programmability, and ease of use. This document provides construction, usage, and performance documentation for the Cyclops LED driver. This document evolves with the repository. To view old revisions, checkout tags or old commits using their SHA.

Note From the Maintainer

I am very happy that this device may enable your scientific endeavors and I'm sincerely grateful for your interest in the project. In general, I hope this project will eventually be one small module in a growing set of **high-quality**, **open-source**, and **affordable** tools that facilitate your research and enable an **open**, **community-oriented** approach to science.

Profits from the sale of Cyclops devices from the [official store](#) go to funding the Open Ephys non-profit organization. Since I receive no monetary compensation from the sale of these devices, it would mean a great deal to me if you would consider referencing the following paper (for which the Cyclops was developed) in published work that makes use of the device.

J.P. Newman, et. al. Optogenetic feedback control of neural activity. *eLife* (4:e07192) 2015. doi: 10.7554/eLife.07192 [\[link\]](#)

For instance, in your methods section:

Optical stimuli were delivered using the open-source Cyclops LED driver (Newman et al., 2015; www.github.com/jonnew/Cyclops).

Pull requests and issue submissions are **welcome** on the github repo and open ephys forum. If you have criticisms, fixes, suggestions for improvement in the docs etc, please let us know so we can implement them ASAP.

Happy stimulating.

Jon Newman MWL@MIT

License

Hardware Licensing

Copyright Jonathan P. Newman.

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Note: This license applies to hardware designs and documentation which reside in the ‘device’, ‘experimental’, ‘resources’ folders of this repository along with information in ‘MANUAL.md’ and ‘MANUAL.pdf’

Software Licensing

Copyright (c) Jonathan P. Newman. All right reserved.

The code associated with the Cyclops project is free software: you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation, either version 3 of the License, or (at your option) any later version.

The code associated with the Cyclops project is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details.

You should have received a copy of the GNU General Public License along with this code. If not, see <http://www.gnu.org/licenses/>.

Note: This license applies to software/fwreware source code which resides in in the ‘lib’ folder of this repository

Features

Circuit Features

- Ultra-precise
- High power
- Up to 1.5A per LED
- Wide bandwidth
 - ~2.5 MHz -3 dB bandwidth
 - Maximum 100 ns 1.0A rise and fall times
- Current and optical feedback modes
- Built-in waveform generation
- Over-current protection
- Modular
 - Arduino compatible: internal waveform generation
 - Also, accepts external analog, gate, or trigger inputs

Multiple stimulus generation options

- External stimulus sequencer
- External digital trigger
 - TTL logic level
- External analog waveform generator
 - 0-5V analog signals
- Internal 12-bit DAC
 - Synchronized across up to 4 drivers
 - Arduino library
 - Programmable triggering logic
 - Respond to USB input

Performance Specifications

Dynamic Characteristics

The following oscilloscope traces give indications of the circuit's precision and speed. These traces are taken from Rev. 3.5c. Rev 3.6 provides considerable improvements but I have not had time to update. Note that time series traces are **not** averaged - these traces display per-pulse temporal characteristics. Optical characteristics and optical feedback signal for the Cyclops driver were provided by a Thorlabs PDA36 amplified photodiode set to 0 dB of transimpedance gain. Measurements were performed using a single blue Osram golden dragon LED. The current-feedback mode -3dB bandwidth was determined by applying a flat noise signal over 50 MHz with mean = 1.0V and V_{pp} = 500 mV into the SIGNAL IN port with maximal current gain. It occurs at around 2.3 MHz.

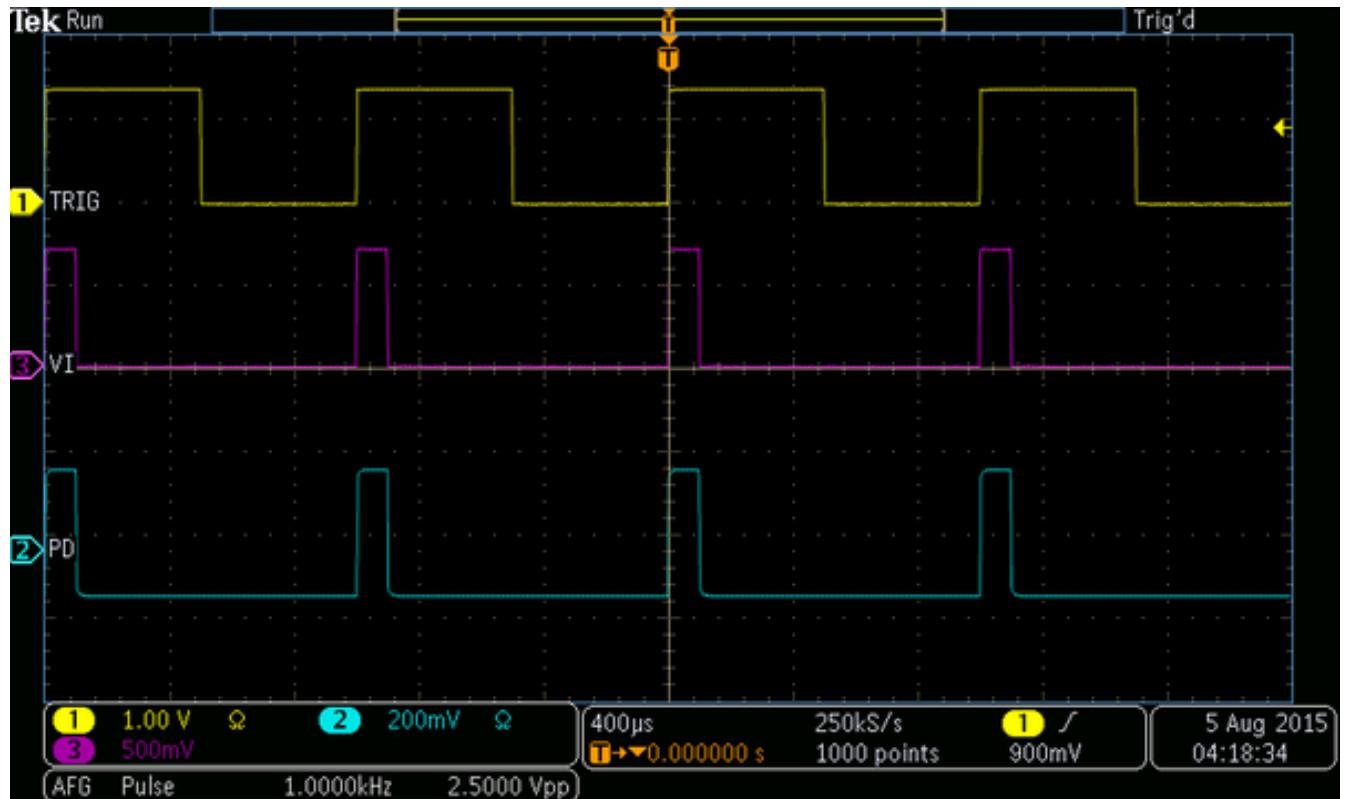


Figure 1: Trigger (yellow), current (pink), and light power (blue) traces during pulsed operation in current feedback mode. Input waveform is a 1 kHz 0 to 750 mV, 10% duty cycle square wave.

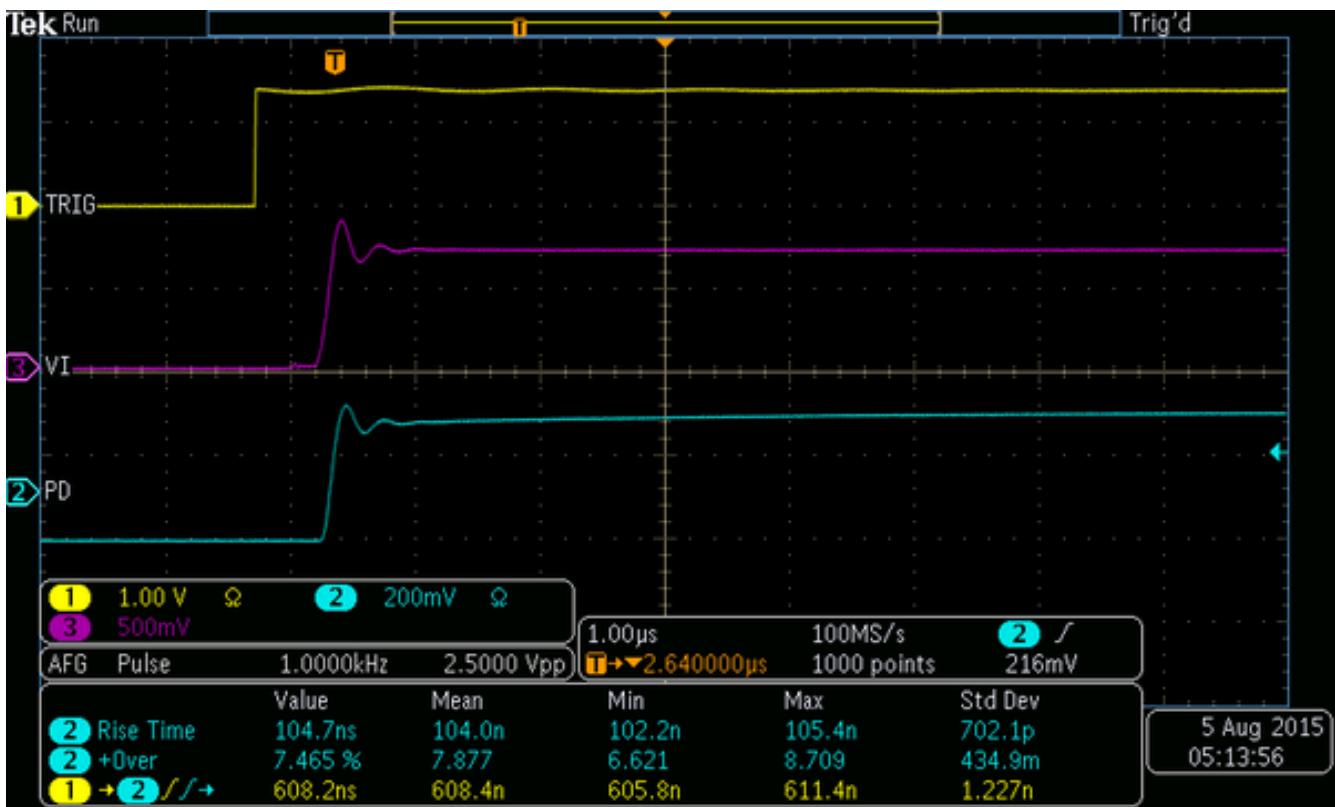


Figure 2: Zoomed traces showing waveform 10-90% rise times. Optical rise time statistics are shown at the bottom of the image.



Figure 3: Zoomed traces showing waveform 10-90% fall times. Optical fall time statistics are shown at the bottom of the image.

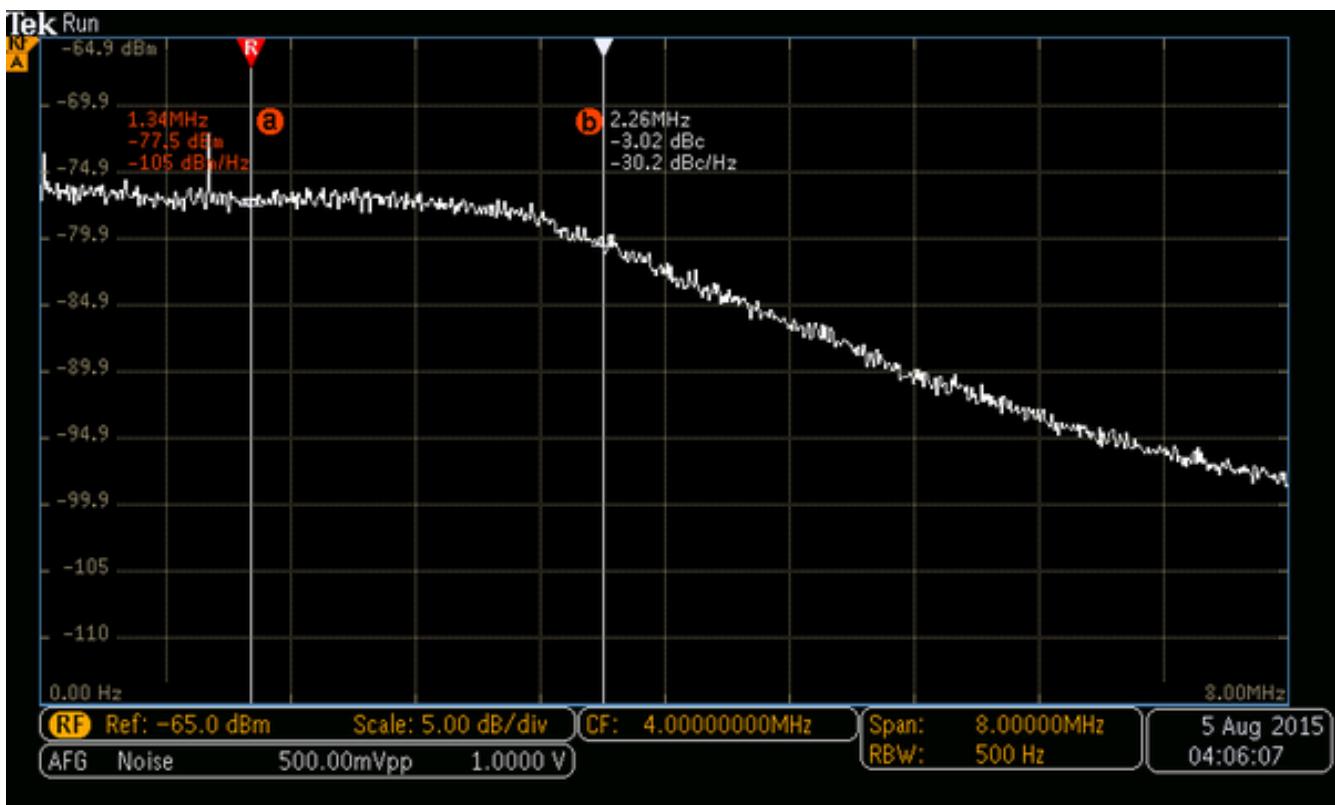


Figure 4: Optical bandwidth in current feedback mode. -3dBm occurs at ~2.3 MHz. Input signal was noise, flat over 50 MHz, mean = 1.0V, V_{pp} = 500 mV.

The following traces are the same as the previous ones except that the amplified photodiode was used to provide optical feedback. The slowdown compared to current feedback is due to a speed of the photodiode. A faster amplified photodiode would provide crisper rise and fall times

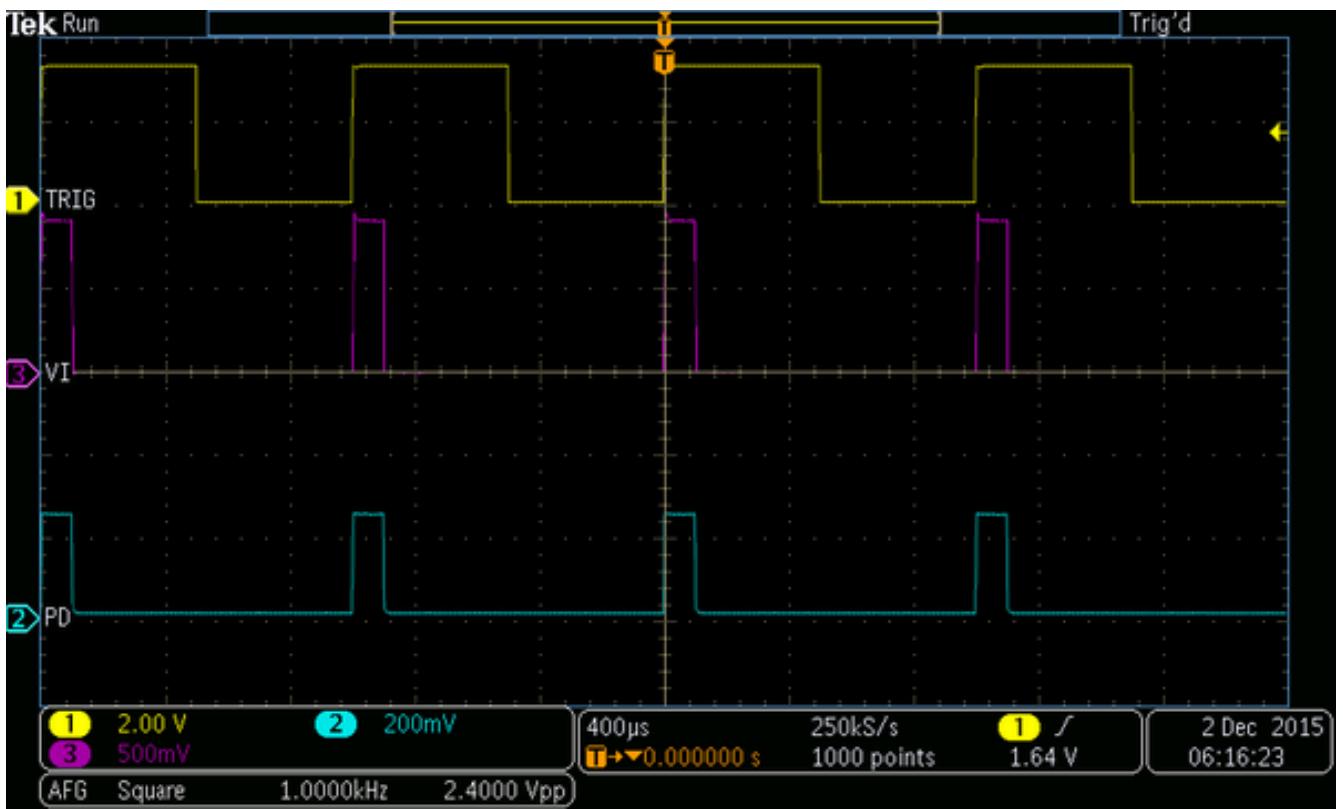


Figure 5: Trigger (yellow), current (pink), and light power (blue) traces during pulsed operation in optical feedback mode. Input waveform is a 1 kHz 0 to 750 mV, 10% duty cycle square wave.



Figure 6: Zoomed traces showing waveform 10-90% rise times in optical feedback mode. Optical rise time statistics are shown at the bottom of the image.

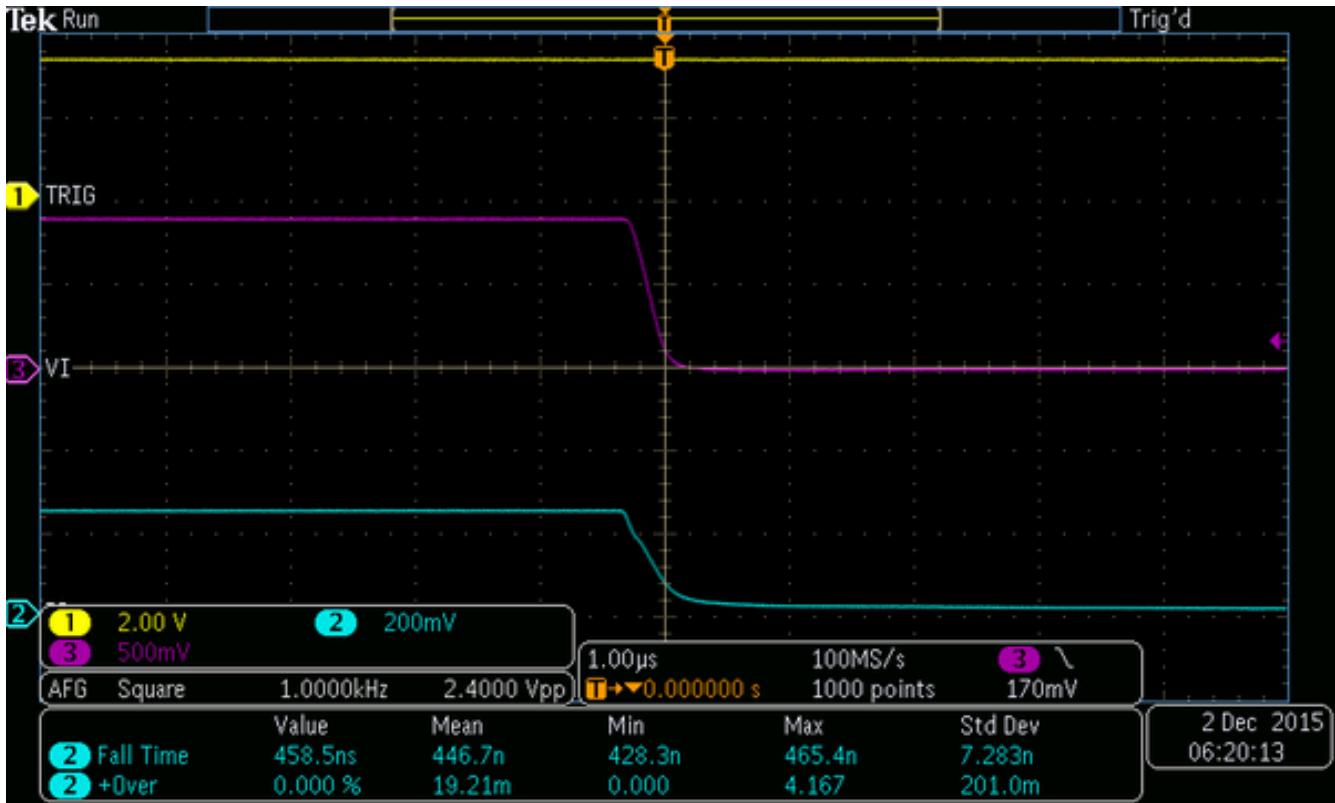


Figure 7: Zoomed traces showing waveform 10-90% fall times in optical feedback mode. Optical fall time statistics are shown at the bottom of the image.

Head to Head Comparison

The following table provides a comparison between Cyclops Rev. 3.6 and commercial LED drivers.

	Plexon LD-1 ¹	Plexon PlexBright ^{2,3}	Thorlabs DC4100 ⁴	Cyclops Rev. 3.6
Speed				
· 10-90% rise time ⁵ (us)	49	76	?	<0.1
· 90-10% fall time ⁵ (us)	39	89	?	<0.1
· Worst case dead time ⁵ (us)	140	160	?	1.0
· Small sig. -3dB bandwidth ⁶ (kHz)	10.5	?	100 ⁷	>2500
Accuracy				
· Overshoot ^{5,8} (%)	0	0	?	1
· THD ⁹ (%)	8.29	?	?	8.2
· THD, Optical F.B. ⁹ (%)	N/A	N/A	N/A	0.41
Power				
· Max current drive (mA)	1200	1100	1000	1500
Features				
· Independent LED channels	1	4	4	1 ¹⁰
· Regulated current output	Yes	Yes	Yes	Yes
· Regulated optical output	No	No	No	Yes
· Prog. overcurr. protection	No	No	Yes	Yes
· Arb. waveform generation	No	Yes	No	Yes
· Independent DAC for each LED	N/A	No	N/A	Yes
· Manual pulse	Yes	No	No	Yes
· Manual continuous on	No	No	No	Yes

	Plexon LD-1¹	Plexon PlexBright^{2,3}	Thorlabs DC4100⁴	Cyclops Rev. 3.6
· Hardware IO	None	None	None	Ref. voltage, sync, Load current, trigger, expansion ports
· LCD display	Yes	No	Yes	No
Programmability				
· Open-source	No	No	No	Yes
· Driver	N/A	“Radiant” software ¹¹ based GUI	NI-VISA ¹² based GUI	Arduino/Teensy
· PC Interface	N/A	GUI/USB cable	GUI or API/USB cable	Arduino IDE; USB 2.0; Serial interface
· Waveform gen. performance	N/A	10 kHz aggregate update across channels	N/A	100 kHz/channel update
· OS compatibility	N/A	Windows	Windows	Windows, Linux, Mac
Cost	\$700.00	\$5300.00	\$3059.0¹³	~\$450.00¹⁴

1. [Plexon LD-1](#)

2. [Plexon PlexBright](#)

3. Essential drive circuit consists of an [Opal-Kelly XEM6001 FPGA De board](#) tied to 4 commercially available buck converters from [Recon](#).

4. [Thorlabs DC4100](#)

5. Test signal: 500 Hz, full off to on 50% duty-cycle square wave resulting in 1A peak-to-peak through LED.

6. Test signal: 1 kHz 500 mA offset, 100 mA peak-to-peak sine wave.

7. Not measured on the bench top. Taken from manufacturer's specifications. Bandwidth threshold (e.g. -3 dB) was not specified. Applies to sine wave only.

8. Relies on short, low-inductance cabling. Longer cabling will degrade performance.

9. Test signal: 1 kHz 500 mA offset, 1A peak-to-peak sine wave.

10. However, PCB is modular. Up to 4 PCBs can be stacked using included 0.1" headers to share the same power supply and allow synchronous DAC operation of 4 light sources.

11. [Radiant Software](#)

12. [NI VISA](#)

13. Includes the cost of the [DC4100-HUB](#) which is required to drive four LEDs.

14. Cost of fully assembled device from [Open Ephys Store](#). Parts cost is ~\$170.00.

Usage

The cyclops is a device that is capable of transforming voltage signals (e.g. sine waves, square pulses, etc.) into optical signals from high-power LEDs or laser diodes. Voltage signals to drive the device can be generated internally using an on-board digital to analog converter or can be delivered from an external source, such as a function generator or stimulus sequencer. The cyclops provides numerous measurements of circuit operation that can be recorded during an experiment such as LED current and stimulus reference voltages. The device can also be controlled over a USB interface using its onboard, Arduino-compatible [Teensy 3.2](#) microcontroller board in combination with the Cyclops Arduino library: `./lib/cyclops`. The device can be used to drive commercially available LED modules from Thorlabs and Doric using its expansion ports.

Below we provide device control and input/output definitions, an explanation of the operational modes of the device, and the different ways it can be used to generate optical stimuli. Refer to the above diagram to locate the physical switches, dials, and connectors corresponding to verbal or iconic descriptions device settings.

Control and IO Definitions

Please refer to the [IO diagram](#) while reading these definitions.

REF OUT: This output operates in two modes depending on the position of the slide switch below the BNC connector:

- When the switch is set to SYNC, this output is set to 5V when the LED is on (>10 mA) and 0 volts when off.
- When the switch is set to V. REF, this output will copy the reference signal that the current source attempts to follow *after* it has been subjected to the GAIN setting. In constant current mode, this means that the voltage at this pin specifies 1 A/V. During successful operation in Current F.B. mode, this signal will match that of LED CURR. During successful operation in AUX F.B. mode, this signal will match that of AUX OUT.

LED CURR.: The voltage on this output measures to the current passed by the load at 1 V/A.

AUX. OUT: This output provides a buffered version of the signal at the AUX. IN connector.

SIGNAL IN: To use this input, the INPUT SELECT toggle switch must be set to SIG. IN. This input operates in two modes depending on the position of the vertical slide switch below the BNC connector:

- When the slide switch below the SIGNAL IN connector is set to the square, triangle, sine icon, SIGNAL IN is used to provide an external target voltage signal for the feedback circuit that drives the load. This voltage is always subjected to the attenuation imposed by the GAIN dial.
- When the local switch is set to 5V CONT, 5V is generated internally and constantly as a reference to drive the load and, again, is subject to the GAIN setting.

TEST: When this button is pressed, the SIGNAL IN line is temporarily disconnected from the BNC connector and tied to an internal 5V reference. This reference is then subject to the current GAIN setting as it would be if it was produced externally and passed to the SIGNAL IN BNC.

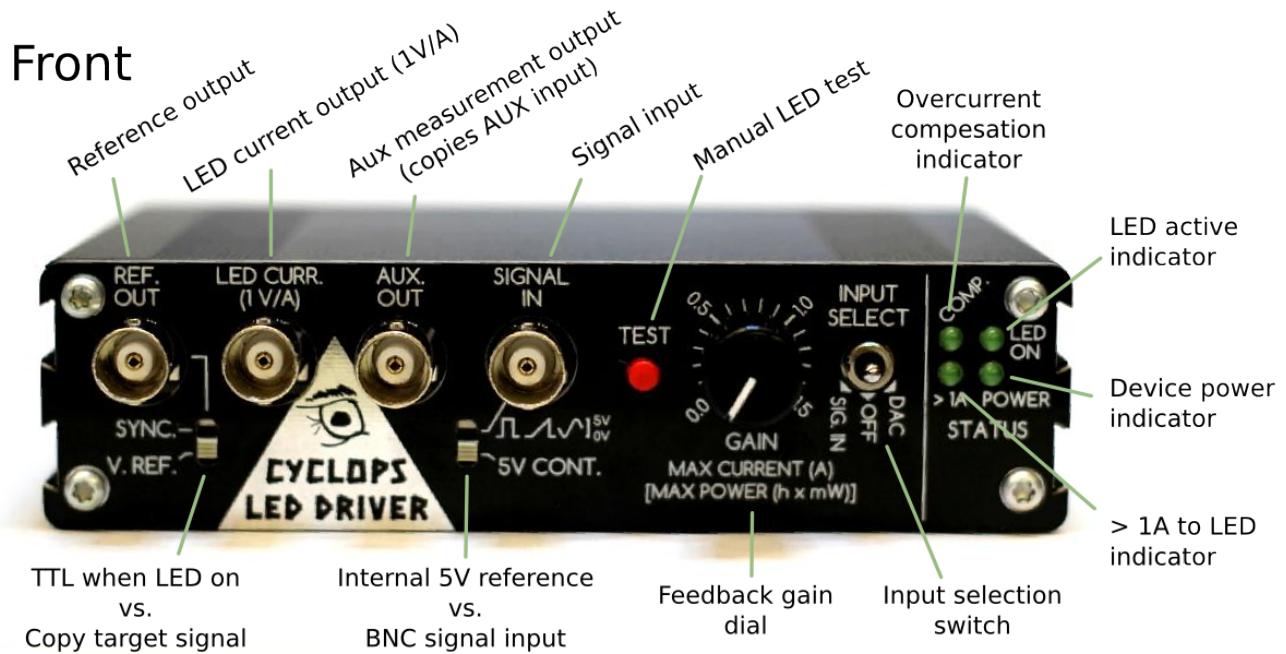
GAIN: Specifies the transimpedance gain between the reference voltage at SIGNAL IN or produced by the DAC and current to the load. During CURR F.B., the gain is given by:

$$\text{Load Current} = \text{Dial Position} * \frac{\text{SIGNAL IN Voltage}}{5V}$$

During AUX F.B. operation, the gain depends on how the optical to AUX signal conversion gain.

INPUT SELECT: Select the source of the reference voltage. SIG. IN selects the SIGNAL IN connector. OFF ties the reference voltage to 0 so that no current is driven through the load. DAC indicates that the onboard DAC should be used in concert with the integrated Teensy 3.2 to generate a reference voltage waveform. Refer to the [Programming the Onboard Microcontroller](#) section for details on how to do this.

Front



Rear

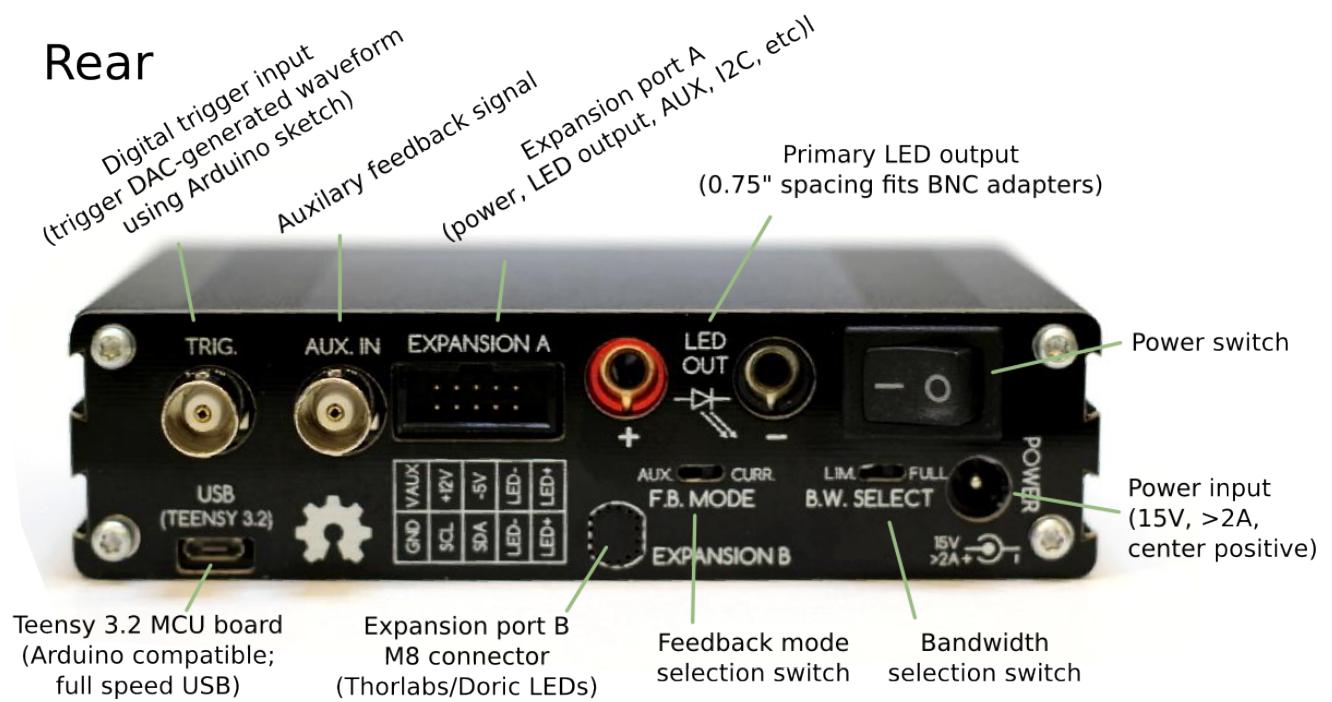


Figure 8: Cyclops panel definitions (Rev. 3.6).

COMP: This LED indicates that overcurrent compensation is being performed by the integrated microcontroller. In this case, the load is toggled off to maintain an *average* (~100's of milliseconds time constant) current below the maximum specified by the firmware running on the Arduino. This value defaults to 1A on devices purchased through the Open Ephys store.

LED ON: This LED indicates that the load is passing more than 10 mA.

>1A: This LED indicates that the load is passing more than 1A, a typical upper limit for high power LEDs.

POWER: This LED indicates that the device has power.

TRIG: This input provides GPIO access to the onboard microcontroller. It can be used as an input or output depending on how the microcontroller is programmed. It has a bi-directional logic level converter. Output will be 5V logic high. 5V or 3.3V logic input can be used.

AUX. IN: Auxiliary feedback signal for use in auxiliary (e.g. optical) feedback mode. This pin is pulled high when not in use which protects the load if the user accidentally switches the device to AUX. feedback mode during operation.

USB: Programming and serial access to the onboard Teensy 3.2.

EXPANSION A: 0.1" pitch, IDC expansion header. Exposes several signals, power rails and LED outputs. This can be used to create and integrated load /photodiode amplifier, for instance.

LED OUT: Main LED or laser diode output. Standard banana connectors are used.

F.B. MODE: Slide switch used to toggle the device between constant current (CURR) and auxiliary (AUX) feedback modes. See the [Feedback Modes](#) section for a detailed explanation.

B.W. SELECT: Bandwidth selection switch. When in the LIM position, the bandwidth of the device is limited and one can expect ~1 usec 1A rise and fall times. If long cables (> 0.5 m) are used between the device and the load, this option must be used to ensure device stability. When set to FULL, the device operates at full bandwidth with rise times in the 10s of nanoseconds. When operating a full bandwidth, the user takes steps to ensure circuit stability: short low inductance cabling to the load. See the [Bandwidth Selection](#) section for details.

POWER: Power connector. Center positive, 15V supply with >2A current sourcing capabilities. Batteries can be used but must be capable of handing large load transients to maintain device stability.

Feedback modes

Current Feedback Mode

To use current feedback mode, push the F.B. MODE slide switch to the CURR position (). Using the circuit in current feedback mode ensures that the forward current across the LED is precisely regulated according the voltage at the VREF pin. This configuration is a standard method for driving LEDs because the relationship between current and LED irradiance is smooth and monotonic. This means that more current across the LED will generate more light power (while staying within the LED's maximum ratings, of course). However, the relationship between current and irradiance is not linear. For most LEDs, it looks like a logarithmic function. Additionally, the efficiency of the LED is inversely related to its temperature. So, as the LED operates and heats up, the amount of light it produces drops even when the current is held constant. The severity of an LED's temperature dependence and current/irradiance nonlinearity depend on the type of LED (roughly, the color and who made it). These properties should be clearly documented in the LED's data sheet. With a quality LED and proper thermal management, the effects of temperature and static current/irradiance nonlinearity are fairly minimal and can be ignored in most situations.

Auxiliary Feedback Mode

To use auxiliary feedback mode, push the F.B. MODE slide switch to the AUX position (). When extremely stable, linear control of light power is required, the auxiliary feedback input can be used to used to compensate for the temperature dependence and static nonlinearity of the current/irradiance relationship of the LED. For example,

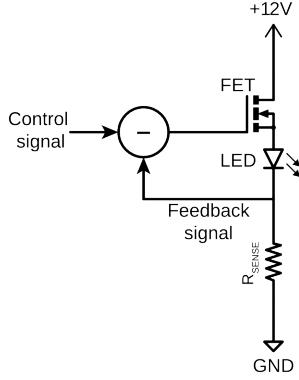


Figure 9: Current feedback configuration.

when the auxiliary voltage is supplied by an amplified photodiode that is somewhere indecent to radiation from the LED, or is sampled from the fiber transporting LED light, the gate voltage is adjusted such that the measured light power matches a DAC-supplied reference voltage. This is the case in the circuit diagram. This configuration is referred to as optical feedback mode. The [PDA36A](#) adjustable amplified photodiode from Thorlabs is a good option for supplying optical feedback. However, you can make your own amplified photodiode for a fraction of the price, and a design is included within the cyclops repository. Optical feedback completely linearizes the relationship between a supplied reference voltage and the light power produced by the LED by compensating for the current/irradiance nonlinearities and temperature dependence.

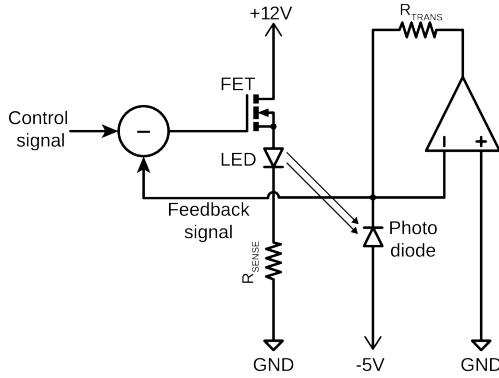


Figure 10: Optical feedback configuration.

Bandwidth Selection

The Cyclops can be operated in two bandwidth modes: **FULL** and **LIM**. This provides user-selectable control over the speed at which the LED can be turned on/off.

Full Bandwidth Mode

To operate the device in full bandwidth mode, move the B.W. SELECT switch to the FULL position (**LIM** **FULL**). When the device is operated at full bandwidth, the user can take advantage very short turn on/off times (1.0 A in about 100 ns rise/fall times). Additionally, continuously varying optical signals are accurately represented up to about 2 MHz. That said, Cyclops is a fairly high-power circuit. The currents and voltage used to drive high power LEDs are many orders of magnitude (like 6 or more...) greater than those recorded during electrophysiology experiments. Also, the Cyclops is a fast circuit. Fast circuits hate long cables because they introduce appreciable delays and parasitics that can adversely affect operating characteristics. Very long cables will introduce ringing into light waveforms with fast edges! Ideally, the LED should be right next to the device. I typically mount my fiber

coupled LEDs directly into the banana sockets on the back of the device using copper-clad printed circuit board so that my ‘cables’ are about 2 cm in length. In any case, the following is always good advice: **keep the cabling to the LED as short as possible and ‘fat’ enough to handle high currents (AWG 18 or thicker).**

Limited Bandwidth Mode

To operate the device in full bandwidth mode, move the B.W. SELECT switch to the LIM. position (**LIM.** **FULL**). In this mode, the feedback circuit within the cyclops will operate at lower speeds. This is useful in situations where the user wishes to place the Cyclops device far away from the LED being driven (e.g. when it is mounted on the head of an animal rather than light being transmitted via optic fiber). In this case, the bandwidth of the device can be lowered to avoid ringing and instability when a long, potentially thin cable is used. I have driven LEDs at 1.5A over AWG 30 cable that is several meters long without issue in bandwidth limit mode. This would cause the device to oscillate wildly in full bandwidth operation. When the device is operated in bandwidth limit mode, the rise and fall times of LED pulse will increase to about 1.5 microseconds, and the -3 dB bandwidth will degrade to ~200 kHz or so. This is plenty fast for almost all neuroscience applications.

Stimulus Generation Options

There are three ways to generate light signals using the driver. The behavior of each of these options is dependent on the feedback mode being used. The behavior of each input option is described in relation to the feedback mode of the driver.

1. **TEST**: The test button is always available and will override all other input modes. Using the TEST button the behavior of the circuit is:
 - **AUX****CURR**: Source the current specified by the GAIN dial.
 - **AUX****CURR**: Generate the optical power specified by the $h * \text{mW}$ level that is specified by the GAIN dial. The intensity of the LED will be dependent on the auxiliary feedback signal used which defines the ‘ h ’ parameter.
2. **EXT****DAC**: External input mode is engaged when the INPUT SELECT switch is moved to the EXT position and user supplied voltage waveforms are present at the EXT BNC input. If the user attempts to supply more than 5V to the EXT input, the circuit will clamp the input signal to 5V. Using EXT mode, the behavior of the circuit is:
 - **AUX****CURR**: Source the current specified by:

$$\text{Load Current} = \text{GAIN Position} * \frac{\text{SIGNAL IN Voltage}}{5V}$$

- **AUX****CURR**: Generate the optical power specified by:

$$\text{Power} = \text{GAIN Position} * h * \frac{\text{SIGNAL IN Voltage}}{5V}$$

The intensity of the LED will be dependent on the auxiliary feedback gain which defines the h parameter.

3. **EXT****DAC**: The internal digital to analog converter (DAC) is engaged when the INPUT SELECT switch is moved to the DAC position and can be used to generate pre-programmed waveforms and waveform sequences triggered by a digital pulse to the TRIG input. This feature relies on optional Arduino installation and programming the device using the [API](#). Using the DAC mode, the behavior of the circuit is:
 - **AUX****CURR** Source the current specified by:

$$\text{Load Current} = \text{GAIN Position} * \frac{\text{DAC Voltage}}{5V}$$

- **AUX****CURR** Generate the optical power specified by:

$$\text{Power} = \text{GAIN Position} * h * \frac{\text{DAC Voltage}}{5V}$$

The intensity of the LED will be dependent on the auxiliary feedback signal used which defines the ‘ h ’ parameter.

Using the Onboard Microcontroller

Cyclops devices include an onboard, Arduino-compatible microcontroller board (Teensy 3.2) that can:

- Generate custom waveforms
- Respond to trigger input
- Provide background over-current protection

The Teensy can be programmed and uploaded to the device using the [Arduino IDE](#) in combination with the Cyclops Arduino library: `./lib/cyclops`. Note that you will need to add the [Teensyduino add-on](#) to the Arduino IDE to program the Teensy. The Cyclops library contains several examples to help you get started. The relevant public programming interface is shown below. Functions are fully documented in the comments.

```
// Each 'channel' defines a board address. A single microcontroller supports up
// to 4 stacked Cyclops boards.
typedef enum
{
    CH0 = 0,
    CH1,
    CH2,
    CH3,
} Channel;

// One Cyclops object should be created for each LED channel. For single LED
// devices (most cases) only CH0 is used.
class Cyclops {

public:
    // Construct a Cyclops object
    // chan:          Cyclops channel to control
    // current_limit_mA: Optional current limit for this Cyclops channel
    Cyclops(Channel chan, float current_limit_mA = 1500);

    // Program the DAC output register
    // voltage: 12-bit integer (0-4095) specify the voltage to program the
    //           DAC with. Voltage is scaled into a 0-5V range.
    //           returns: 0 on success, 1 otherwise.
    int dac_prog_voltage(const uint16_t voltage) const;

    // Load the DAC output register to affect a voltage change on the output
    // pin. This function affects all running cyclops devices that have had
    // their DAC's programmed using the dac_prog_voltage() function.
    static void dac_load(void);

    // Convenience method for programming and loading a DAC voltage. Equivalent
    // to calling dac_prog_voltage() followed by dac_load()
    // voltage: 12-bit integer (0-4095) specify the voltage to program the
    //           DAC with. Voltage is scaled into a 0-5V range.
    //           returns: 0 on success, 1 otherwise.
    int dac_load_voltage(const uint16_t voltage) const;

    // Use the DAC to generate a period waveform
    // sample_period_us: Sample period of voltage sequence in microseconds.
    // voltage: Pointer to array of 12-bit integers (0-4095) specify the
    //           voltage sequence to program the DAC with. Voltage is scaled
    //           into a 0-5V range.
    // length: Length of voltage sequence.
    void dac_generate_waveform(const uint32_t sample_period_us,
```

```

        const uint16_t *voltage,
        uint16_t length) const;

// Get an LED current measurement in millamps
// returns: LED current measurement in millamps.
inline float measure_current(void) const;

// Attach/detach user provided interrupt function to TRIG pin
// mode indicates the pin transition state at which the function is called,
// RISING, FALLING or CHANGED
// user_func: User define function specifying action to take when the
//             TRIG pin transitions according the the mode argument. e.g.
//             can be a function that generates a waveform using
//             dac_load_voltage() or similar.
// mode:      Indicates the TRIG transition state at which the user_func
//             is called. Can be either RISING, FALLING, CHANGED, HIGH,
//             or LOW. See AttachInterrupt() Arduino function for more
//             detail.
void set_trigger(void (*user_func)(void), const int mode);

// Call this static method after creating all cyclops channels to start the
// internal overcurrent protection engine and waveform generation machinery.
// This function is used to start all channels.
static void begin(void);

// *this's channel ID
const Channel channel;
};


```

A simple example Arduino sketch, which uses the Cyclops to produce a sinusodal chirp, is shown here:

```
#include <Cyclops.h>

#define PI_CONST 3.14159265358979323846

// Parameters of the chirp waveform
#define CHIRP_TIME_MS 5000 // Length of chirp waveform in msec
#define FREQ_START 0.5f // Start frequency in Hz
#define FREQ_END 30.0f // End frequency in Hz

// Create a single cyclops object. CH0 corresponds to a physical board with
// jumper pads soldered so that OC0, CS0, TRIGO, and A0 are used. Set the
// current limit to 1A on this channel.
Cyclops cyclops0(CH0, 1000);

// Chirp frequency ramp parameter
float beta = 1.0;

void setup()
{
    // Chirp parameter
    beta = (FREQ_END - FREQ_START) / (((float)CHIRP_TIME_MS) / 1000.0);

    // Start the device and zero out its DAC
    Cyclops::begin();
    cyclops0.dac_load_voltage(0);
}

void loop()
{
    // Calculate current chirp amplitude
    float now = ((float)(millis() % CHIRP_TIME_MS)) / 1000.0;
    float freq
        = 2.0 * PI_CONST * (FREQ_START * now + (beta / 2.0) * pow(now, 2));
    unsigned int voltage = (unsigned int)(4095.0 * (sin(freq) / 2.0 + 0.5));

    // Program the DAC and load the voltage
    cyclops0.dac_load_voltage(voltage);
}
```

LEDs and Laser Diodes

There are several things to consider when determining the type of LED or laser diode you wish to drive with the Cyclops:

- Will optical stimulation be used in-vivo or through a microscope?
- Do you need to take advantage of the full device bandwidth or are slower (~1 usec) optical dynamics acceptable?
- Will it be performed on freely behaving animals?
- Do you need to perform bilateral stimulation?
- Will you need to incorporate an amplified photodiode into your stimulator to measure optical power or use optical feedback to produce ultra precise light waveforms?
- What wavelength do you require?
- Will the LED or laser diode need a heatsink to maintain operation at the power levels you require?
- Should light be launched into a fiber or placed directly at the target?

The answers to these questions will determine the type of LED or laser diode you use, how it is coupled to the preparation (e.g. collimated for the back aperture of your microscope objective lens or, fiber coupled for in-vivo stimulation), and whether or not it needs to be commutated in some way. The following provide a few simple options for LED configurations, but there are many more to consider for your experiments.

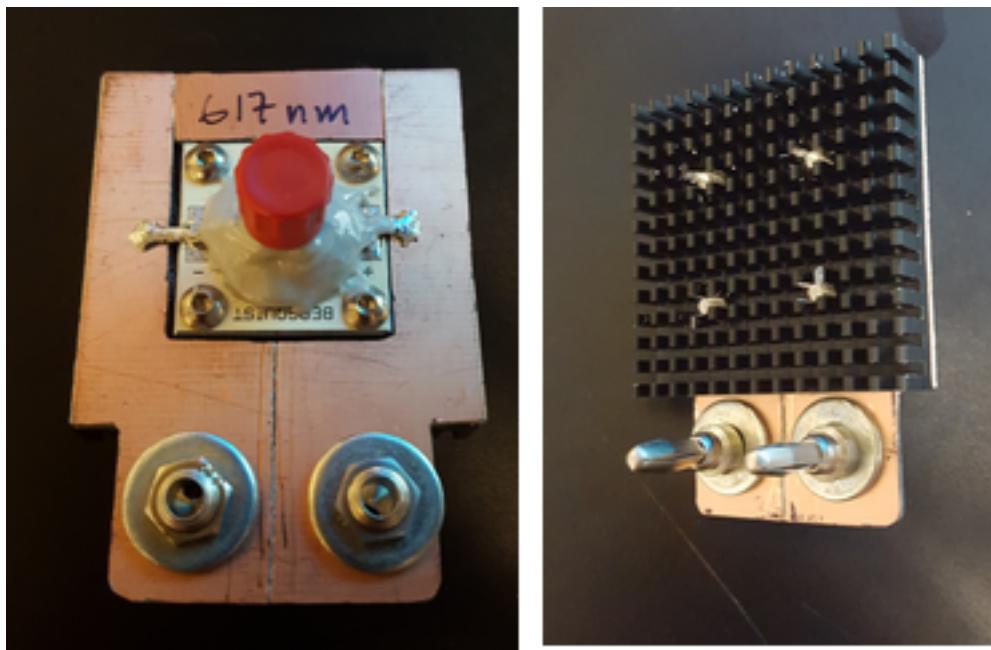


Figure 11: A simple ‘pigtailed’ LED module. A female SMA connector is cemented over a lens-free high power LED to form a near optimal butt-coupling between the fiber and the LED die.

Fiber-Coupled LED

DIY Solution

Anders Asp has contributed the following PDF document containing detailed instructions for fabricating a bilateral, commutated fiber-coupled LED for use in freely moving animals that works with the Cyclops driver:

[Bilateral fiber-coupled LED](#)

Thorlabs fiber-Coupled LED modules

The cyclops can be used to drive [Thorlabs fiber-coupled LED modules](#). You will need to install the [M8 4-position connector](#) in EXPANSION PORT B to drive these LEDs. Solder the wires from the connector to the cyclops PCB as shown in the following image **after** you have installed the connector into the rear panel of the device.

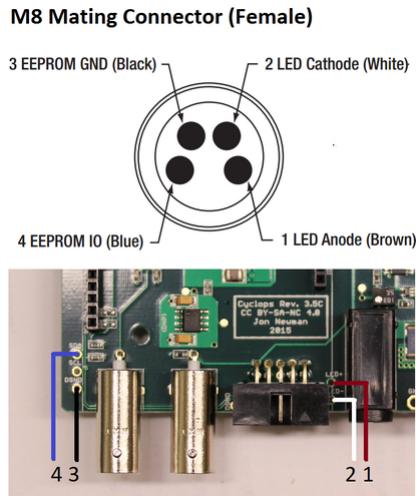


Figure 12: Thorlabs LED M8 connector pinout

Doric LED fiber-coupled modules

The cyclops can be used to Drive [Doric fiber-coupled LED modules](#). You will need to install the [M8 4-position connector](#) in EXPANSION PORT B to drive these LEDs.

TODO: Pictures/instructions for M8 installation process in Doric configuration

Microscope mounted LEDs

The cyclops can be used to Drive [Thorlabs collimated LEDs](#) for microscope-based stimulation. You will need to install the [M8 4-position connector](#) in expansion port B to drive these LEDs. See [Thorlab fiber-coupled LED instructions](#) for instructions.

Laser Diodes

In addition to LEDs, cyclops can be used to drive laser diodes. This can be an appealing alternative to DPSS lasers for optogenetic stimulation. Cheap DPSS lasers common for optogenetic use typically have very poor power stability and temporal control characteristics. Laser diodes driven by cyclops behave similarly to LEDs but offer much better fiber coupling efficiency. It is easy to produce 100's of mW at the fiber tip simply by butt-coupling to a laser diode. Alternatively, a [focusing tube](#) can be used to launch laser diode light into a bench top fiber-coupling system as a direct replacement for a DPSS laser. Further, due to the cyclops' on/off speed, a collimator can be used to send LD light into a 2P imaging system in between row scans. This process occurs so quickly that it is averaged out by the opsin kinetics to look like continuous power.



Figure 13: Thorlabs LD focusing tube

Construction

If you have questions during device assembly, please direct them to the [open-ephys forum](#) so that others may benefit. Pull requests improving this documentation are welcome.

This portion of the manual provides instructions for assembling a Cyclops device. If you have any questions, do not hesitate to post them to the open-ephys mailing list:

<https://groups.google.com/forum/#!forum/open-ephys>

Also, **pull requests and bug reports are welcome**. I would love your help in improving this device and its documentation!

<https://github.com/jonnew/cyclops/issues>

Components

PCB

Unpopulated Cyclops PCBs can be fabricated by uploading the [gerber files](#) to the PCB fabrication service of your choice. I have had success with:

- OSH Park - made in America, excellent quality. Minimum of 3 boards per order
- Seeed Studio - made in China, passable quality. Minimum of 5 boards per order.

The layer of each gerber file is identified by its file extension:

```
*.GKO = board outline
*.GTS = top solder mask
*.GBS = bottom solder mask
*.GTO = top silk screen
*.GBO = bottom silk screen
*.GTL = top copper
*.G2L = inner layer 2 copper
```

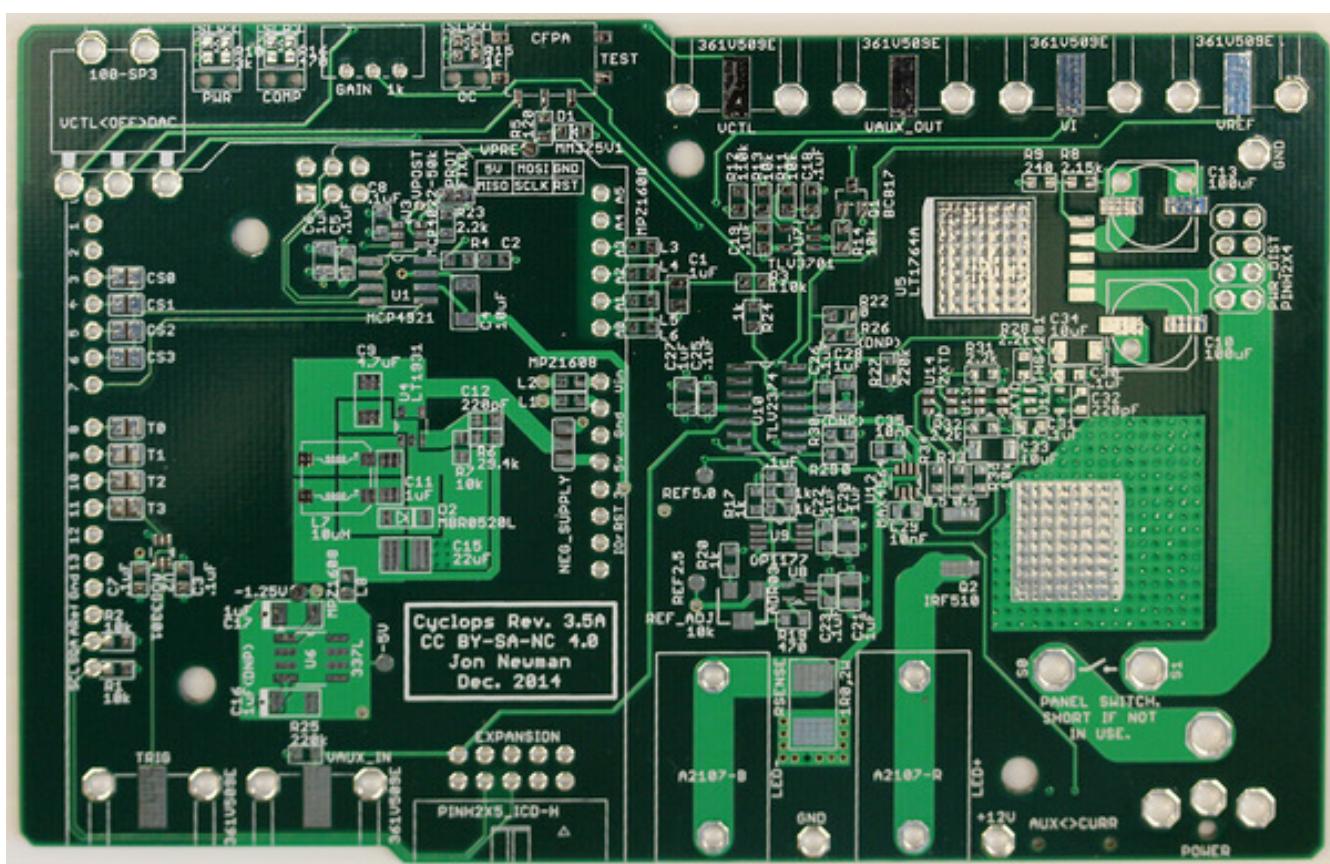


Figure 14: A bare Cyclops PCB, top side, fabricated by Seeed Studio.

*.G3L = inner layer 3 copper
*.GBL = bottom copper
*.XLN = drill hits and sizes

PCB stencils, which are useful for applying solder paste to the boards, can be purchased from a service like [Seeed Studio](#) using the gerber files located in `/cyclops/device/stencil/` folder. If you plan to hand solder the board, or don't mind dispensing solder paste yourself, then you do not need to purchase these stencils.

PCB Bill of Materials

The PCB bill of materials is available on [this google sheet](#)

Other Materials

A complete device requires several additional components aside from the assembled PCB itself. These pre-populated Digikey cart. These can be found following the PCB parts on [this google sheet](#). These parts include - An **extruded aluminum enclosure**, which houses the completed board. The enclosure is recommended because the large voltages and current transients used to drive high power LEDs can cause capacitive and inductive interference with nearby recording equipment. Acrylic front and rear panels can be purchased from Ponoko using the links supplied in the BOM. The instructions below show how these plastic pieces are modified to provide proper electrical shielding. - **Custom heatsink**, a waterjet-cut aluminum heatsink. Designs can be found in the `./device/heatsink` folder. - **Teensy 3.2 MCU**, a 32-bit microcontroller development board. Can be purchased [here](#) - An **M8-4 connector** (Optional). This is a rather expensive connector that allows cyclops to drive [Thorlabs LED modules](#) or [Doric LED modules](#).

Device Assembly Manual

Required Parts and Tools

Before starting, please ensure you have the following components. Suggested part numbers and suppliers are provided on [this google spreadsheet](#). In the lists below, numbers (#XX) correspond to the labels on the image below.

1. Assembled Cyclops PCB (#6, 1x)
2. Extruded aluminum enclosure (#1,1x)
3. Enclosure panels (front: #20, 1x; rear: #21, 1x)
4. Rocker switch (#18, 1x)
5. 18 AWG silicone insulated hookup wire (#17, 2x)
6. Shrink tube (#19, 2x)
7. Gain knob (#7, 1x), jam nut (#8, 1x), and toothed washer (#9, 1x)
8. Button cover (#10, 1x)
9. Waterjet-cut aluminum heatsink (#13, 1x)
10. 6mm length, M3 thread-forming screws (#11, 11x)
11. Nylon washers (#12, 3x)
12. Silicon thermal compound (#4)
13. Thermal tape (#5)
14. Teensy 3.2 MCU board (#15, 1x)
15. 0.1" sockets for Teensy 3.1 (#16, 2x 1x14 pin; 1x 1x2 pin; 1x 2x7 pin SMD)

You will also need the following tools.

1. Scissors
2. Soldering iron
3. Hot air gun or lighter
4. T10 Torx key or driver (#2)
5. XX Allen key or driver (#3)

6. Teensy soldering jig made from breadboard with male headers (#14)

Additionally, to use your device once it is assembled, you will need:

1. An LED or laser diode to drive [Required]

- See the [LED/laser diode section](#) for options.

2. A power supply [Required]

- Any wall-wart, battery pack, or bench-top power supply providing 15-20 VDC that can source $\geq 2A$ will work.
- The power jack is **center positive** (but reversing this will not ruin the device, it just won't turn on).
- Look around and see if you have a wall-wart laying around the lab that meets the specs. They are pretty common and the jack is likely to fit.
- [Digikey part number 1470-3096-ND](#) or equivalent is a good option for those that need to buy a supply.

3. An M8, 4-pin connector [Optional]

- An inexpensive, standard, non-insane, 2x5 header (**EXPANSION A**) provides access to most of the internal signals on the Cyclops board, e.g. for driving an LED or providing auxiliary feedback using an amplified photodiode etc.
- An expensive, strange, moderately insane, M8 expansion connector that is used by two major companies in the optics space (**EXPANSION B**) is left unpopulated. You can populate this port if you wish to drive Thorlabs or Doric LED modules using the Cyclops. For instructions, see this the complete manual.

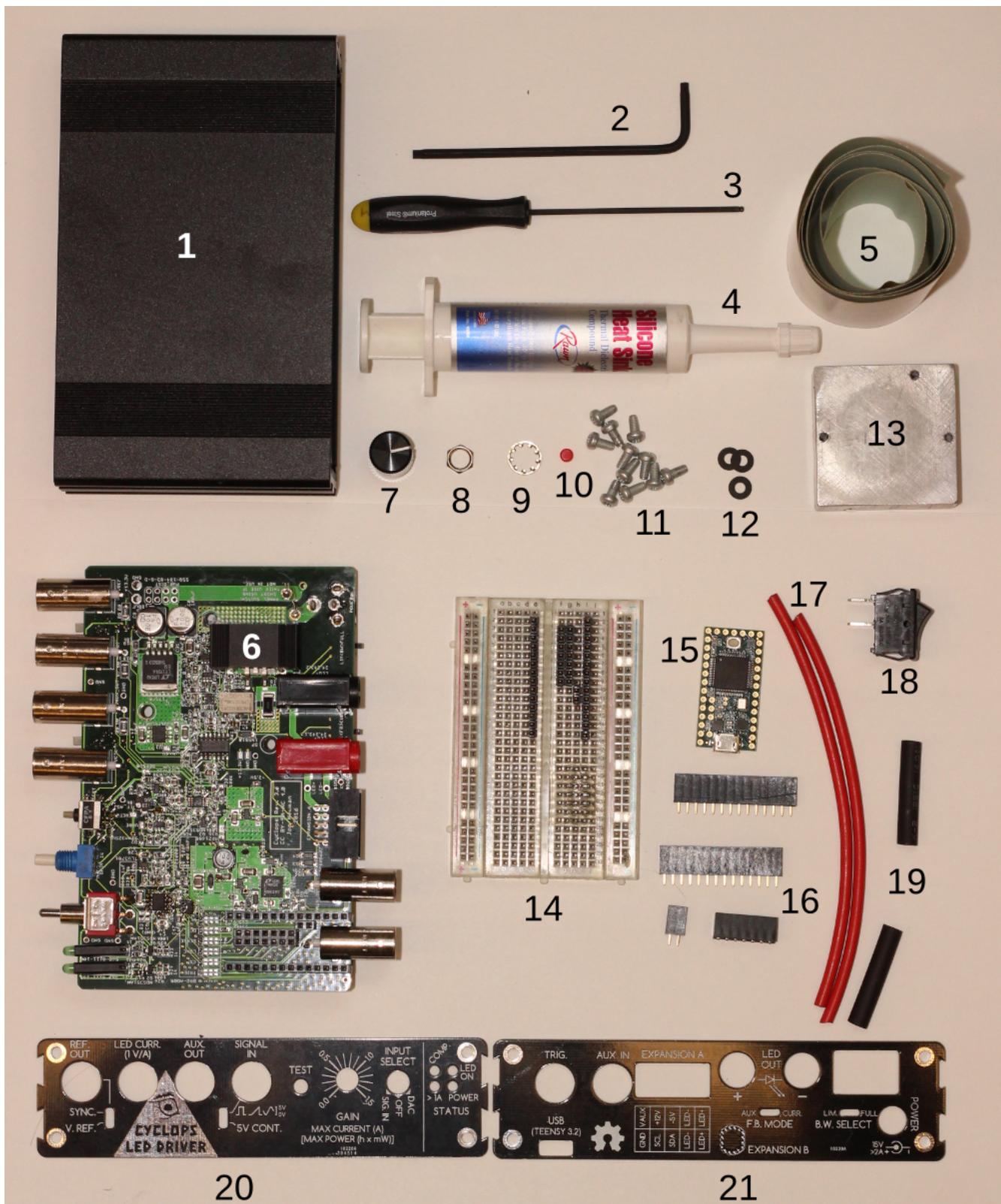


Figure 15: Cyclops device parts and tools

Device Assembly Instructions

1. Assemble the teensy 3.2

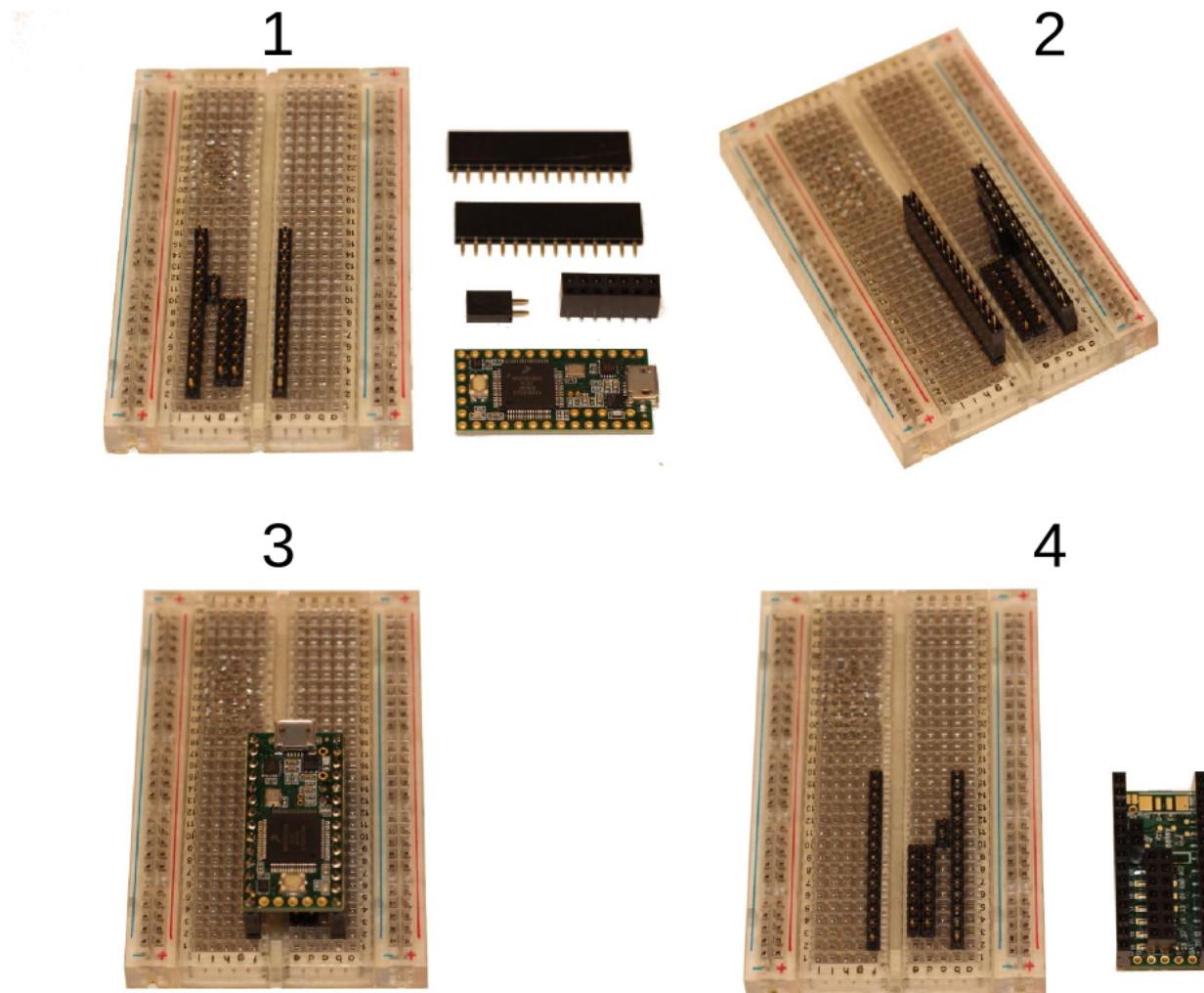


Figure 16: Teensy MCU assembly

- Solder the surface mount, 2x7 pin header to the bottom of the teensy. It is important to do this first because its very hard to get to after the other headers are installed.
- Put the single row headers on the soldering jig (panel 2, above), followed by the Teensy (panel 3, above). The microcontroller chip should be facing up.
- Solder the headers in place.

2. Assemble the power switch

- Strip about 1 cm of insulation from each end of the hookup wires
- Thread the stripped portion of the wire halfway through each of the switch's solder terminals. Fold the wire back, so that the stripped part is touching both sides of the terminal.
- Solder the hookup wire to the terminals. Make sure the solder flows between the wires' copper braid and the switch terminals.
- Slide the heat shrink from the back of each wire, over the solder joints. Hit them with a hot air gun or pass a lighter underneath them to shrink them into place over the solder joints.

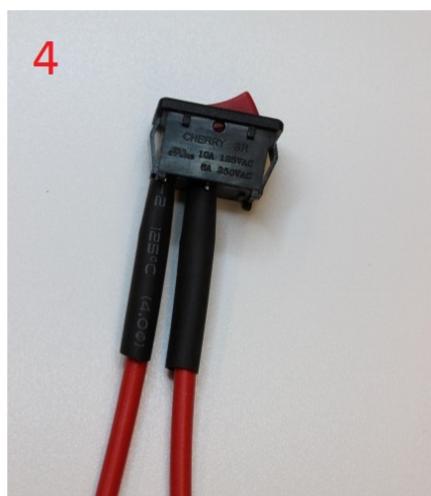
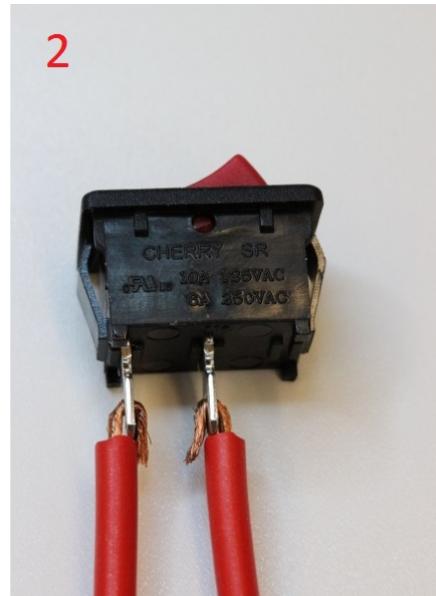
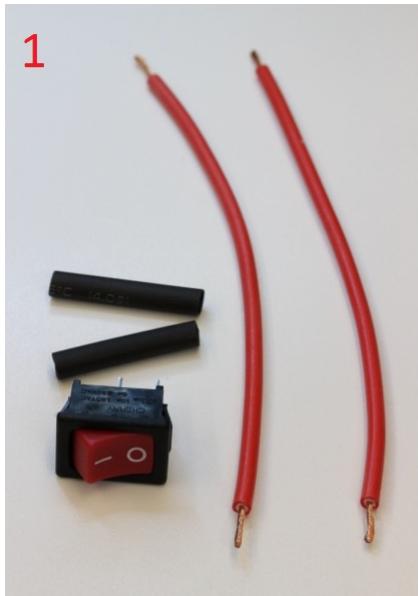


Figure 17: Power switch assembly

3. Prepare the back panel

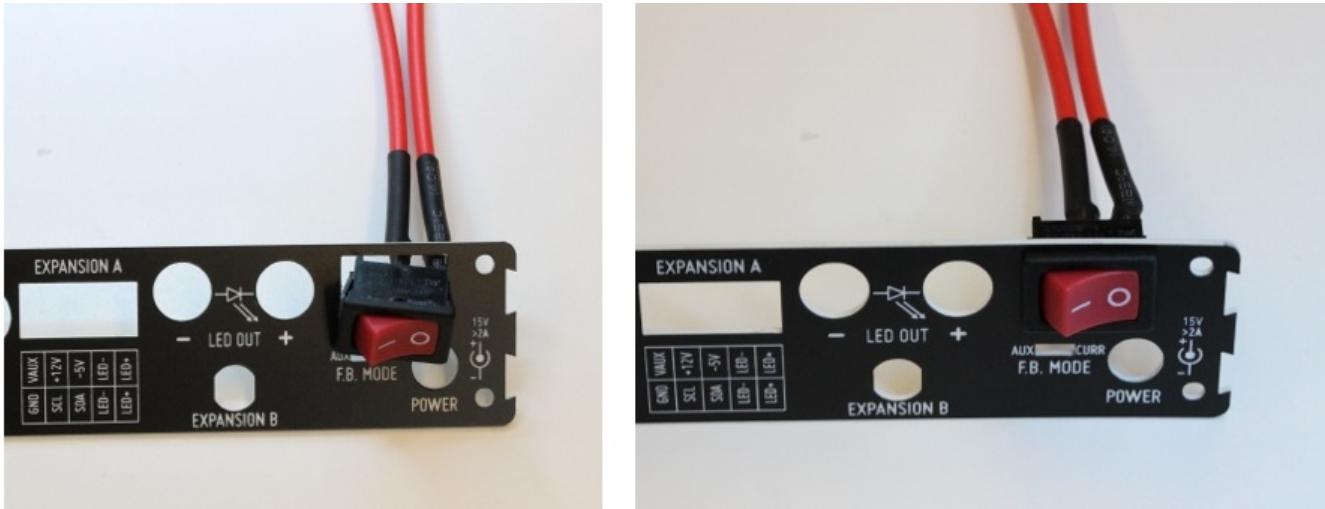


Figure 18: Power switch installation

- Press the power switch into position on the back panel. Orient the switch so that the ‘on’ symbol (-) is toward the middle of the panel and the ‘off’ symbol (o) is toward the outside. This will make the panel easier to mount on the enclosure.
- The switch will snap into place.

4. Install the teensy on the cyclops

- Press the previously assembled teensy onto the 0.1” pitch male headers. It should be *upside down* on the bottom of the cyclops PCB.

5. Put thermally conductive tape on the heatsink

- Cut a square of thermal tape from the roll
- Peal off the backing and press the tape on the back of the heatsink.
- Poke holes through the tape to expose the bolt holes in the heatsink.

6. Install the heatsink on the PCB

- Flip the PCB so that the bottom is exposed.
- Locate the large white square surrounding the exposed copper pad indicating the heatsink mounting location
- Apply an even layer of thermal paste to the area.
- Remove the paper backing from the tape on the heatsink to expose the adhesive surface
- Press the heatsink into place on the PCB
- Filp the PCB so the top is up and locate the three holes used to mount the heatsink to the PCB. Thread three self-tapping screws through a nylon washer and then into the heatsink itself. Hand tighten until the heat sink is firmly head against the back of the PCB. You should see thermal compound coming through the numerous vias in the PCB. This is desired because it provides a low thermal resistance path between the PCB and the heatsink.

7. Solder the power switch to the PCB.

- Solder the power switch to the two indicated terminals on the PCB.
- Make sure you do this **after** you have installed the switch in the rear panel.
- The wires can be soldered to either solder point, orientation does not matter since this is a SPST switch.

8. Install the front panel on the enclosure

- Using 4 of the 11 self-trapping screws, install the front panel on the enclosure.
- **Note:** The orientation of the enclosure matters. The top of the enclosure is indicated by rows of decorative lines as indicated in the above figure.

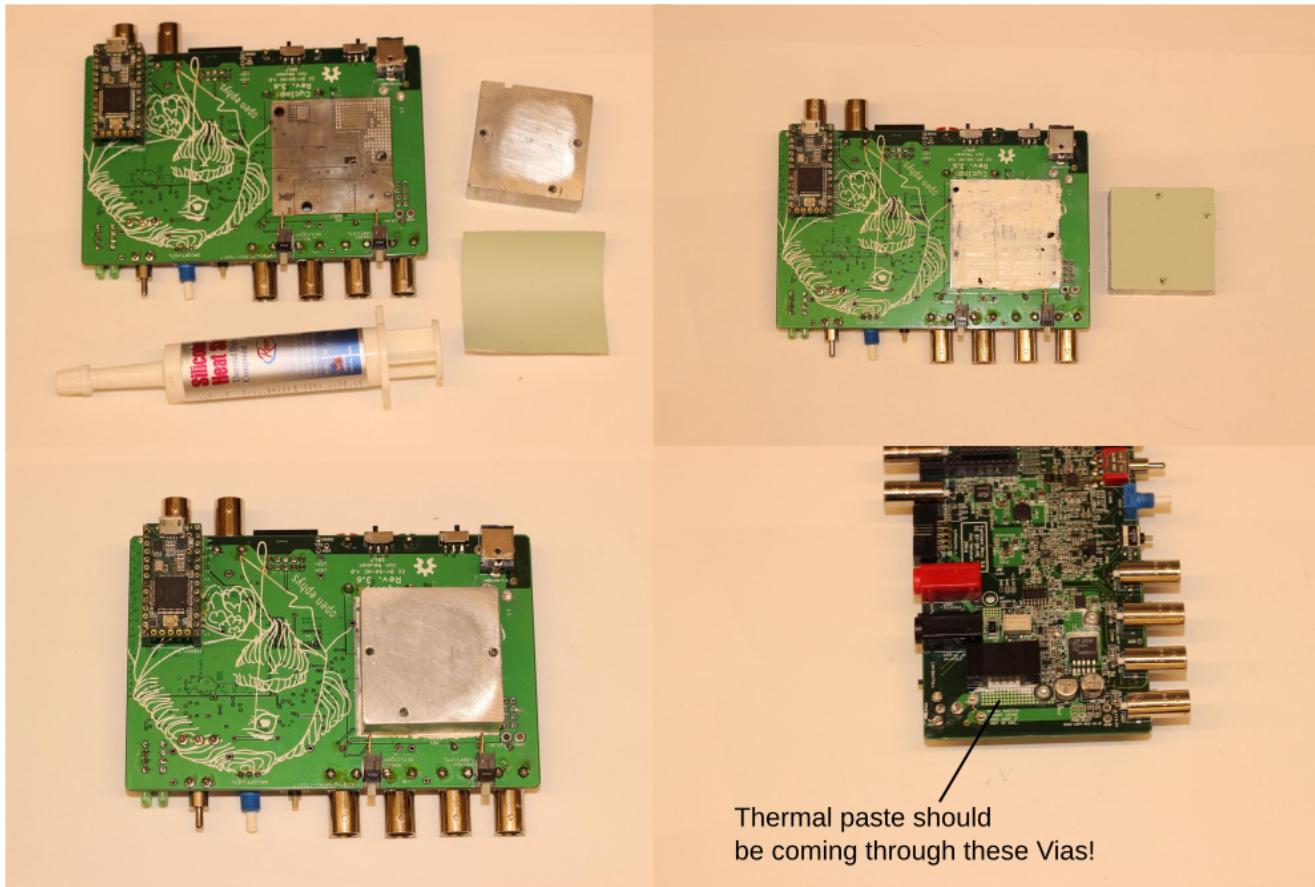


Figure 19: Heatsink installation

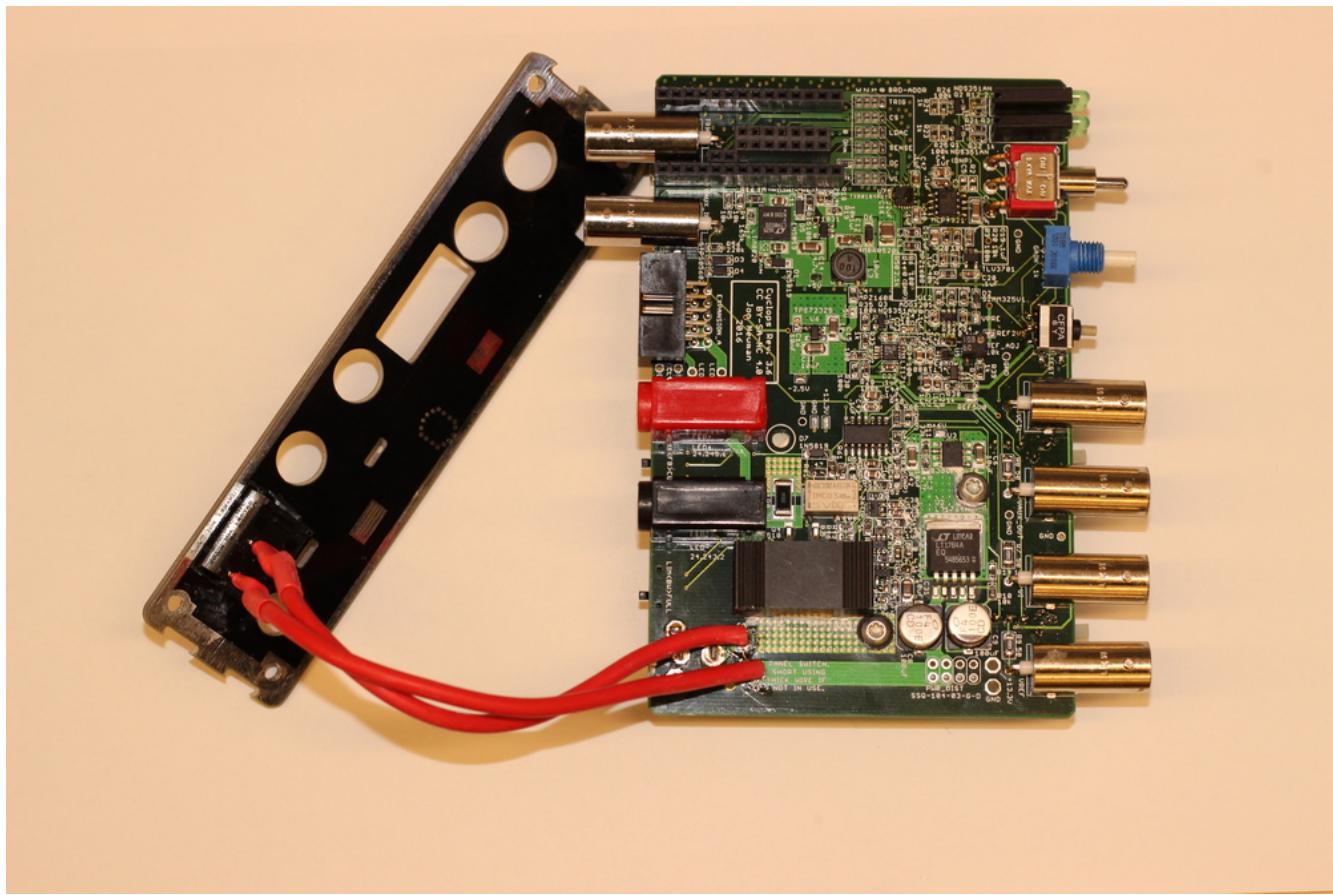


Figure 20: Power switch soldering



Figure 21: Front panel installation

9. Install the PCB in the enclosure.

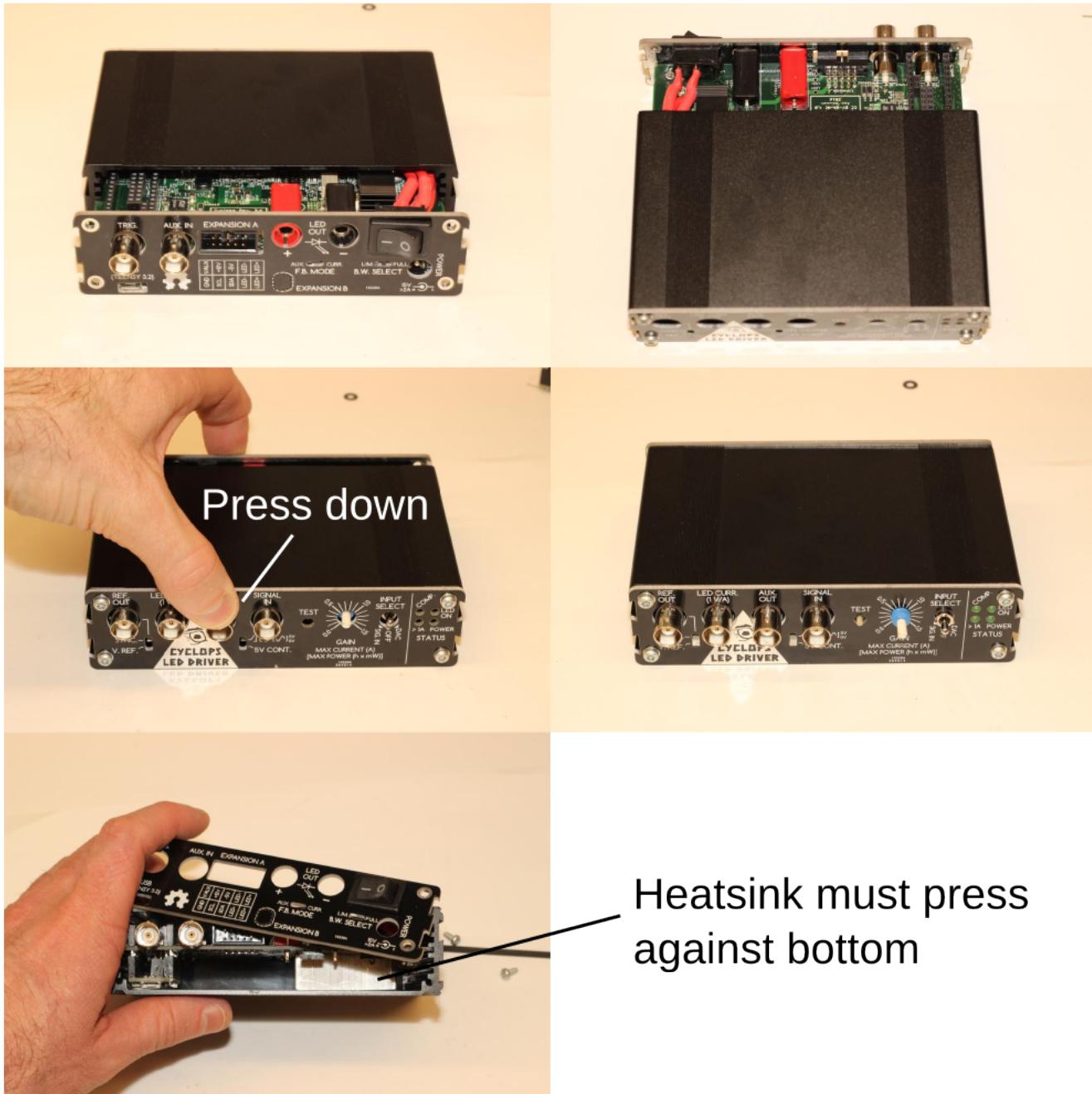


Figure 22: Front panel installation

- Slide the PCB into the box using the **middle** mounting rail.
- **Note:** The heatsink should be making firm contact with the bottom of the enclosure. If it is not, you should add thermal paste to the bottom of the heatsink to fill the gap. The heatsink must have a low thermal resistance path to the enclosure to dissipate heat during operation.
- **Note:** When the BNC connectors come through the front panel, you will need to push them down a bit, slightly flexing the PCB to get the panel mount controls through the front panel.

10. Install the rear panel.

- Loop the two hook up wires and push them into the enclosure on top of the PCB.
- Use the panel the push the remaining wire into the enclosure.

- Use the remaining 4 screws to install the rear panel.

11. Install gain knob and button cover.



Figure 23: Gain knob installation

- Slip the toothed washer over the gain dial.
- Tighten the jam nut on the gain dial's threads until just past finger tight using a pair of needle nose pliers.
- **Note:** Do not over-tighten using a combination spanner or you will strip the threads.
- Turn the dial on the front panel *fully counter-clockwise*.
- Slip the gain knob over the dial with the tick mark pointed slightly below the 0 position.
- Tighten the set screw on the side of the knob to lock it into place using an Allen key.
- When you turn the knob fully clockwise, the tick mark should be pointing close to the 1.5A position.
- Press the red cover over the TEST switch until it snaps into place.

This concludes device assembly. To begin using your device, please refer to the [usage](#) section above.

Board Assembly Manual

Board Assembly Materials

To assemble a Cyclops board, you will need the following materials

- Cyclops PCB
- PCB Bill of Materials
- A soldering iron and, if possible, a hot-air reflow device.
 - At minimum, a soldering iron regulated to ~370 deg. C will do the job.
 - In addition to the iron, a hot-air rework tool or reflow oven are recommended and the assembly instructions below assume you are using one of these two options. A low cost, high-quality hot-air rework station can be purchased from SparkFun [here](#).



Figure 24: A soldering iron can be used to assemble the PCB, but a hot air rework station makes things much easier. These can be purchased from [Sparkfun](#).

- Copper braid ('solder wick') for solder removal (e.g. [this](#))
- Liquid flux ([no-clean](#) variants are easiest since they don't have to be thoroughly removed after use)
- Solder paste (e.g. [this](#))



Figure 25: Wire solder and an soldering iron can be used to construct the PCB, but solder paste combined with a hot air rework station or a reflow oven makes things much easier. We use [Chipquik 291ax10](#).

- Stereoscope or loupe (optional but nice for tracking down shorts.)
- Isopropyl alcohol for cleaning flux off the board (e.g. [this](#); optional)
- An anti-static mat (e.g. [this](#); optional but recommended to protect your work...)

Board Assembly Instructions

PCB component population and soldering is fairly straightforward and requires standard surface mount construction techniques.

- A tutorial on hot-air soldering can be found [here](#).
- A great tutorial filled with general tips and tricks for surface mount soldering can be found [here](#).

The following steps provide a visual guide to construct your own board. The goal is to create a fully populated PCB like this one:

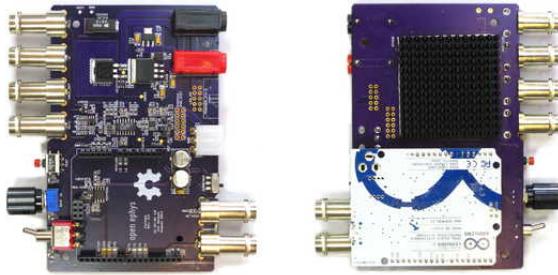


Figure 26: Finished device (revision 3.3).

Following board construction, you should run through the electrical tests outlined in the next section before applying power.

1. Place the bare PCB on a flat surface, preferably one that is static dissipative or anti-static. Alternatively, the board can be mounted in a PCB vice.

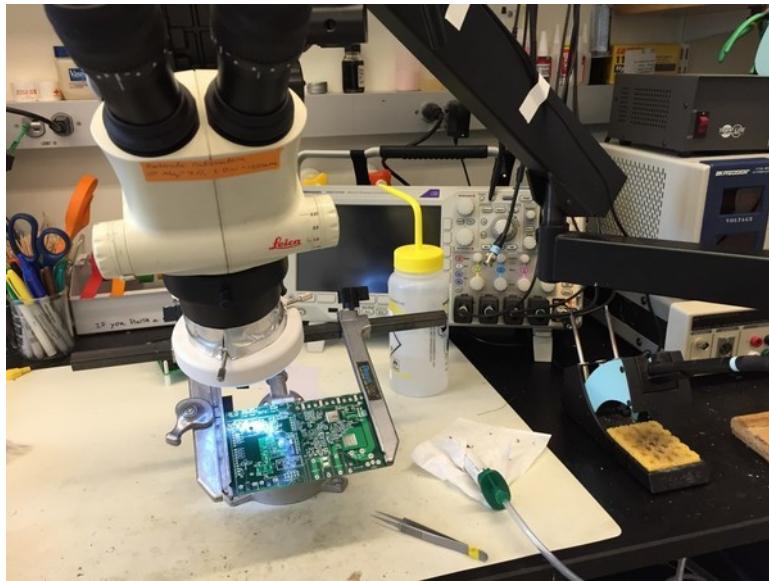


Figure 27: Instead of populating components on a table, holding the PCB using a PanaVise can be helpful.

2. The silkscreen layer on the PCB (white text) has almost all the information you will need to properly populated the PCB. However, its a good ideal to open the [cyclops design](#) in [EAGLE](#). This will allow you to get detailed information on components before placing them on the board.

You can then the **information** tool to get detailed information on each component, e.g. to ensure you are placing the correct value resistor or capacitor.

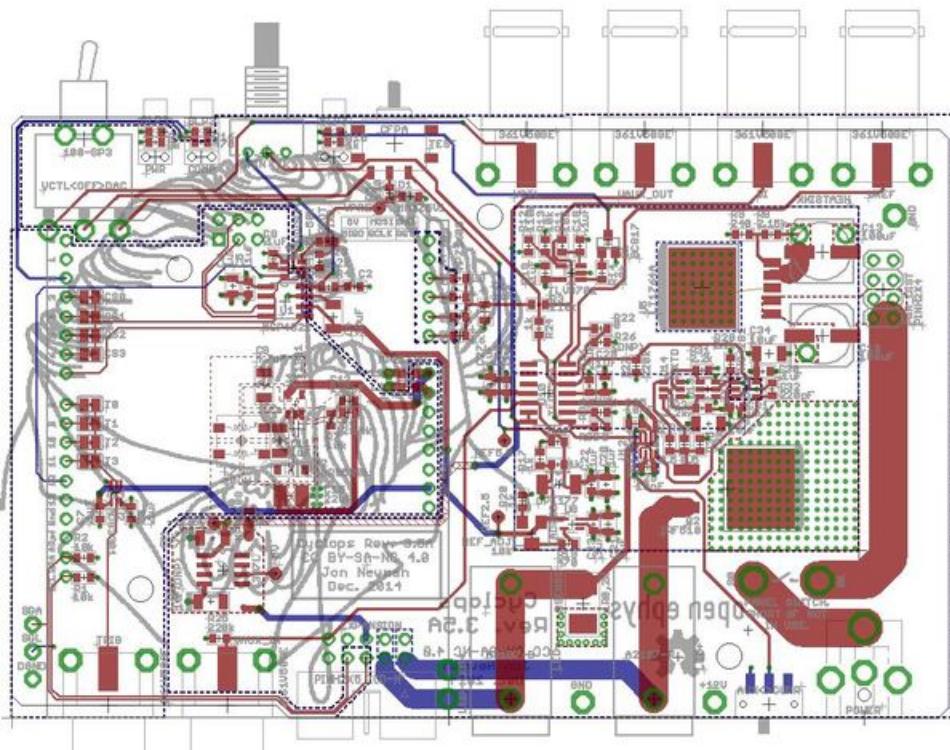


Figure 28: The cyclops PCB design in CadSoft EAGLE

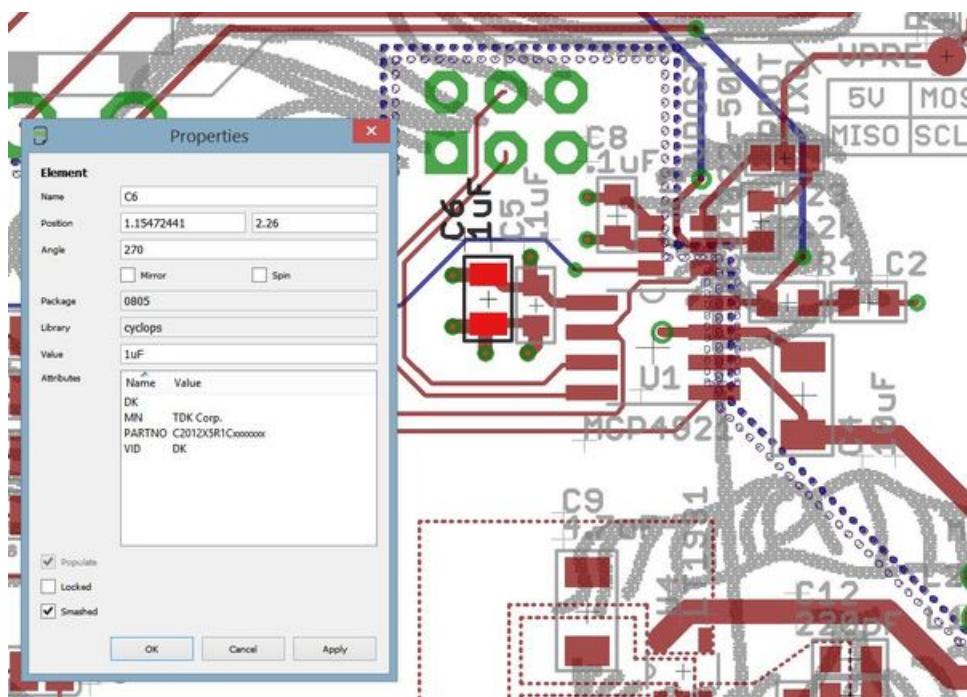


Figure 29: By selecting the information tool and clicking the cross at the center of a component, you can pull up detailed info (e.g. part number)

- After cleaning the surface of the board with isopropyl alcohol or similar, apply solder paste to each of the pads. For an excellent series of tips on effective methods for dispensing solder paste, see [Mike's video on the subject](#). Do not apply solder paste to through-holes or the pads shown outlined in red in the following image. These will be hand soldered later in the assembly process.

The correct amount of solder paste to apply is ‘enough’. Each component contact should sit in a small amount of paste, but blobs of paste that envelop the component pad or pin may later result in a short. The following images show examples of good and bad solder placement.

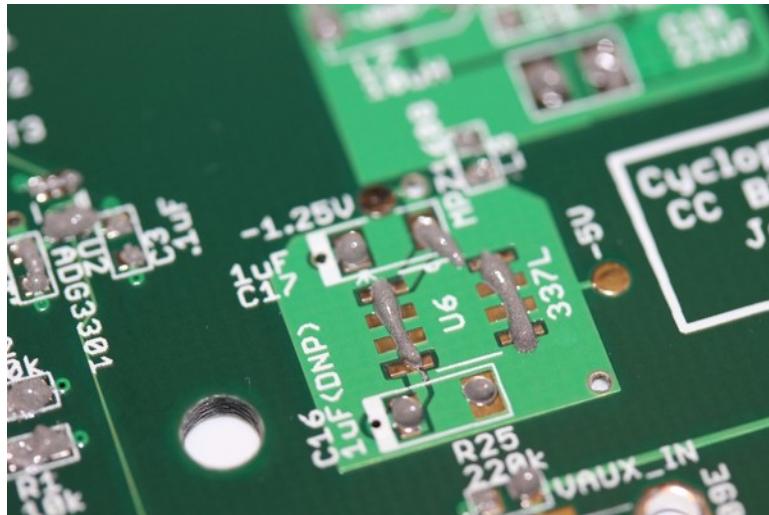


Figure 30: Good solder placement.

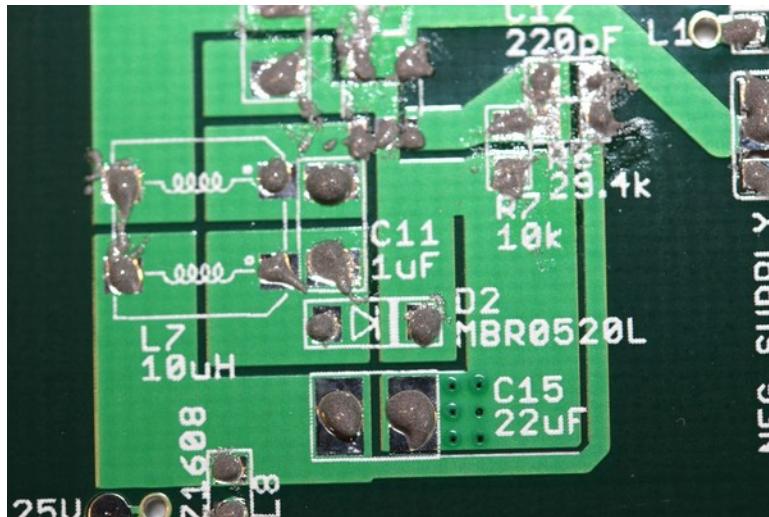


Figure 31: Bad solder placement. Too much paste!

If you need to pause at any point, you should store place the PCB in the fridge to prevent the flux in the solder paste from breaking down.

- Populate all **top-side surface mount** components on the board. There is a single surface mount switch on the back of the board that will be hand soldered later. Additionally, all through hole components (e.g. power jack, BNC connectors, etc) will be populated later. Start by placing the integrated circuits (ICs). Use the stereoscope or loupe to ensure that pads are making contact with the pins of the placed components. Precise component alignment is not necessary. Components will self-align during the reflow process.
- After placing the ICs, place the passive components (resistors, capacitors, inductors, diodes, and ferrite chips).

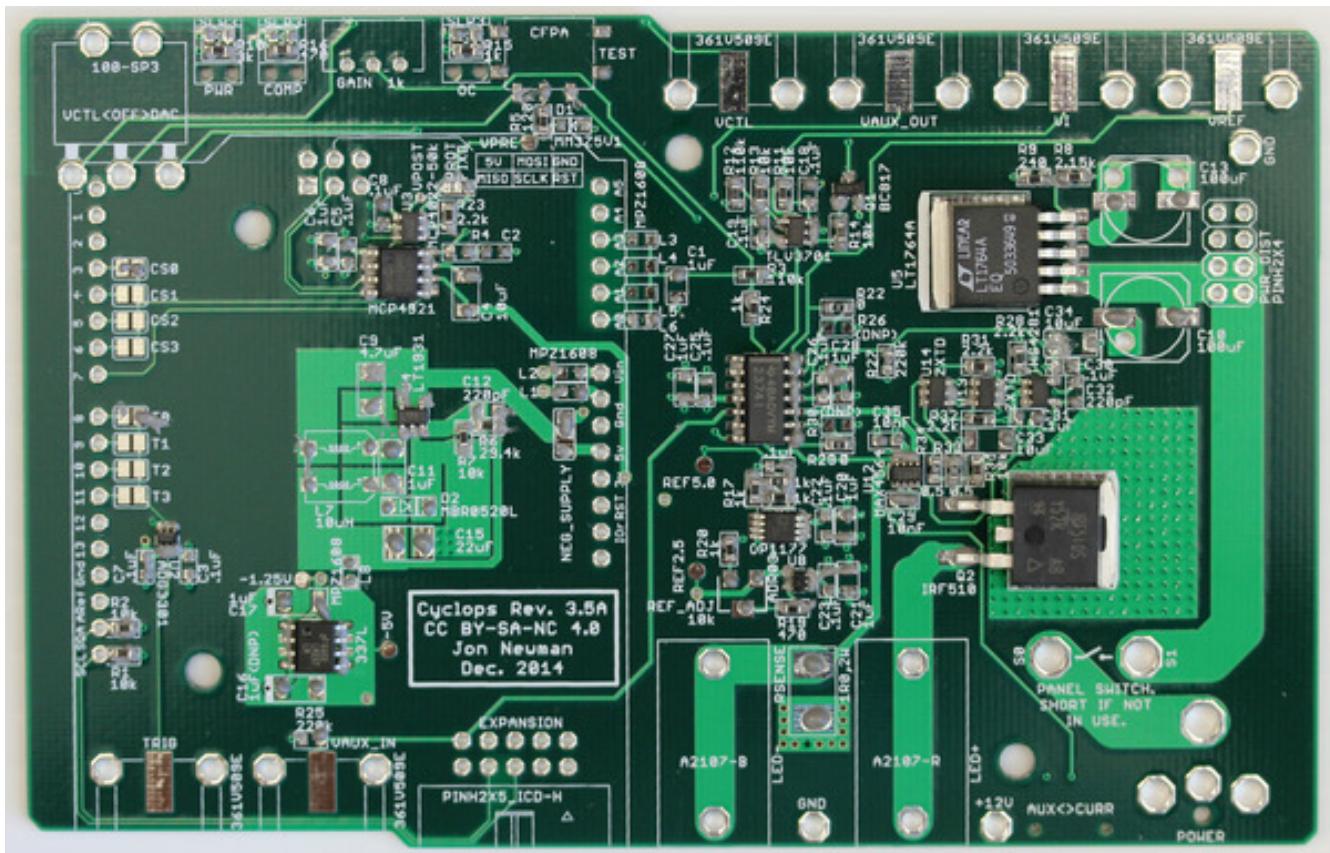


Figure 32: Integrated circuit population.

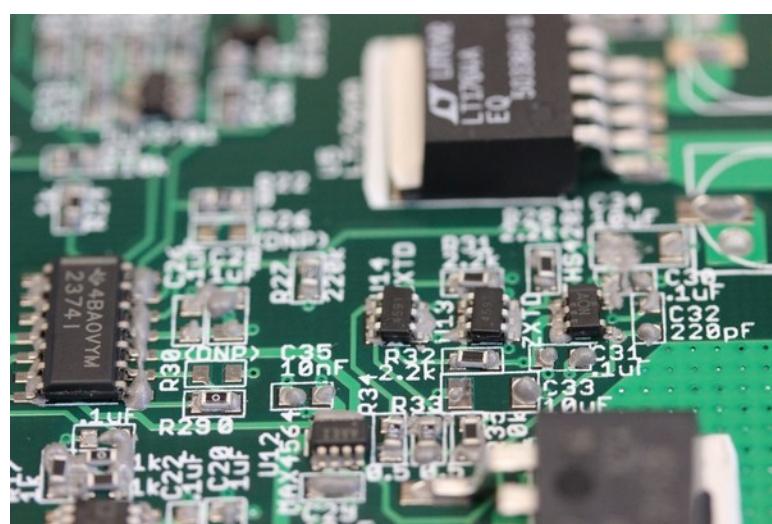


Figure 33: Zoomed view of integrated circuit placement.

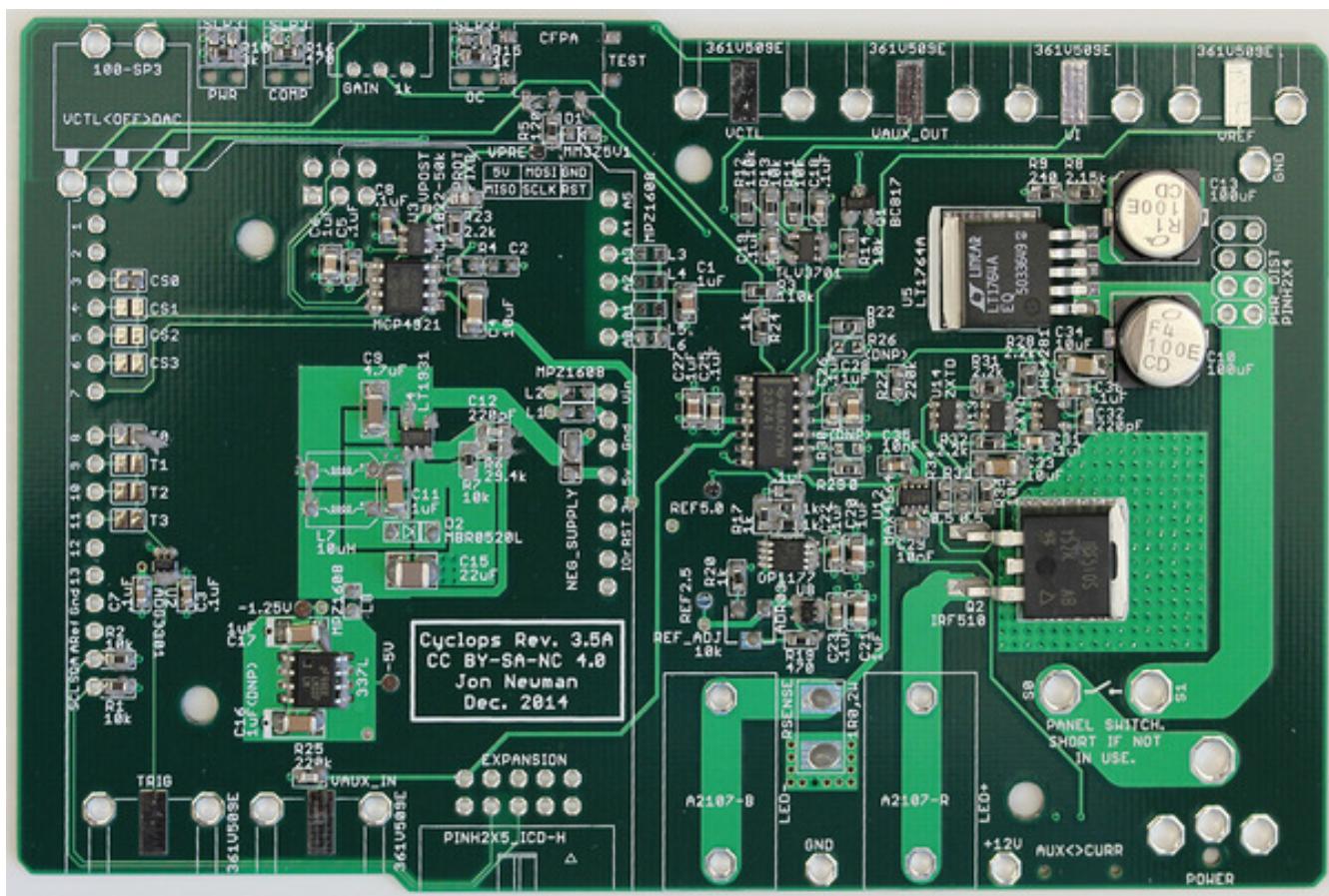


Figure 34: Board following resistor and capacitor population.

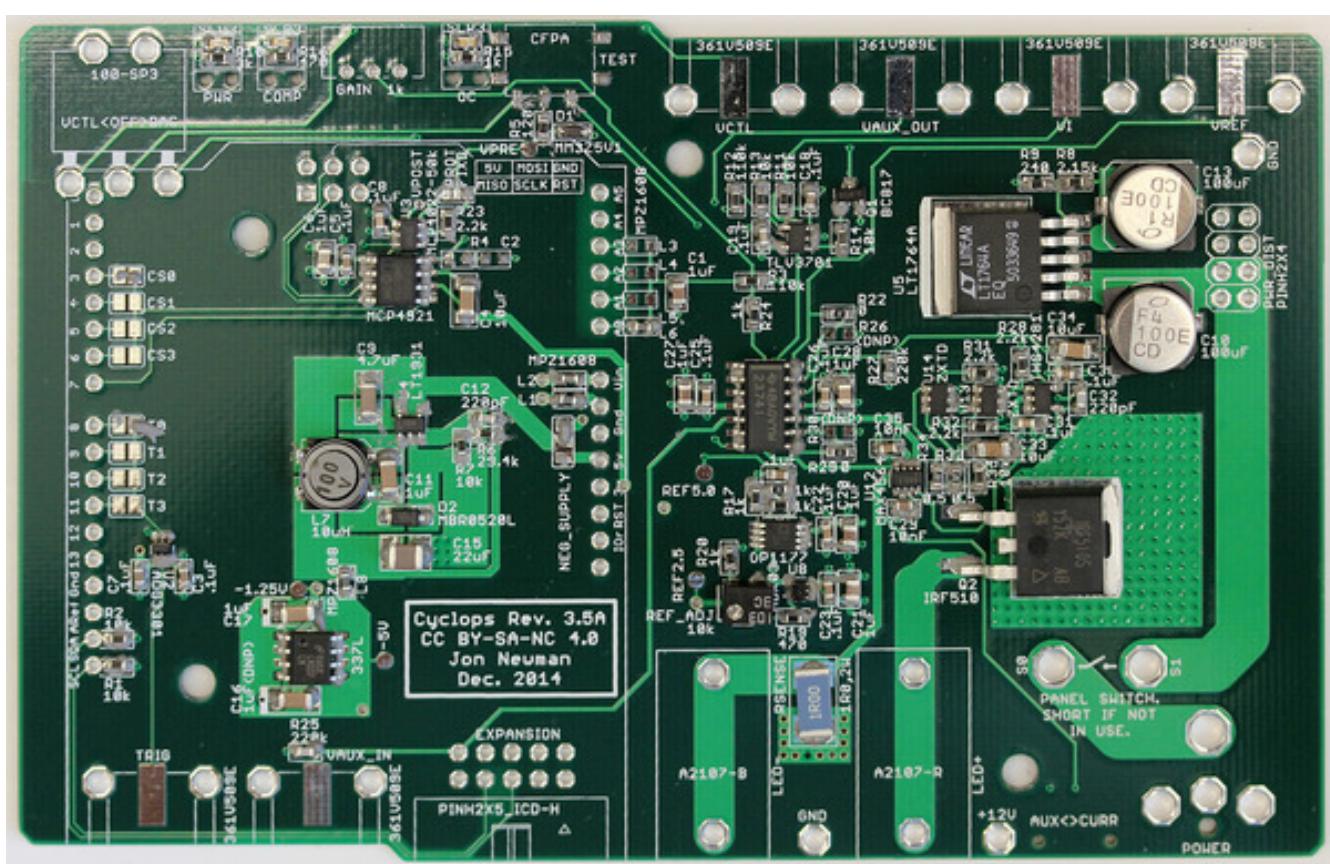


Figure 35: Board with all top-side surface mount components installed.

6. Next, reflow solder the board. We use a homemade reflow oven constructed from a toaster oven, Arduino board, [reflow oven control shield](#), and [mains relay](#). You can make a similar one, use a commercial reflow oven, or use the hot air station. Reflow the solder paste on the board using your oven or hot air gun as described in the links above.



Figure 36: Homemade reflow oven with the populated board inside.

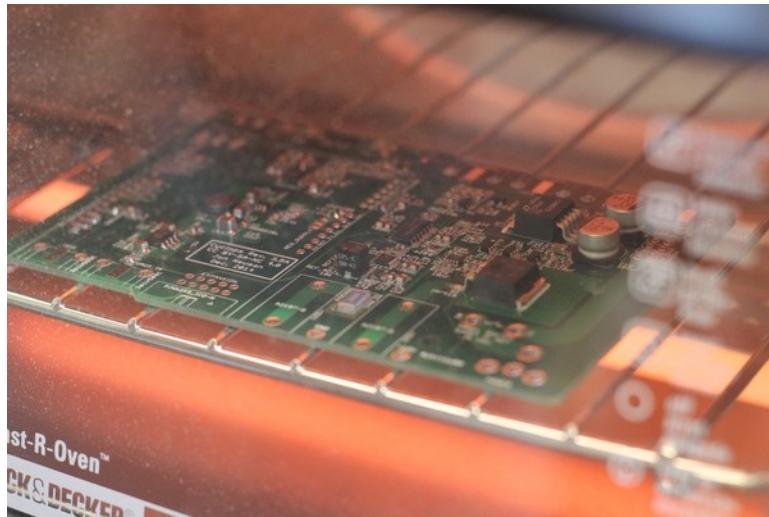


Figure 37: The board is shown after the reflow temperature has been reached. Reflow will occur at different temperatures depending on the specification of the solder paste you are using.

7. After the solder has cooled, examine solder pads using the stereoscope or loupe for solder bridges between pins, solder that has not melted, or pads lacking a decent solder joint. Fix any issues using a standard soldering iron. If there are solder bridges present, get rid of them using some solder wick before moving on. Solder through-hole components in place using a standard soldering iron. A low cost reflow oven can be made from a toaster oven as shown [here](#).
8. Each board has an address (0 through 3) that is defined by two solder jumpers and the location of a ferrite chip. This allows cyclops boards to be stacked to share a power supply while being driven by a common microcontroller. For each board that will share a microcontroller, a unique address must be specified and the solder jumpers and ferrite chip must be soldered in appropriate positions to reflect this address. See the picture below to better understand this addressing scheme.

TODO: Pictures of circled 0 ohm jumpers

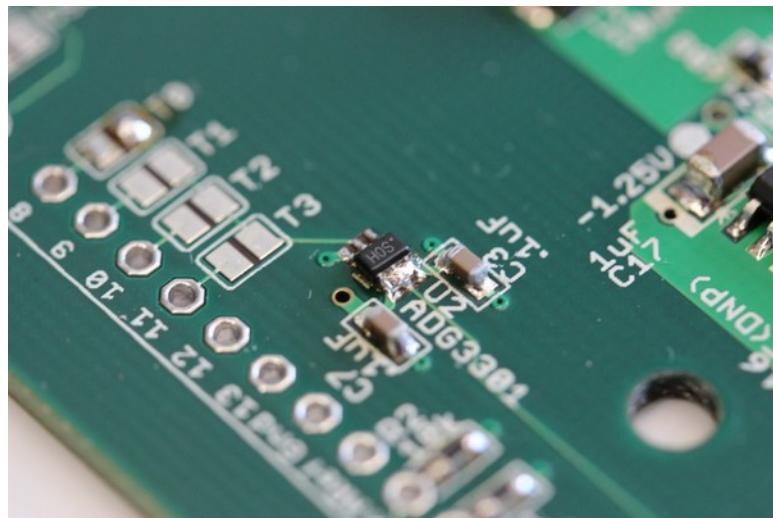


Figure 38: Example of a short between IC pins. This must be resolved before moving forward.



Figure 39: Dipping the copper braid in flux will make the solder wick much more readily.

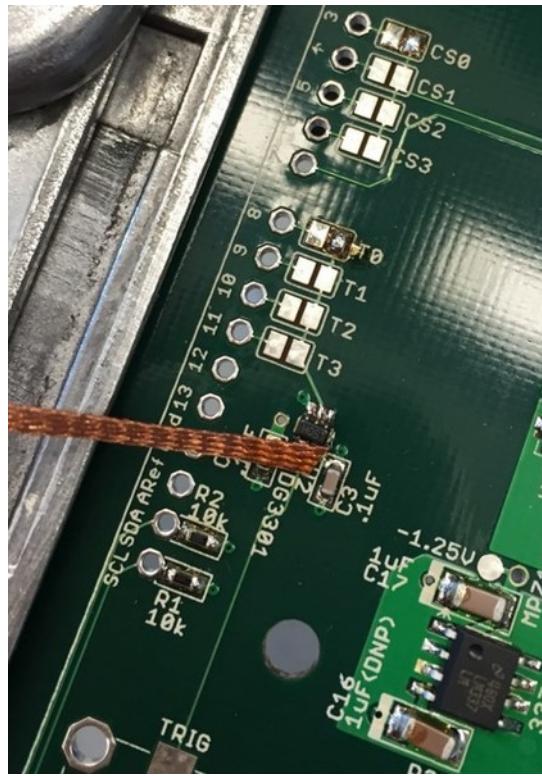


Figure 40: Place the copper braid over the solder blob and then press with the soldering iron. You should see the excess solder wick up the copper braid.

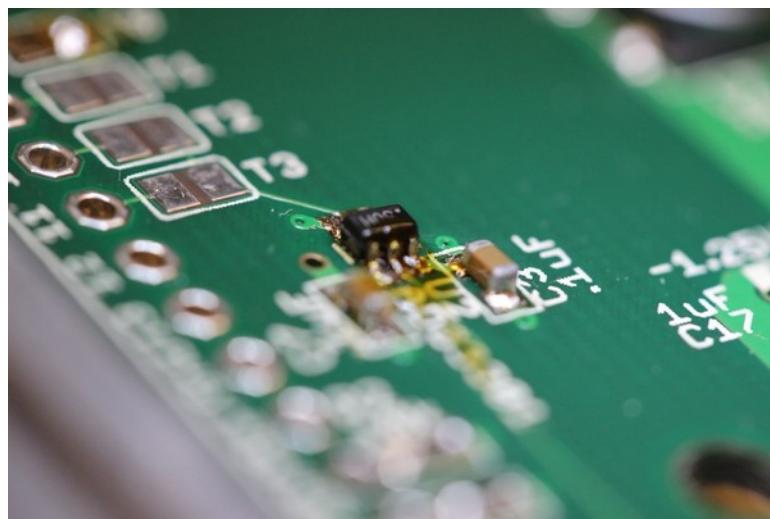


Figure 41: Often you will not have to re-apply solder after this process because there will be enough left over to maintain a good electrical contact. Once you are satisfied the flux residue can be cleaned using isopropyl alcohol

9. Flip the board over and install the final surface mount component, the AUX<>CURR and BW LIM slide switches, by hand soldering.
10. Next, populate all electromechanical components. This can be soldered in place with a standard soldering iron and a large chisel tip.

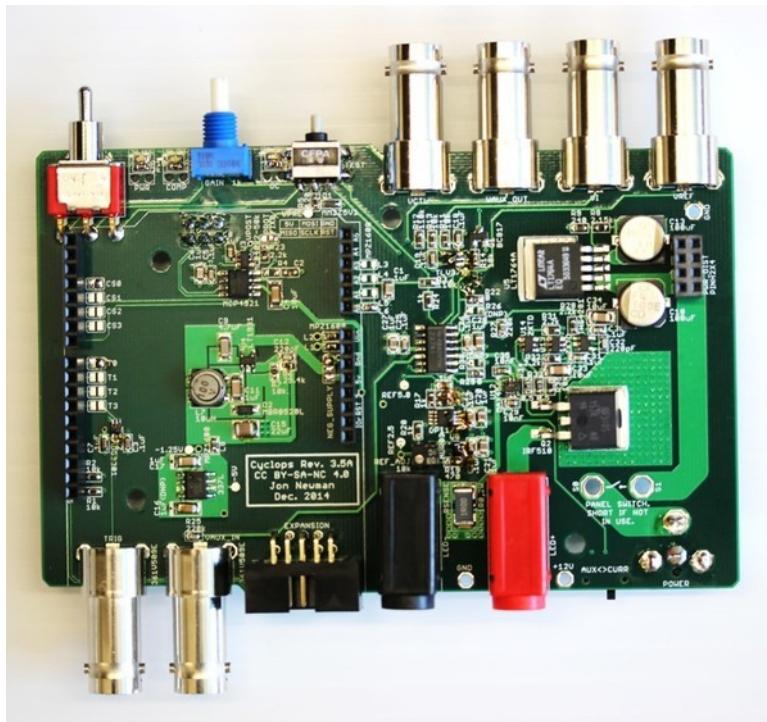


Figure 42: Top side of board following electromechanical component installation.

Note: The the barrel power jack (name: POWER, value: PJ-063BH on the schematic) should be mounted on the **bottom** of the board. It fits on both the top and the bottom, and will properly supply the board with power if mounted on the top. However, if the barrel jack is mounted on the top side of the board, it will not fit inside the enclosure.

11. If you are not planning on putting the PCB in an enclosure, jumper the solder points for the power switch together using AWG 20 (~1.8 mm diameter) braided copper wire or thicker.

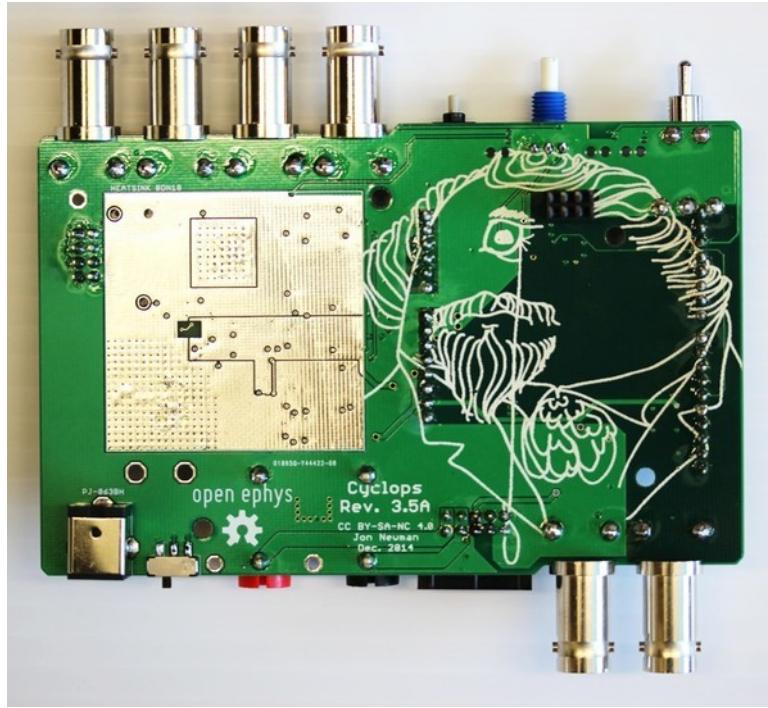


Figure 43: Bottom side of board following electromechanical component installation.

Quality Control Procedure

The following procedure can be performed on assembled boards to ensure functionality. It is performed on devices sold by open ephys.

Setup

- Insert alligator clip across power switch solder points
- Power from 15V, 1.5A capable bench-top power supply.
 - Power indicator LED turns on?

DC Levels

- Using a multimeter, probe the 12V, 2.5V, -5V, and -1.25V test points
 - 12V good?
 - -5V good?
 - -1.25V good?
- While probing the 2.5V test point, use a ESD-safe screwdriver on the trimpot to get exactly 2.5V.
- Seal the pot with a dab of hot-glue.

Dynamic characteristics

- Use external waveform generator to produce 1-5V, 100 Hz, 10% duty cycle square wave.
- Insert LED/amplified photodiode test fixture into banana sockets, IDC connector, and AUX BNC port.
- Insert AFG output of MDO3000 output into VCTL BNC port of device
- Bring CURR output of device to scope
- Bring VREF output to scope
- Triggering on VREF Channel set scope to measure rise and fall times

- Bring front panel potentiometer to 50% position.
- Input switch to EXT source
- Examine wave shape and rise/fall times in **current** FB mode.
 - Rise/fall times < 300 ns? No ringing on waveform?
- Examine wave shape and rise/fall times in **optical** FB mode.
 - Rise/fall times < 300 ns? No ringing on waveform?
- **Return FB switch to curr position**
- Return input switch to OFF (middle) position

Overcurrent indication

- Bring gain potentiometer to full on position
- Briefly tap on the TEST button.
- Ensure that the >1A indicator LED turned on during pulse.
- **Return gain potentiometer to zero position**

Finish

- Remove all power connectors.
- Remove alligator clip.
- Initial and serial number the board using sharpie on the large power trace on the right side of the board.
- Enter board serial number into the spreadsheet.

References

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