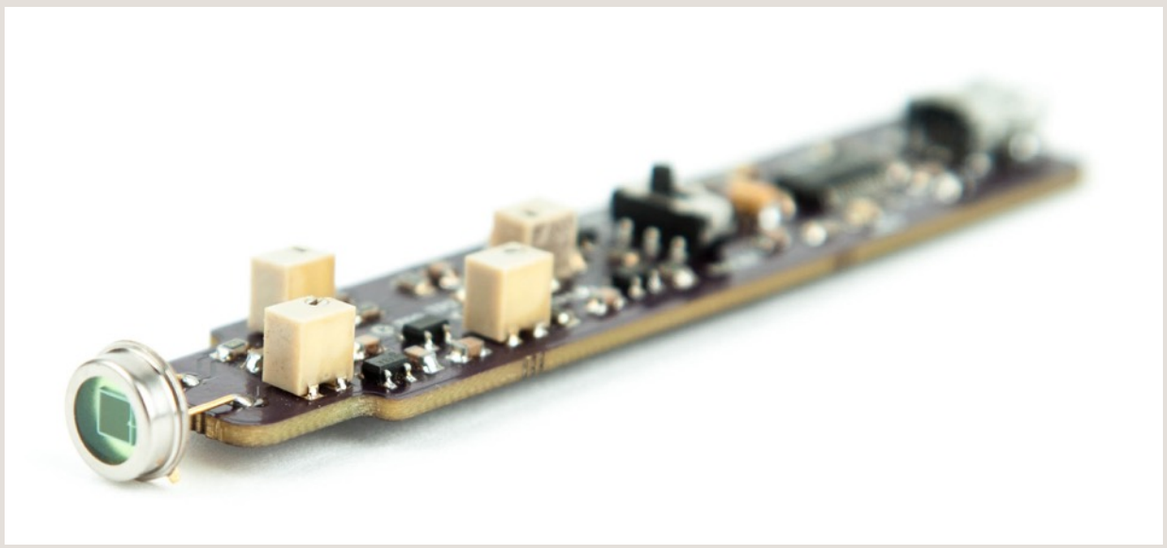
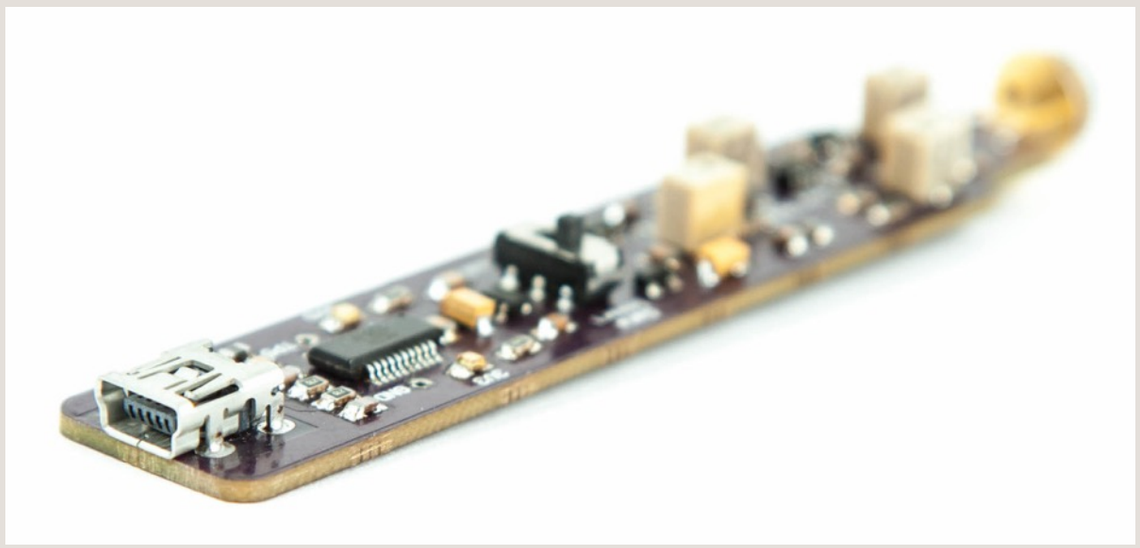
Searching for the Light: Adventures w/ OpticSpy

Joe Grand (@joegrand)

OpticSpy

- Optical receiver to convert light into voltage
- Wavelength: Visible and near IR light (420-940nm)
- Signal speed: 100Hz-1.5MHz
- Data stream polarity: Select normal v. inverted
- Gain and threshold adjustment via potentiometers
- USB interface for direct connection to host PC





Covert Channels

- Hidden methods to intentionally exfiltrate/transfer data from a normally functioning system
- Could be achieved with HW and/or FW modification
  - Specifications modified or misdesigned before manufacturing
  - On physical device during manufacturing or in-the-field
  - Hardware implant via interdiction

Exploiting the Environment

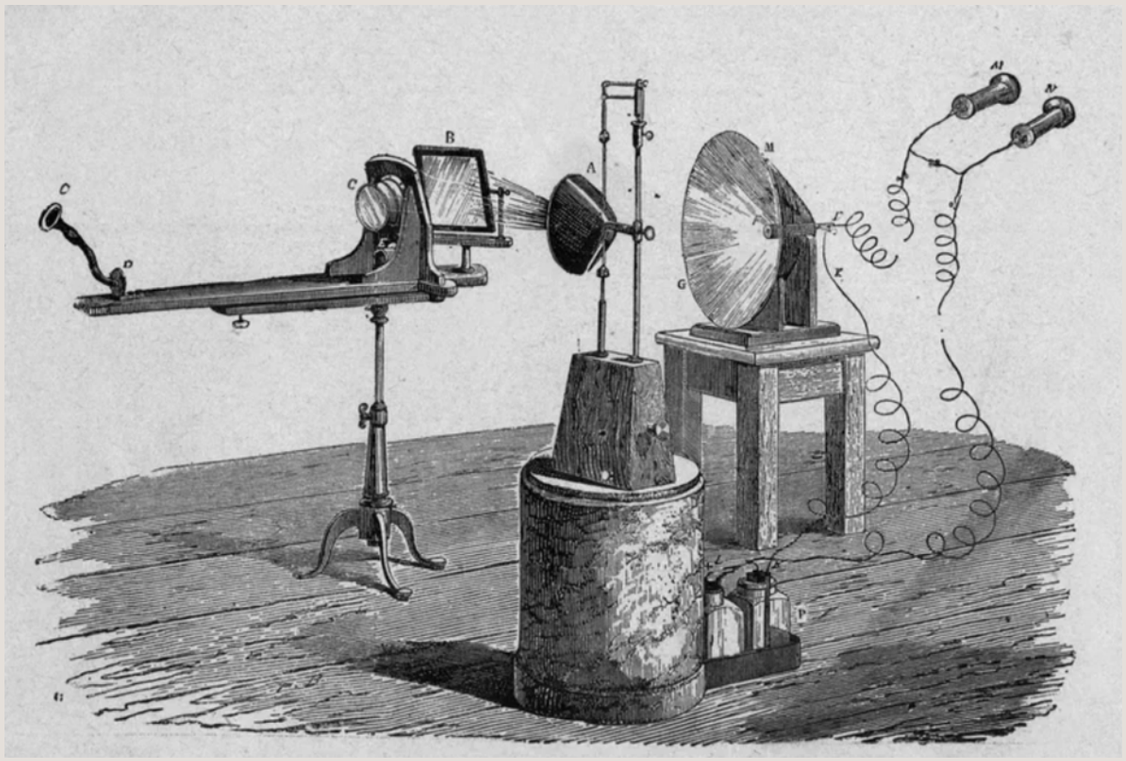
- Leakage based on optical, acoustic, thermal, or RF characteristics of a system
  - Soft Tempest: Hidden Data Transmission Using Electromagnetic Emanations (Kuhn, Anderson)
  - Emanate Like a Boss: Generalized Covert Data Exfiltration with Funtenna (Cui)
  - Inaudible Sound as a Covert Channel in Mobile Devices (Deshotels)
  - BitWhisper: Covert Signaling Channel between Air-Gapped Computers using Thermal Manipulations (Guri et al.)

Blinkenlights

- Using LEDs to exfiltrate/send data
  - Modulation faster than the human eye can detect
- Optical covert channels
  - Information Leakage from Optical Emanations (Loughry and Umphress, 2002)
  - Silence on the Wire: A Field Guide to Passive Reconnaissance and Indirect Attacks (Zalewski)
  - Extended Functionality Attacks on IoT Devices: The Case of Smart Lights (Ronen, Shamir)
  - xLED: Covert Data Exfiltration from Air-Gapped Networks via Router LEDs (Guri et al.)

A Selection of Optical History

- Alexander Graham Bell's Photophone (1880)
- Fiber optic communications (~1963)
- Laser tag (~1979)
- Optical networking systems (VLC, Li-Fi, FSO) (2011)



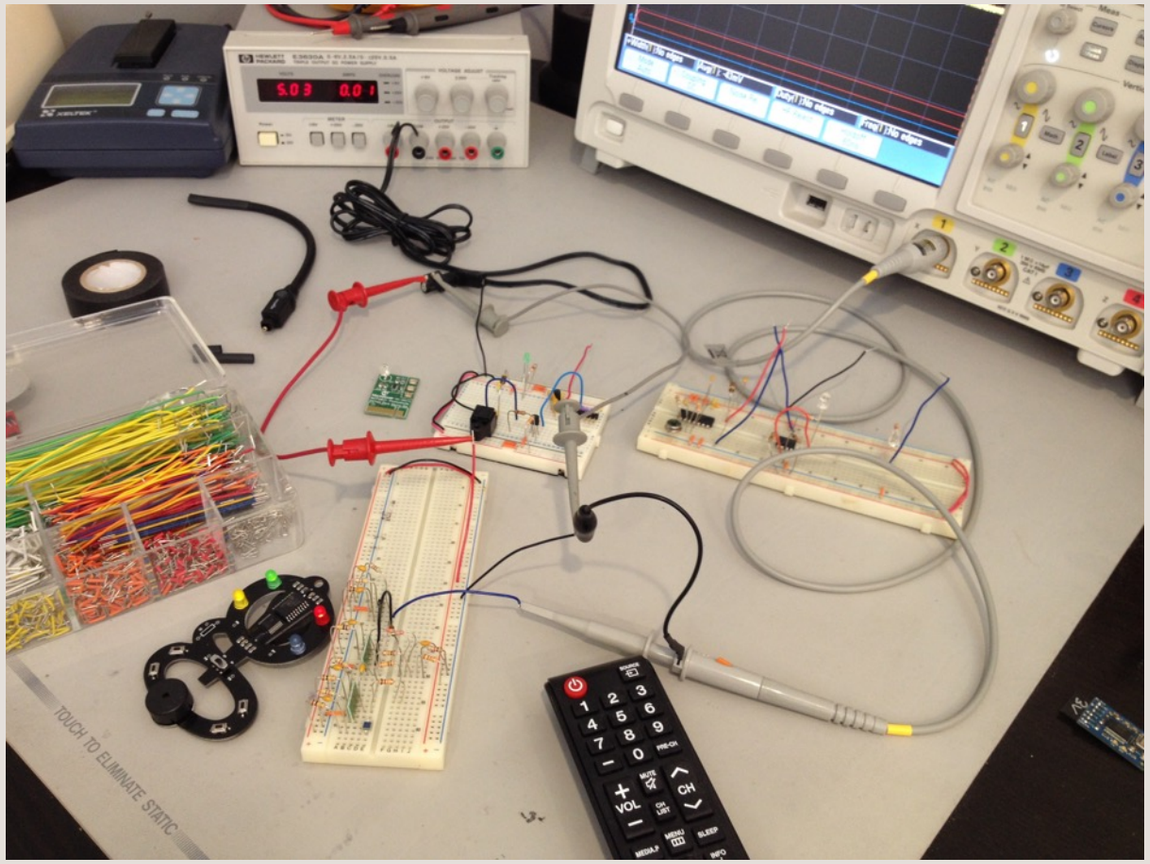
Related Projects

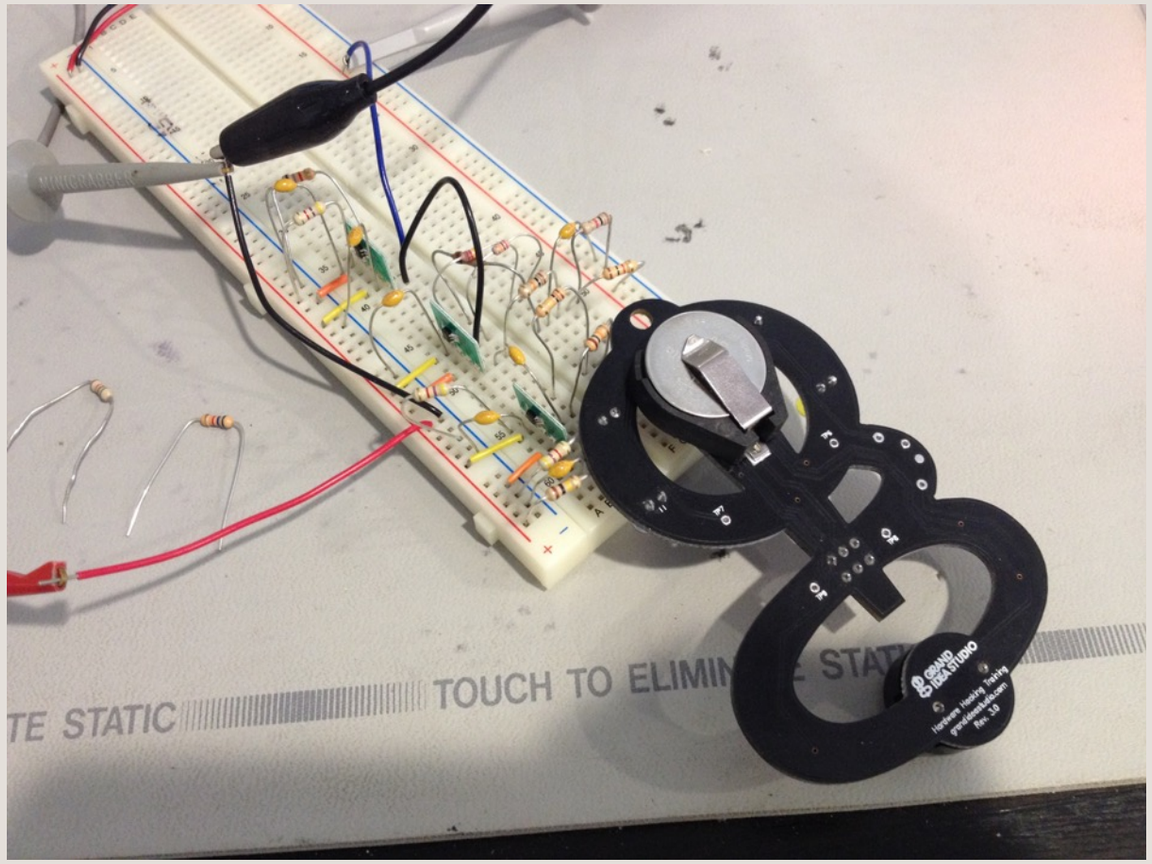
- Heathkit Laser Trainer/Receiver (1985)
- Engineer's Mini Notebook: Optoelectronics Circuits (Forest Mims III, 1985)
- IRis (Craig Heffner, 2016)
- See no evil, hear no evil: Hacking invisibly & silently with light & sound (Matt Wixey, 2017)

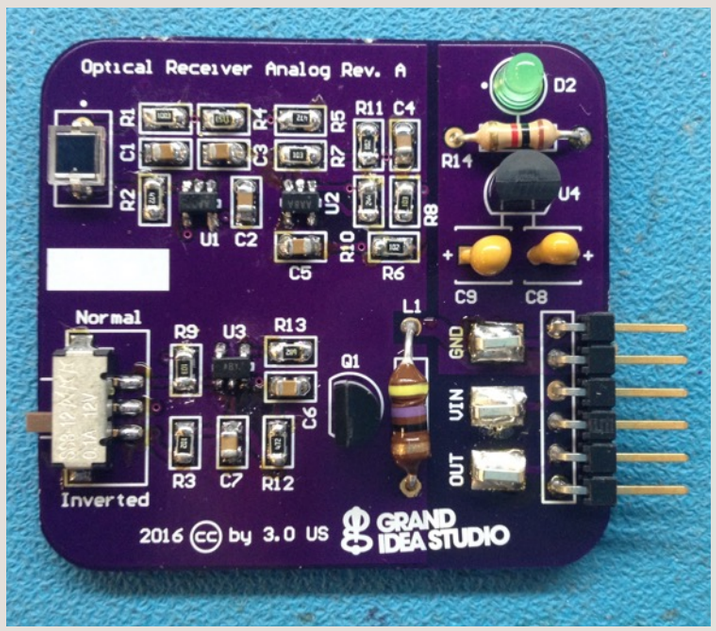
Design Goals

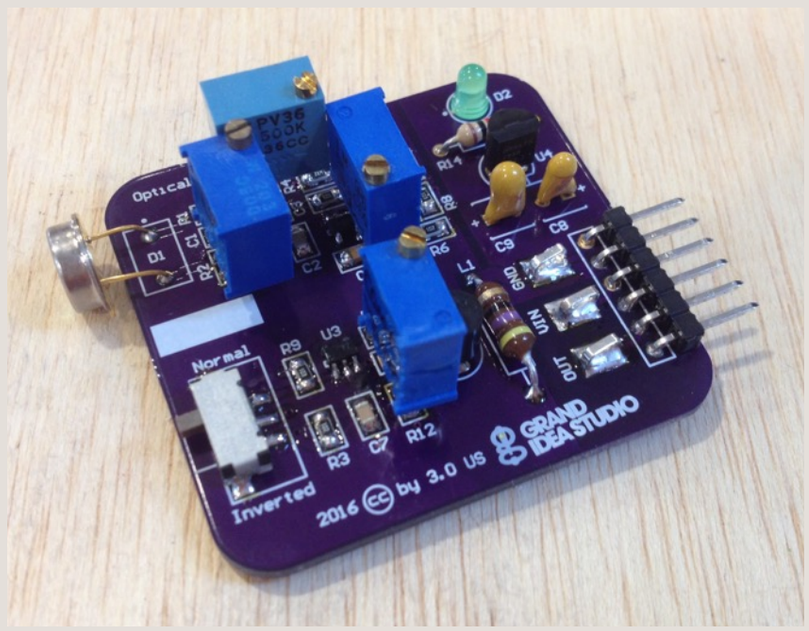
- Open source tool for optoelectronic experimentation
  - Easy to understand theory
  - Off-the-shelf components
  - Hand solderable
- Raise awareness of other interesting communication/ exfiltration methods

Early Versions

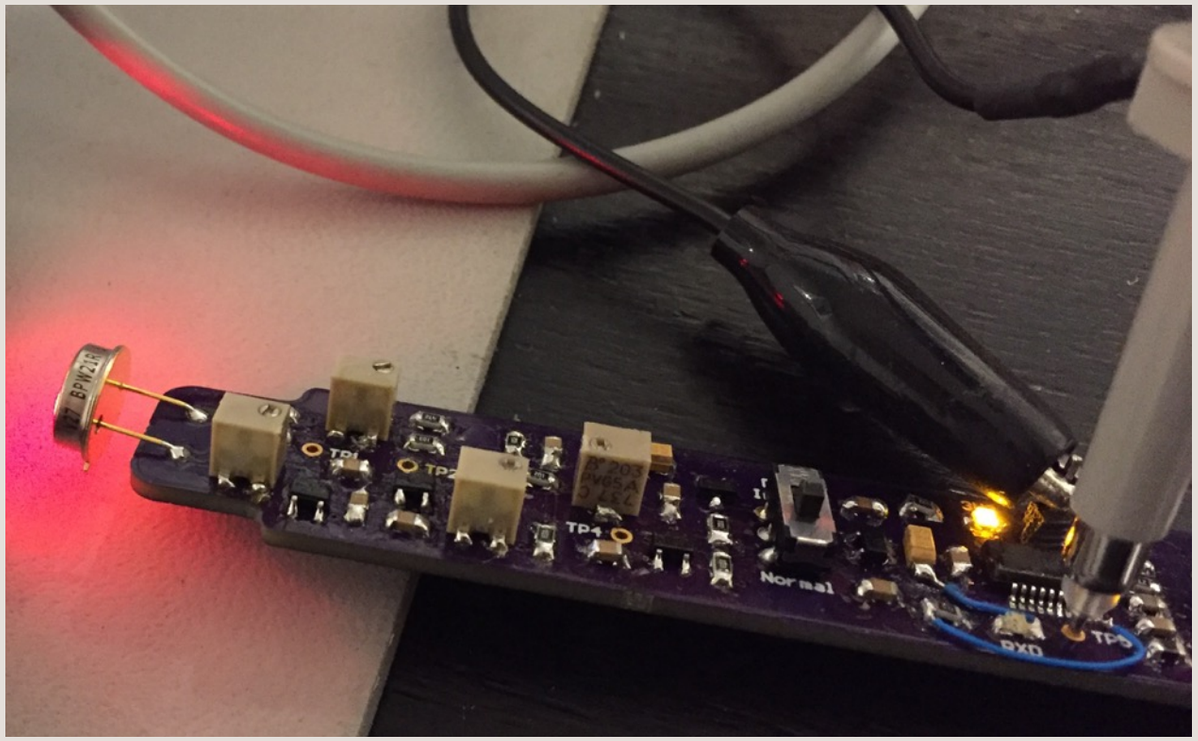


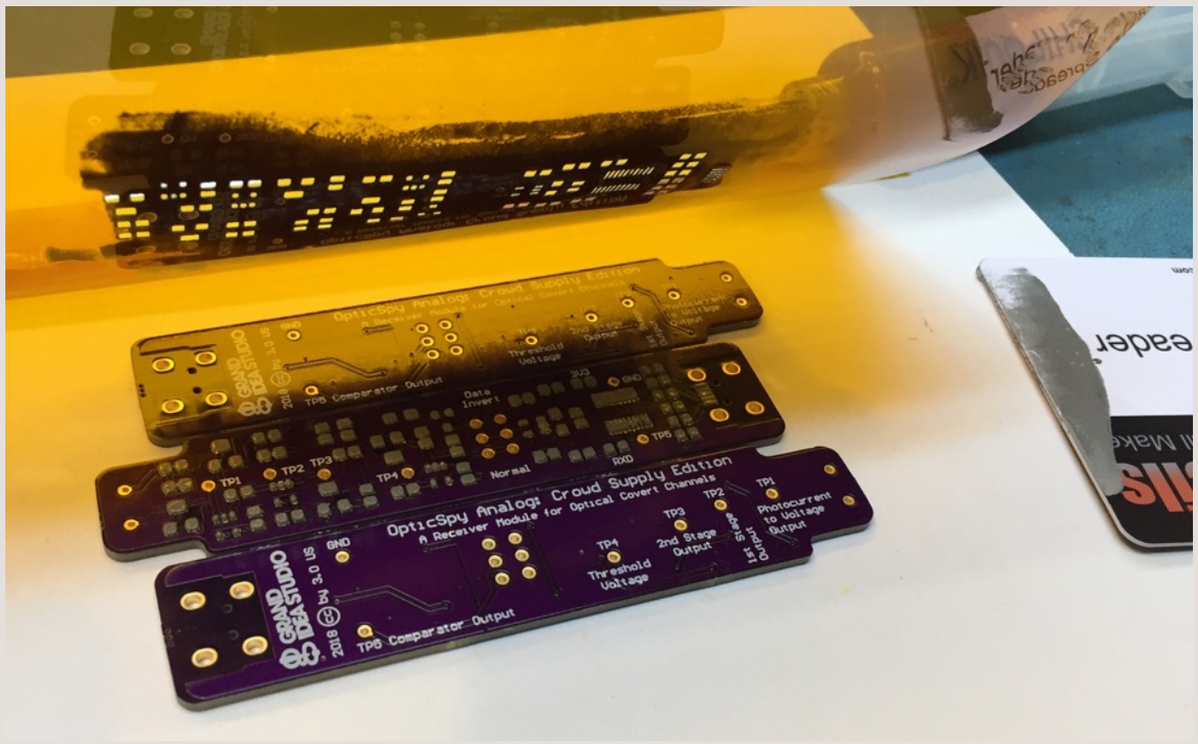




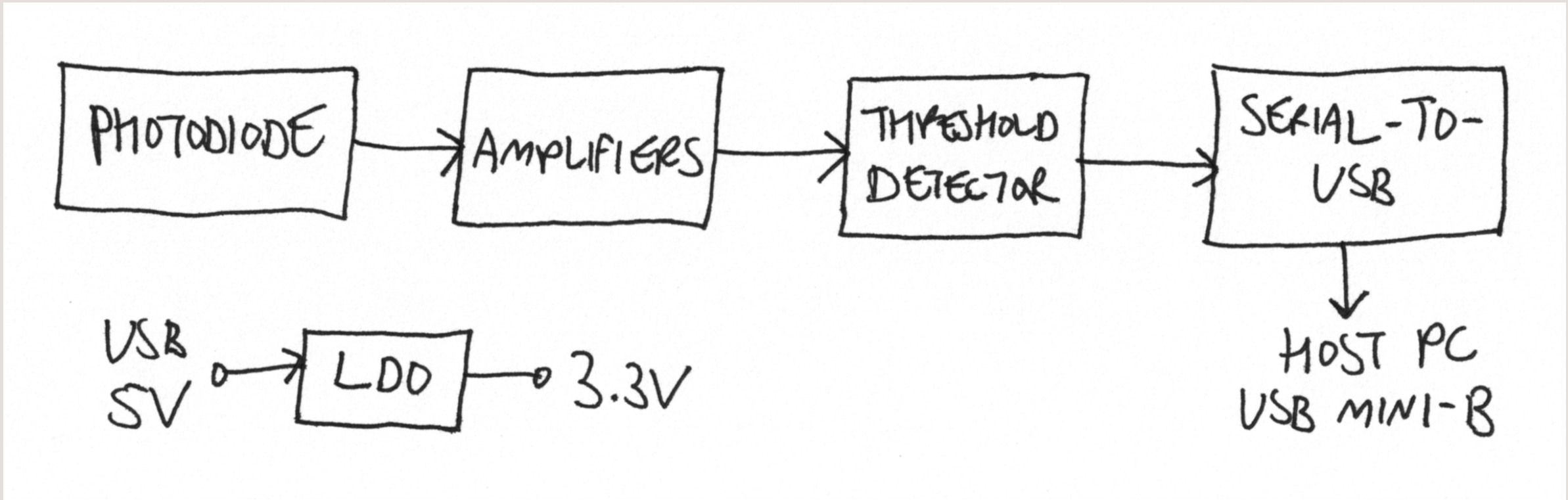


Development

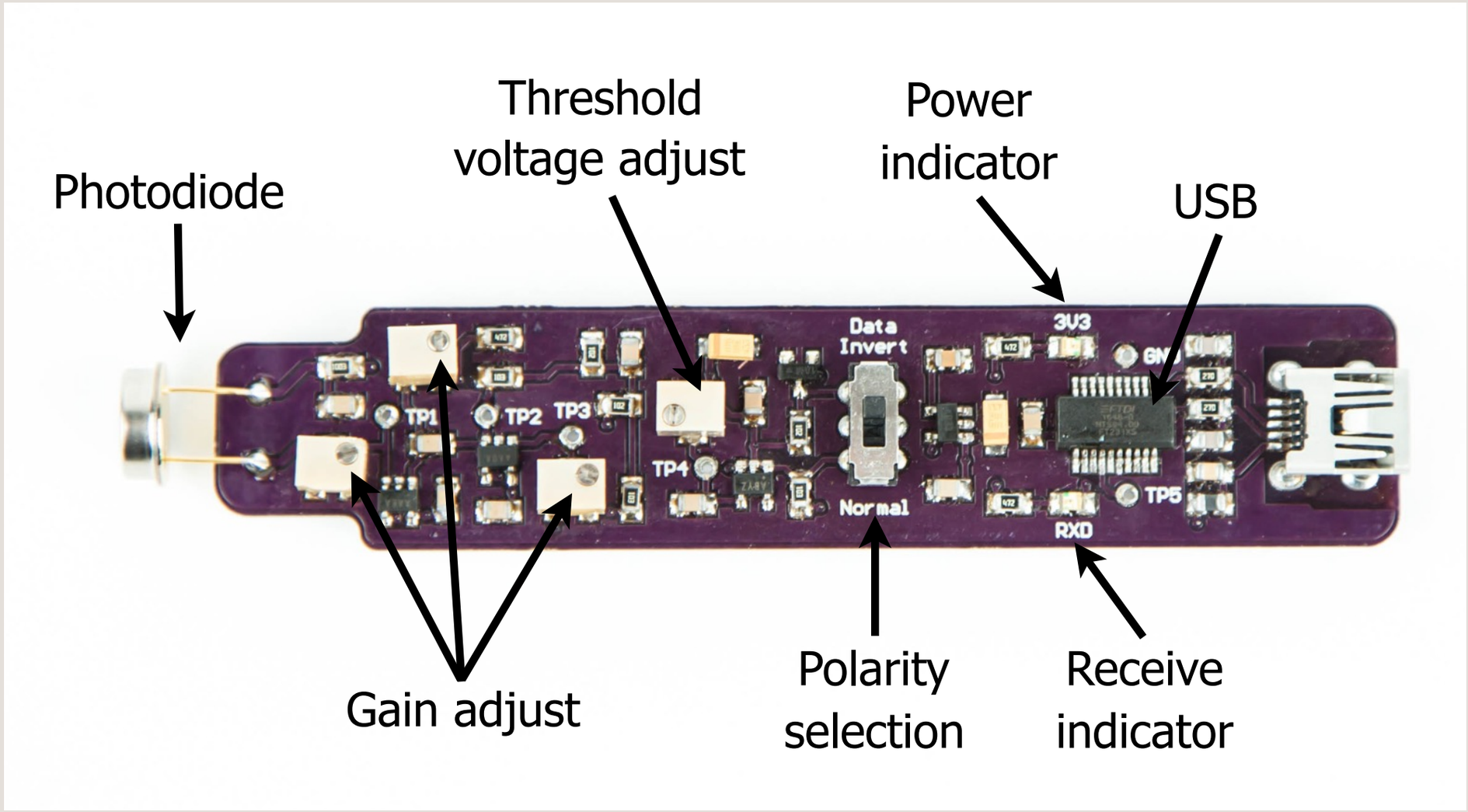




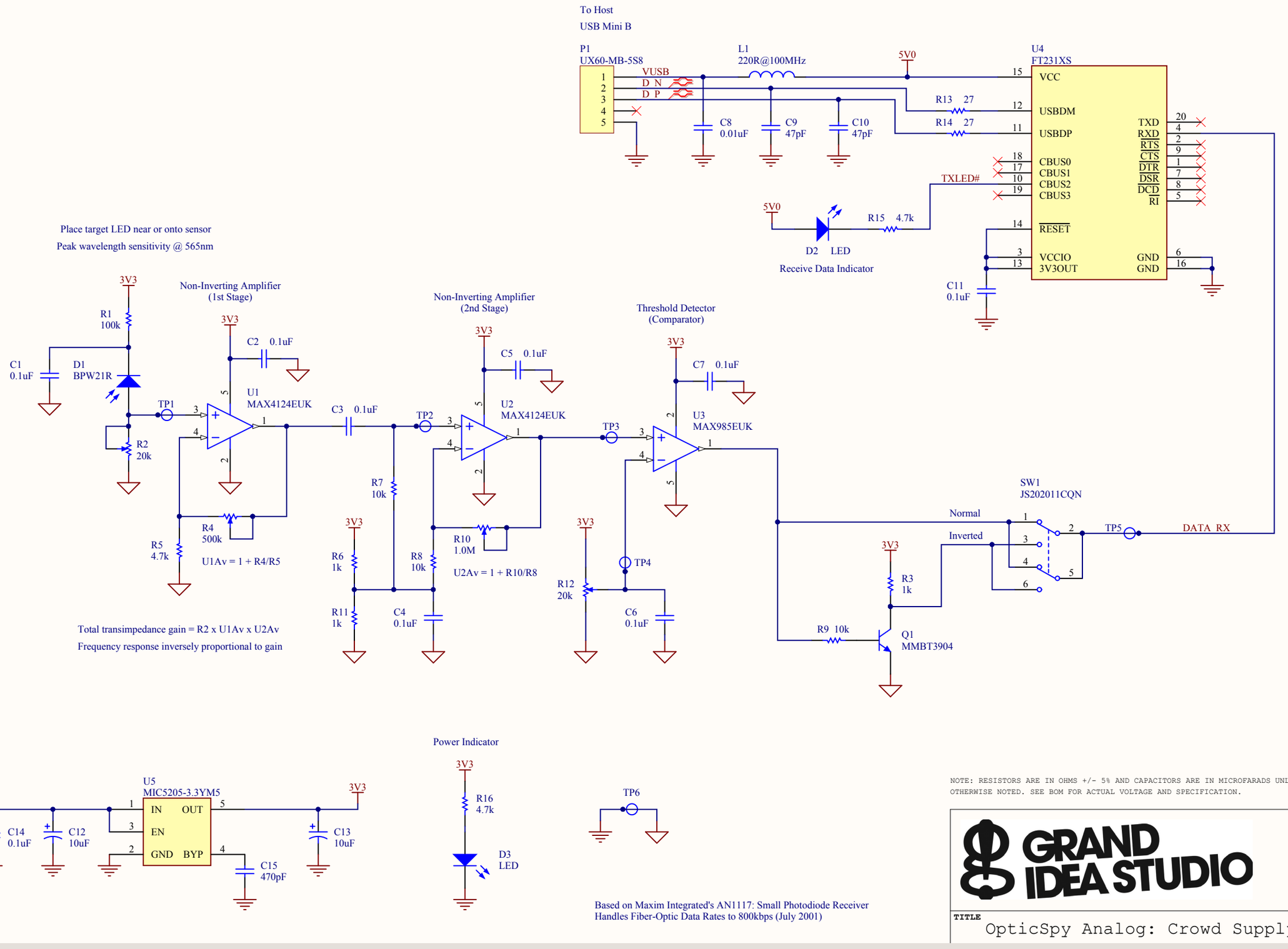
Block Diagram



Points of Interest



Schematic



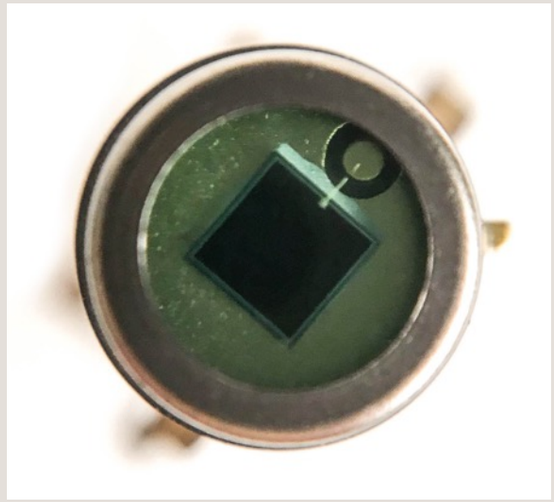
NOTE: RESISTORS ARE IN OHMS +/- 5% AND CAPACITORS ARE IN MICROFARADS UNLESS OTHERWISE NOTED. SEE BOM FOR ACTUAL VOLTAGE AND SPECIFICATION.

GRAND IDEA STUDIO

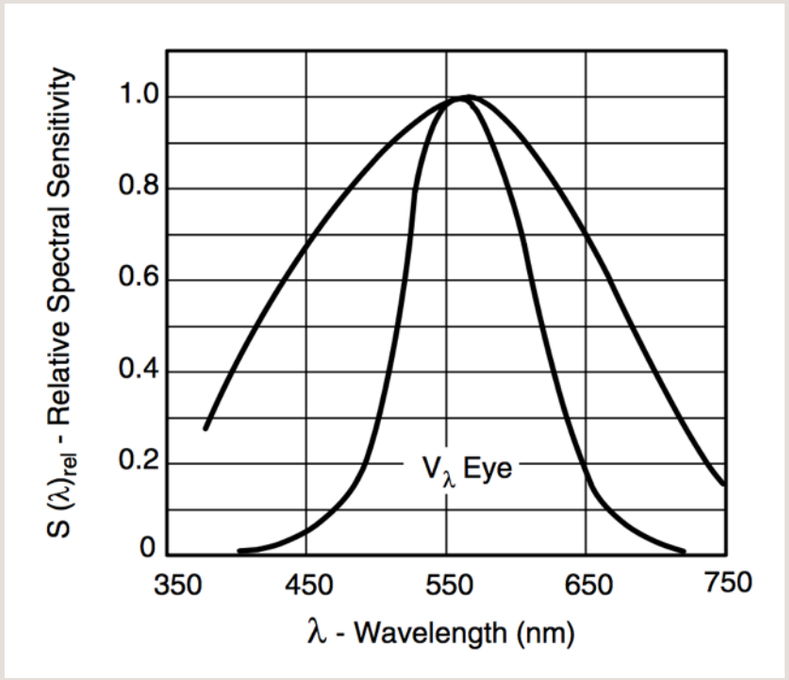
TITLE

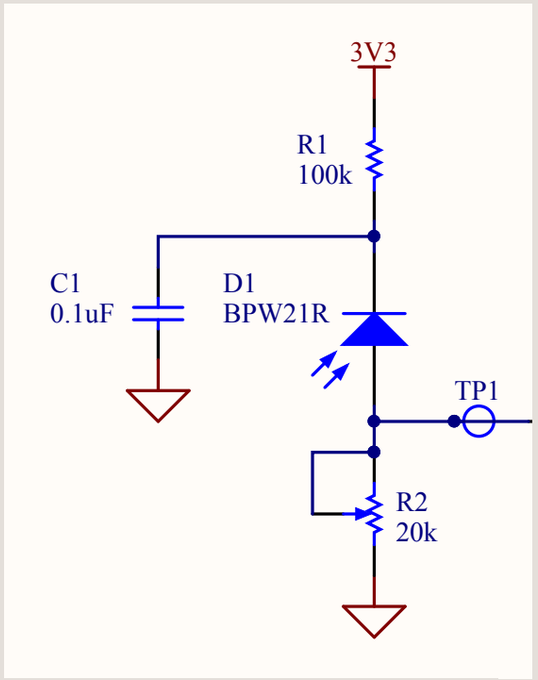
OpticSpy Analog: Crowd Supply

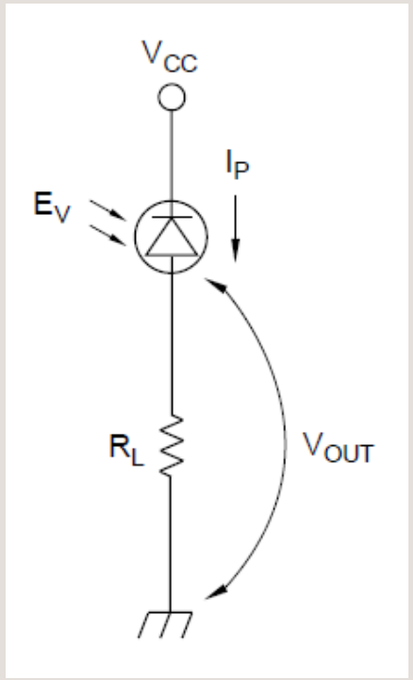
Photodiode



- Vishay Semiconductor BPW21R
- Converts light into current
- Photoconductive mode (reverse bias)
  - Faster response -> higher bandwidth
  - Less sensitivity, increased dark current
- Bias resistor affects response/sensitivity

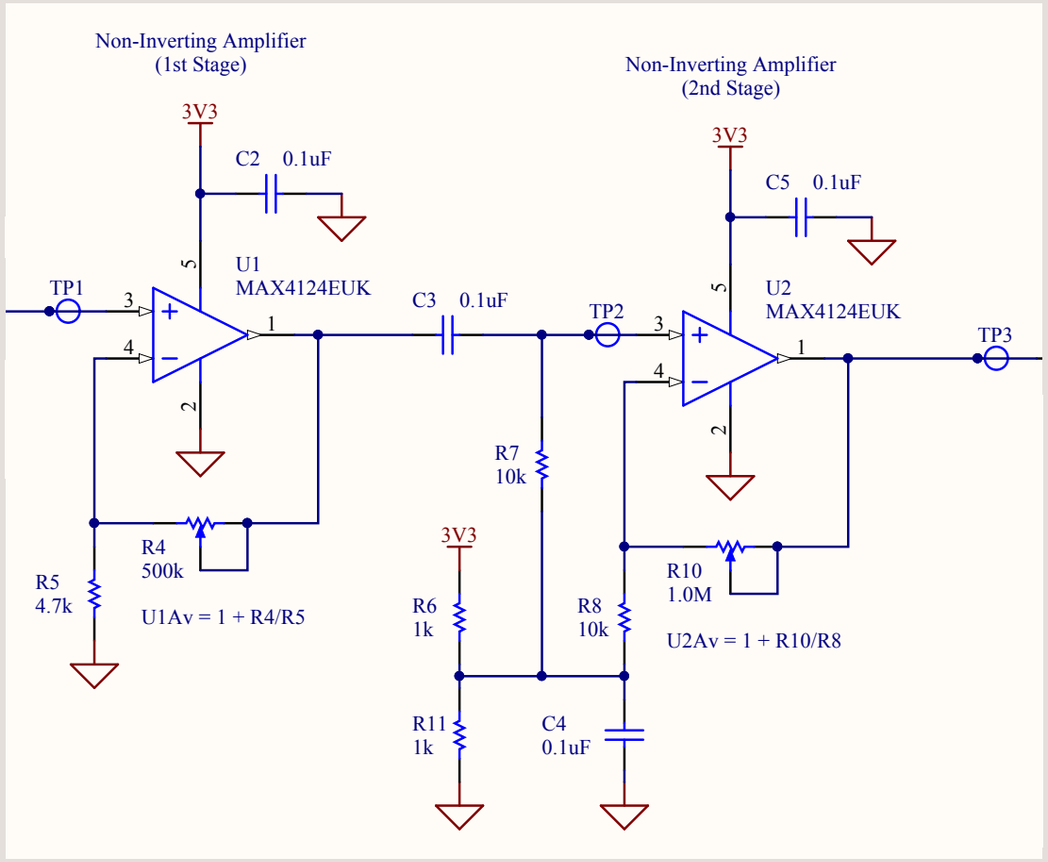






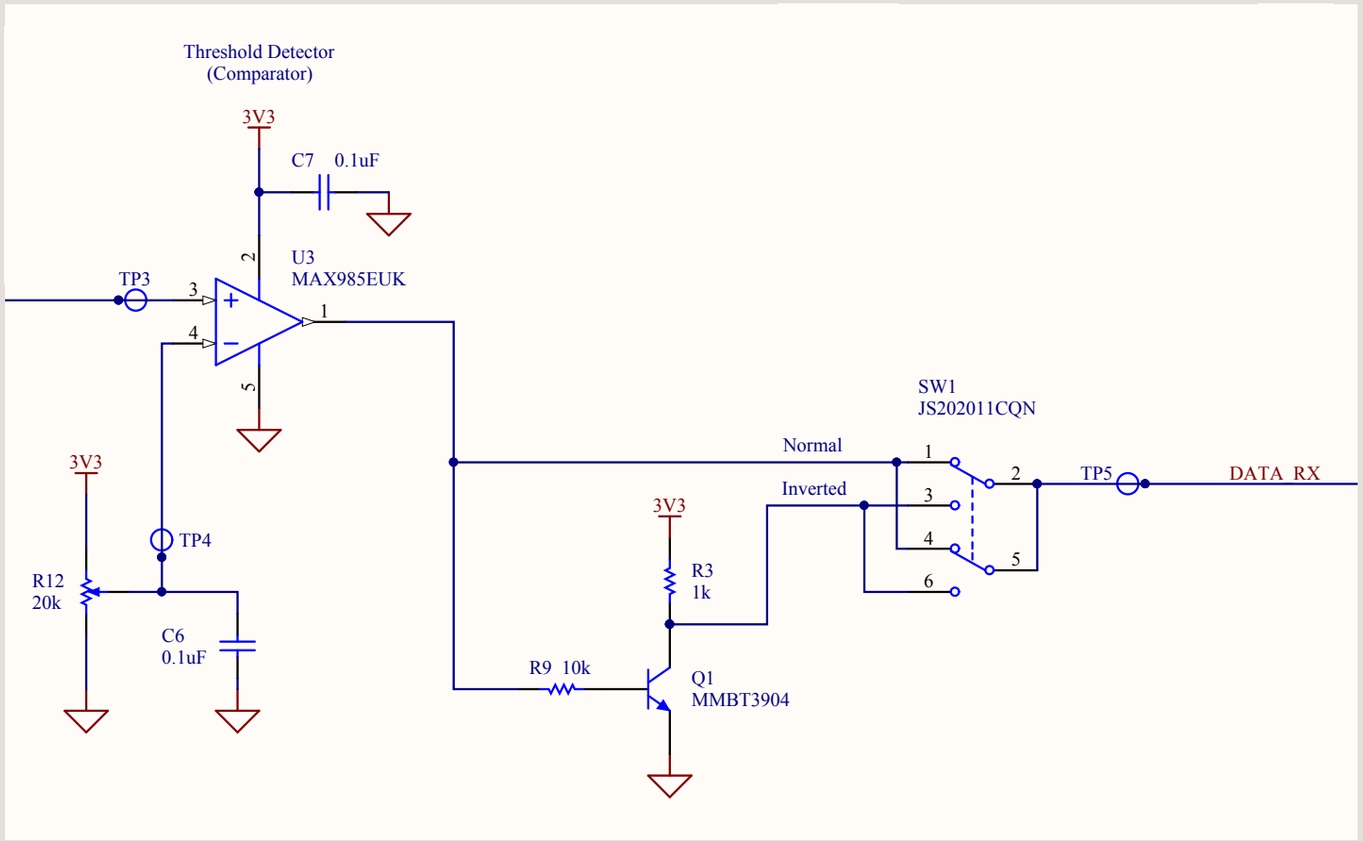
Amplification

- Maxim MAX4124 Wide Bandwidth, Low Power, Rail-to-Rail Operational Amplifier
- Two stages w/ signal massaging in between
  - Lower gain per stage -> less overall noise
- Total transimpedance gain = R2 x U1Av x U2Av



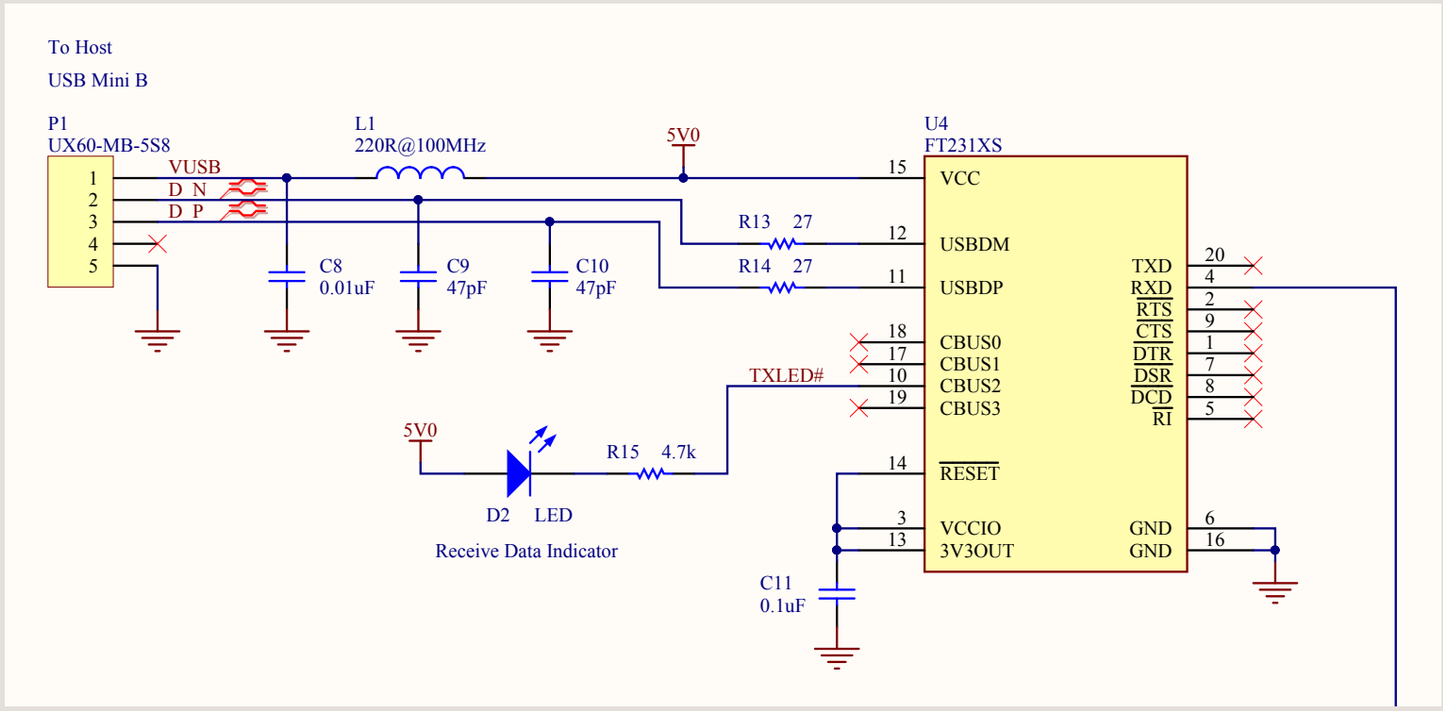
Comparator

- Maxim MAX985 Micropower, Low Voltage, Rail-to-Rail Comparator
- Determine what portion of signal treated as logic level '0' or '1'
- Adjustable threshold voltage w/ potentiometer R12

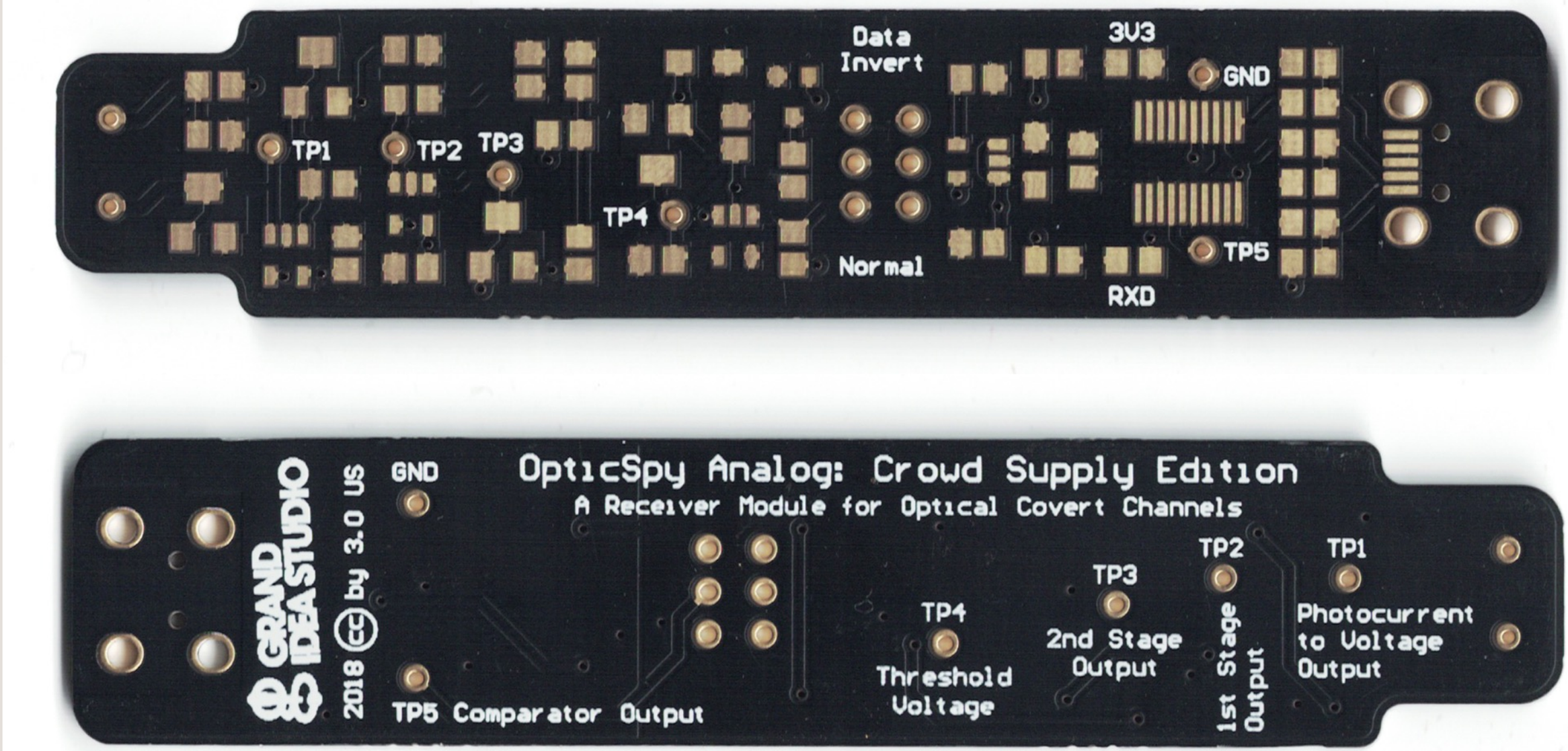


USB Interface

- Powers OpticSpy from bus (5V)
- FTDI FT231X USB-to-Serial UART
  - Entire USB protocol handled on-chip
  - Host will recognize as a virtual serial port (Windows, OS X, Linux)
- Decode asynchronous data streams and pass to host PC



PCB


Data
Invert
3V3
GND
TP1
TP2
TP3
TP4
TP5
Normal
RXD
OpticSpy Analog: Crowd Supply Edition
A Receiver Module for Optical Covert Channels
GRAND IDEA STUDIO
2018 CC by 3.0 US
GND
TP5 Comparator Output
TP4
Threshold Voltage
TP3
2nd Stage Output
TP2
1st Stage Output
TP1
Photocurrent to Voltage Output

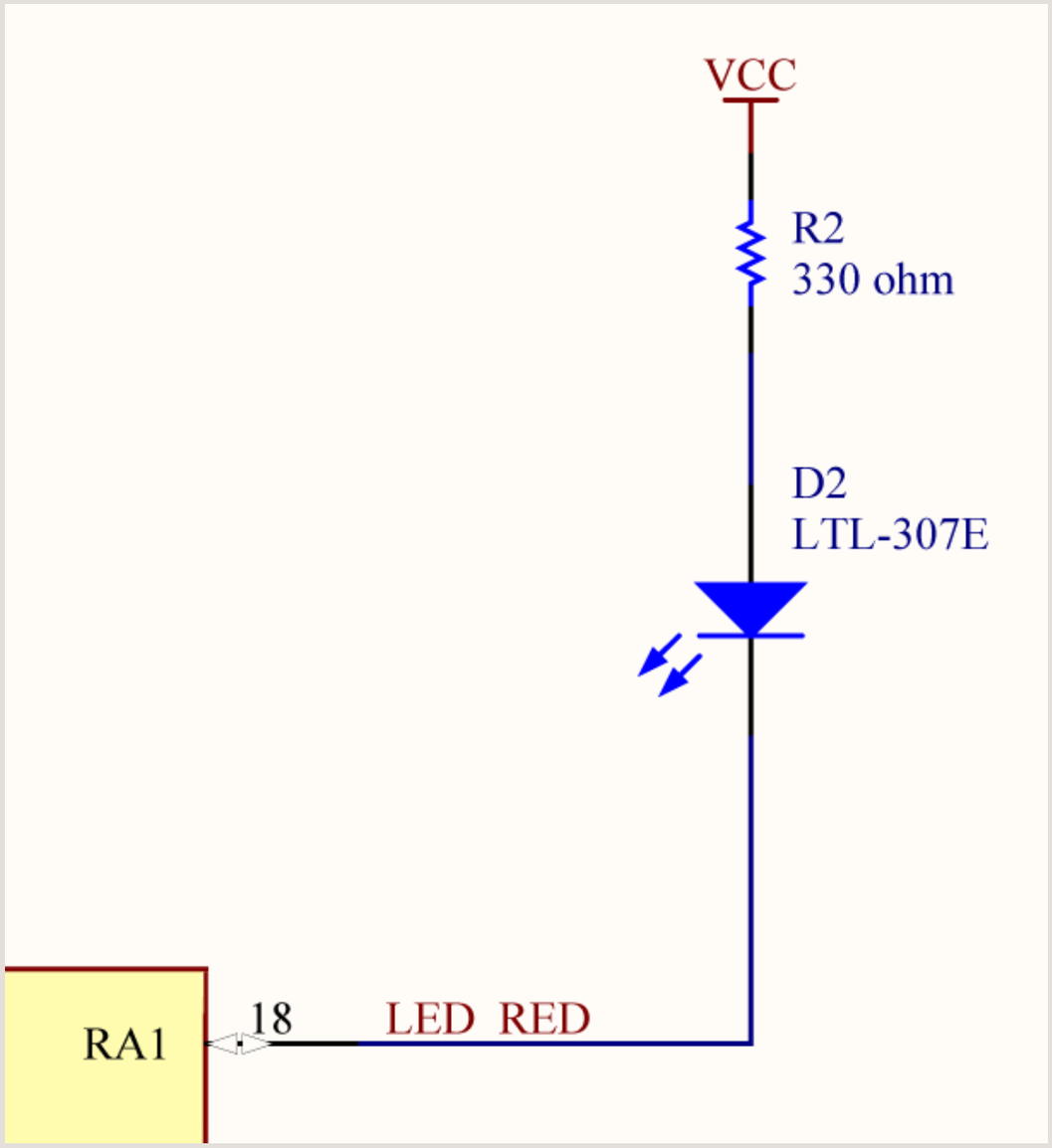
Bill-of-Materials

Item	Quantity	Reference	Manufacturer	Manuf. Part #	Distributor	Distrib. Part #	Description
1	9	C1, C2, C3, C4, C5, C6, C7, C11, C14	Kemet	C0805C104K5RACTU	Digi-Key	399-1170-1-ND	Capacitor, 0.1uF, 50V, Ceramic, 10%, X7R, 0805
2	1	C8	Kemet	C0805C103K5RACTU	Digi-Key	399-1158-1-ND	Capacitor, 0.01uF, 50V, Ceramic, 10%, X7R, 0805
3	2	C9, C10	Samsung	CL21C470JBANNNC	Digi-Key	1276-1156-1-ND	Capacitor, 47pF, 50V, Ceramic, 5%, C0G, 0805
4	2	C12, C13	Vishay Sprague	293D106X0016A2TE3	Digi-Key	718-1956-1-ND	Capacitor, 10uF, 16V, Tantalum, 20%, Size A
5	1	C15	Yageo	CC0805KRX7R9BB471	Digi-Key	311-1124-1-ND	Capacitor, 470pF, 50V, Ceramic, 10%, X7R, 0805
6	1	D1	Vishay Semiconductor	BPW21R	Digi-Key	751-1013-ND	Photodiode, Silicon PN, 420-675nm, TO-5
7	2	D2, D3	Kingbright	APT2012SYCK	Digi-Key	754-1134-1-ND	LED, Yellow clear, 150mcd, 2.0Vf, 590nm, 0805
8	1	L1	TDK	MPZ2012S221AT000	Digi-Key	445-1568-1-ND	Inductor, Ferrite Bead, 220R @ 100MHz, 3A, 0805
9	1	P1	Hirose Electric	UX60-MB-5S8	Digi-Key	H2960CT-ND	Connector, Mini-USB, 5-pin, SMT w/ PCB mount
10	1	Q1	ON Semiconductor	MMBT3904	Digi-Key	MMBT3904FSCT-ND	Transistor, NPN, 40V, 200mA, SOT23-3
11	1	R1	Any	Any	Digi-Key	P100KACT-ND	Resistor, 100k, 5%, 1/8W, 0805
12	2	R2, R12	Bourns	PVG5A203C03R00	Digi-Key	490-2667-1-ND	Resistor, Variable Trimmer, 20k, 1/8W, SMD
13	3	R3, R6, R11	Any	Any	Digi-Key	P1.0KACT-ND	Resistor, 1k, 5%, 1/8W, 0805
14	1	R4	Bourns	PVG5A504C03R00	Digi-Key	490-2674-1-ND	Resistor, Variable Trimmer, 500k, 1/8W, SMD
15	3	R5, R15, R16	Any	Any	Digi-Key	P4.7KACT-ND	Resistor, 4.7k, 5%, 1/8W, 0805
16	3	R7, R8, R9	Any	Any	Digi-Key	P10KACT-ND	Resistor, 10k, 5%, 1/8W, 0805
17	1	R10	Bourns	PVG5A105C03R00	Digi-Key	490-2663-1-ND	Resistor, Variable Trimmer, 1.0M, 1/8W, SMD
18	2	R13, R14	Any	Any	Digi-Key	P27ACT-ND	Resistor, 27 ohm, 5%, 1/8W, 0805
19	1	SW1	C&K Components	JS202011CQN	Digi-Key	401-2001-ND	Switch, DPDT slide, 300mA @ 6VDC, PCB mount
20	2	U1, U2	Maxim Integrated	MAX4124EUK+T	Digi-Key	MAX4124EUK+TCT-ND	IC, Operational Amplifier, Rail-to-Rail, SOT23-5
21	1	U3	Maxim Integrated	MAX985EUK+T	Digi-Key	MAX985EUK+TCT-ND	IC, Comparator, Push-Pull, Rail-to-Rail, SOT23-5
22	1	U4	FTDI	FT231XS-R	Digi-Key	768-1129-1-ND	IC, USB-to-UART Bridge, SSOP20
23	1	U5	Microchip	MIC5205-3.3YM5	Digi-Key	576-1259-1-ND	Linear Regulator, LDO, 3.3V, 150mA, SOT23-5

- All components available from Digi-Key, Mouser
- Total cost per unit @ 100 quantity = ~$40.77
- High ticket items: Photodiode, op amp, comparator, potentiometers, PCB fab/assembly/test

Target Data Transmission

- Standard LED driver circuit



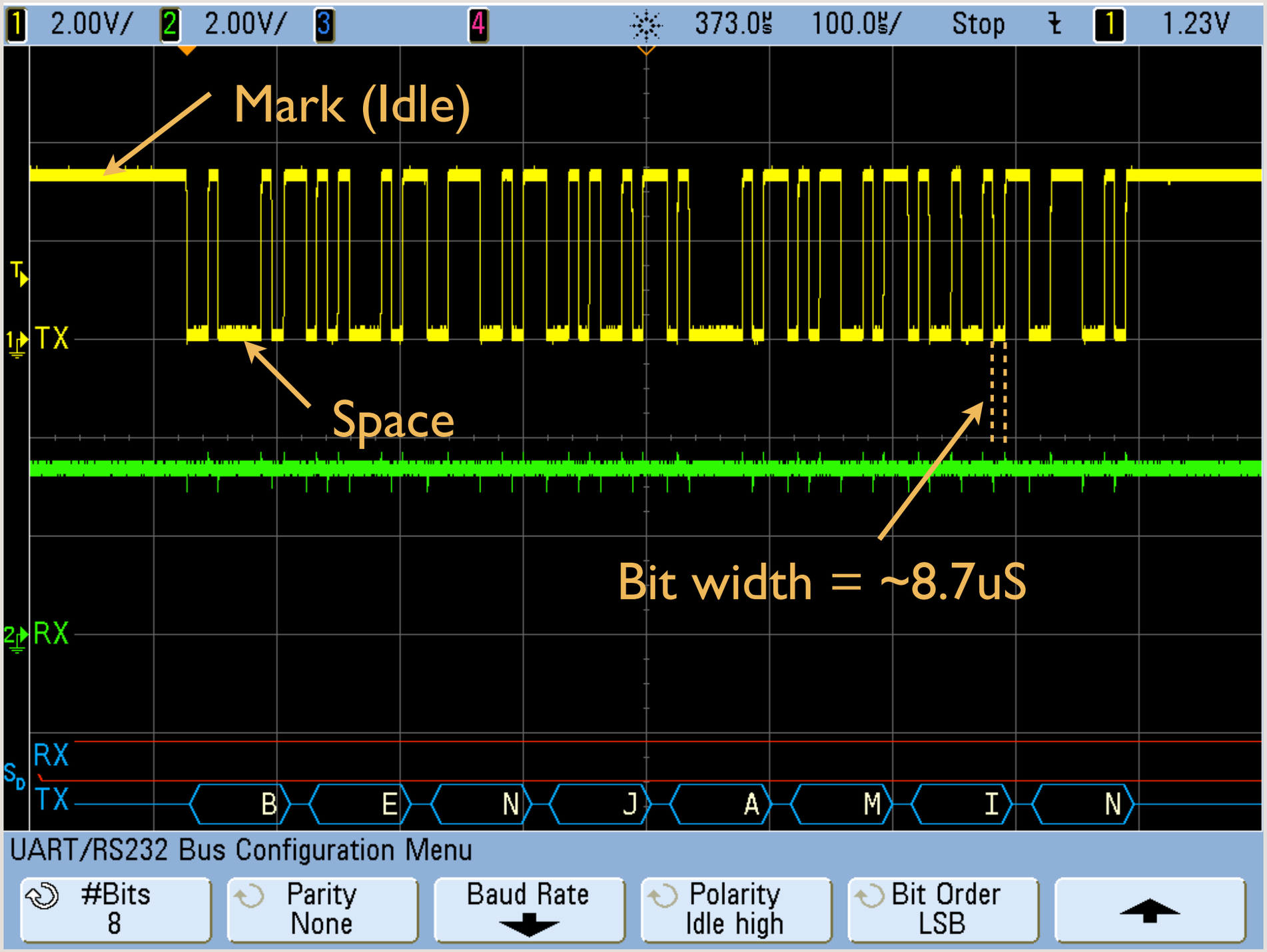
Target Data Transmission

- Asynchronous serial (UART)
  - No external clock needed
  - NRZ (Non-Return-To-Zero) coding
  - Transfer speed (baud rate) selectable
  - Data bits sent LSB first (D0)

1	2	3	4	5	6	7	8	9	10	11
Start bit	**5–8 data bits**								**Stop bit(s)**	
Start	Data 0	Data 1	Data 2	Data 3	Data 4	Data 5	Data 6	Data 7	Stop	

*** Start bit + Data bits + Parity (optional) + Stop bit(s)

Target Data Transmission



Target Data Transmission

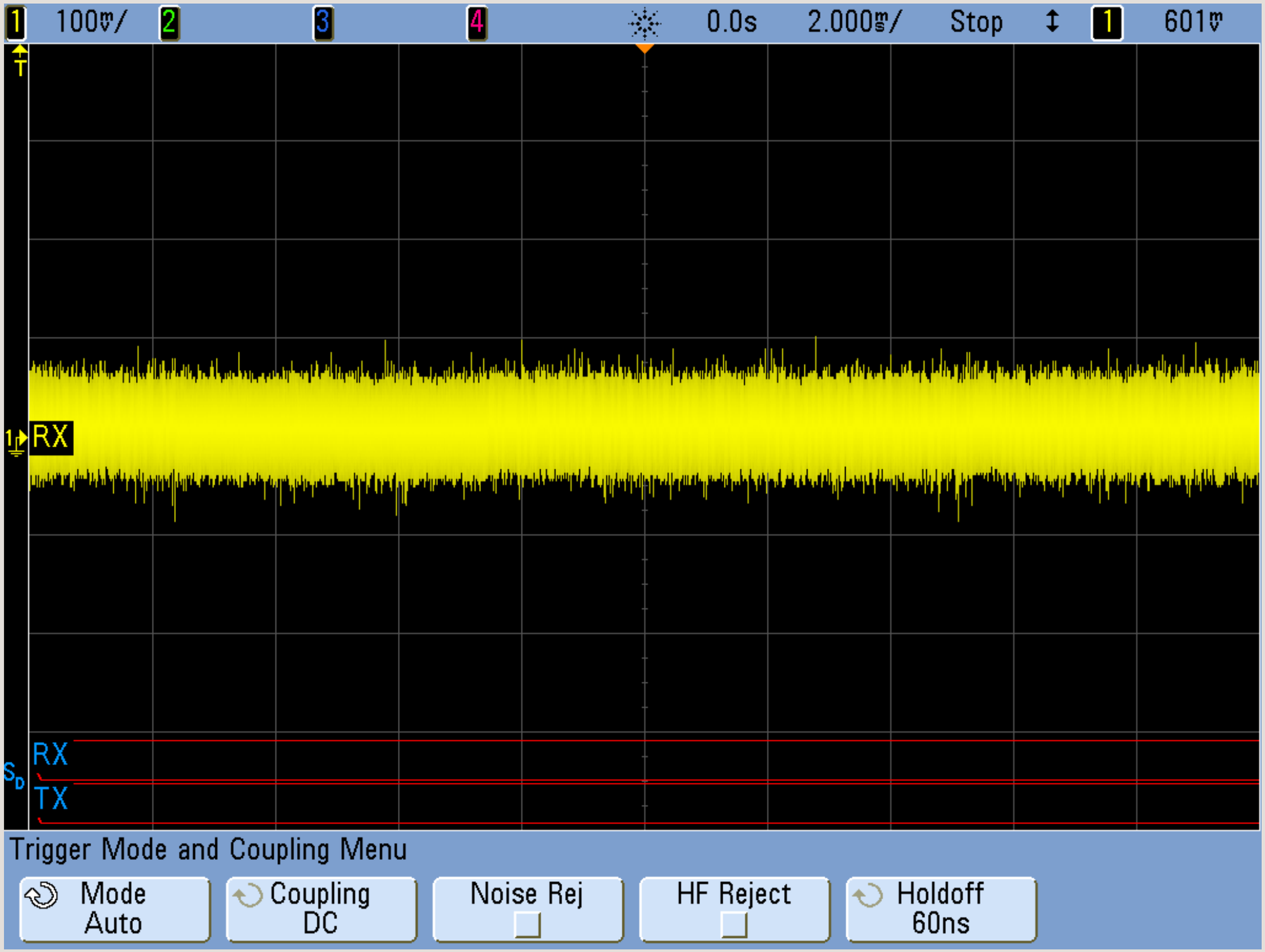
- Printable ASCII data via standard UART
- printf(message) or equivalent

```
while(1)
{
    #use delay(clock=4000000)
    #use rs232(baud=19200, parity=N, bits=8, xmit=LED_RED, force_sw, stream=LED)
    setup_oscillator(OSC_4MHZ | OSC_INTRC | OSC_PLL_OFF); // increase clock speed
    fprintf(LED, msg_covert); // transmit secret message through the LED
}
```

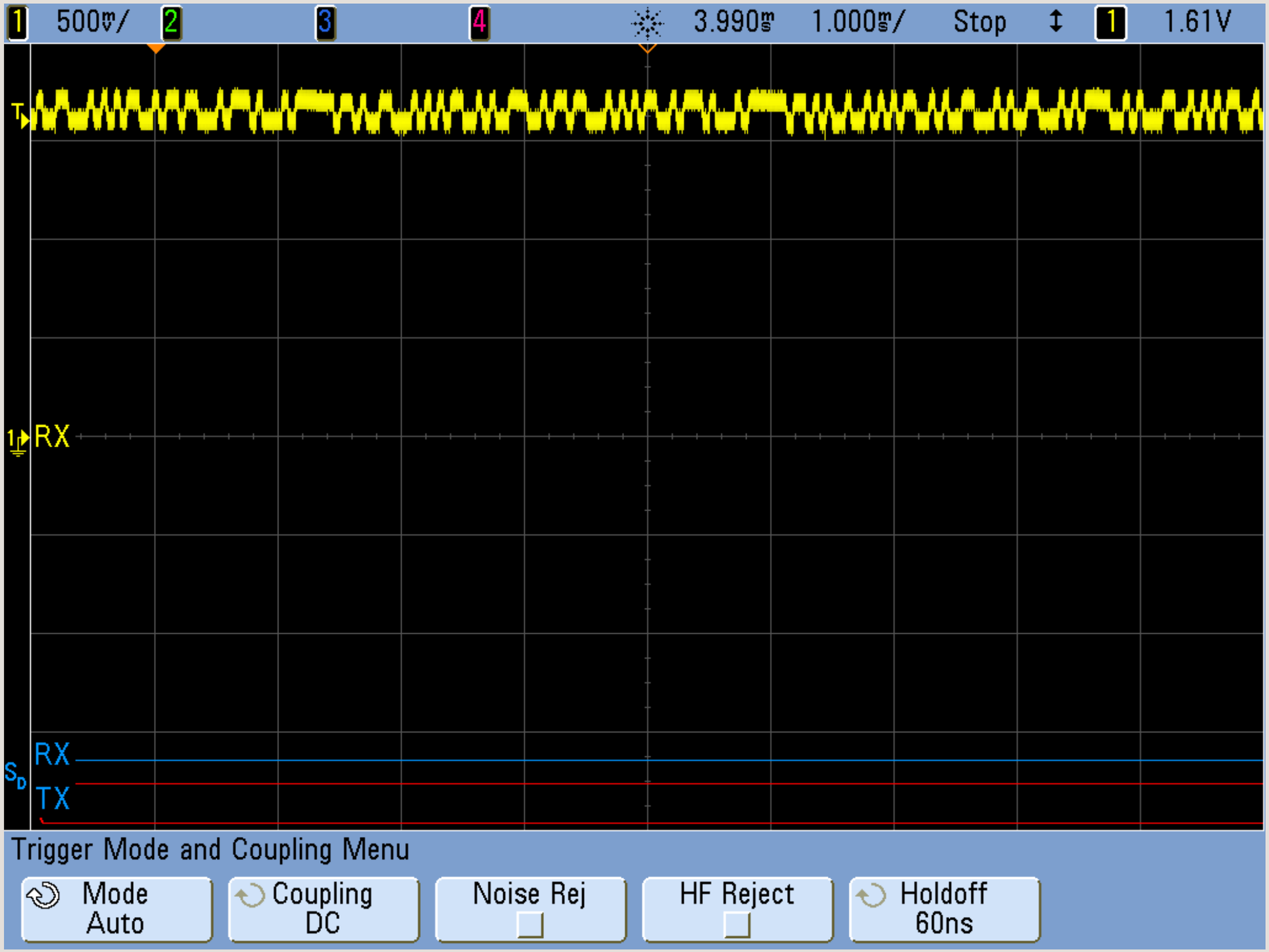
```
// Set up a new serial port
SoftwareSerial opticSerial =  SoftwareSerial(rxPin, txPin);

opticSerial.print(msg_covert); // Transmit secret message through the LED
opticSerial.flush();           // Wait for all bytes to be transmitted
```

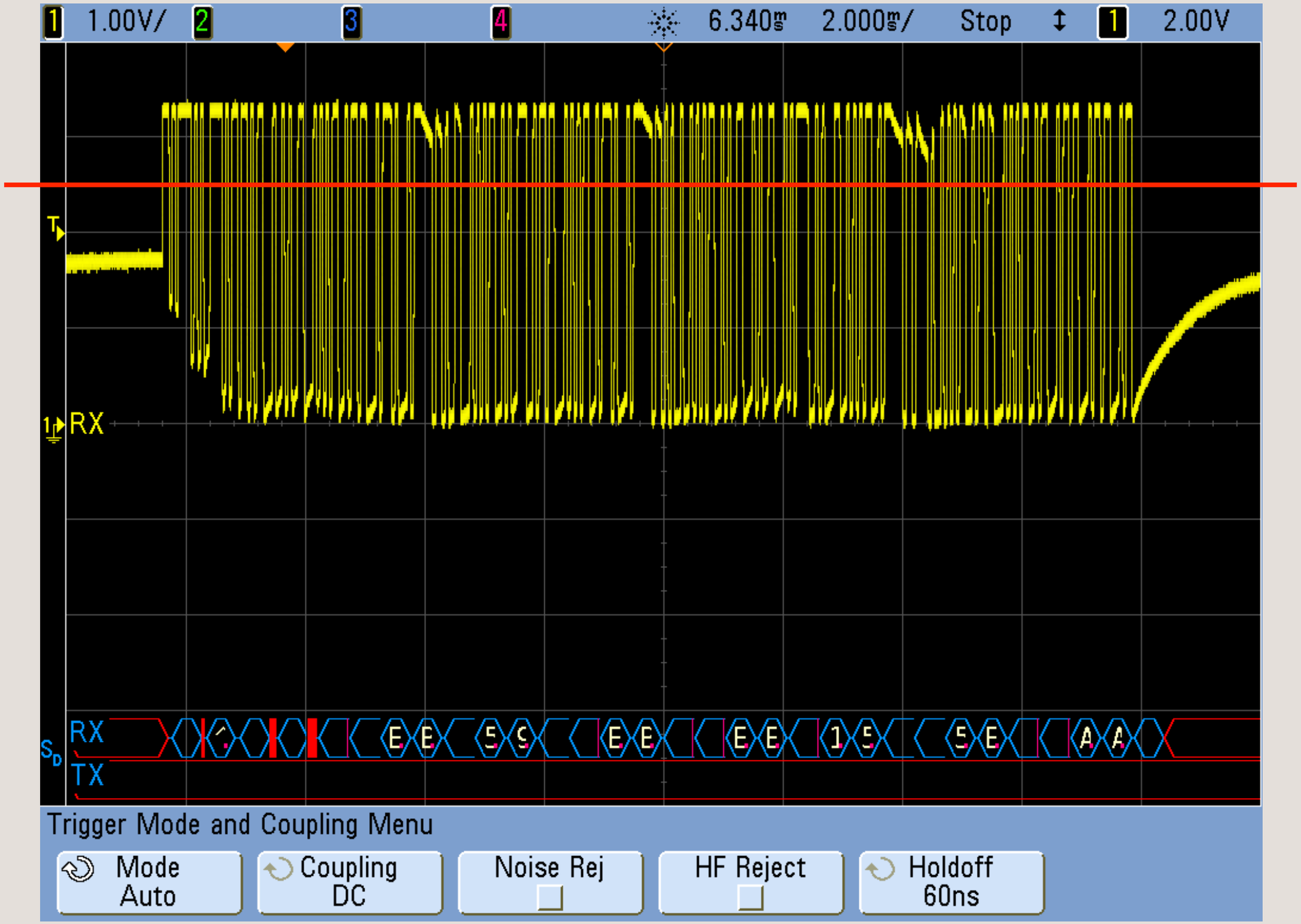
TP1: Photocurrent-to-Voltage



TP2: 1st Stage Amp Output

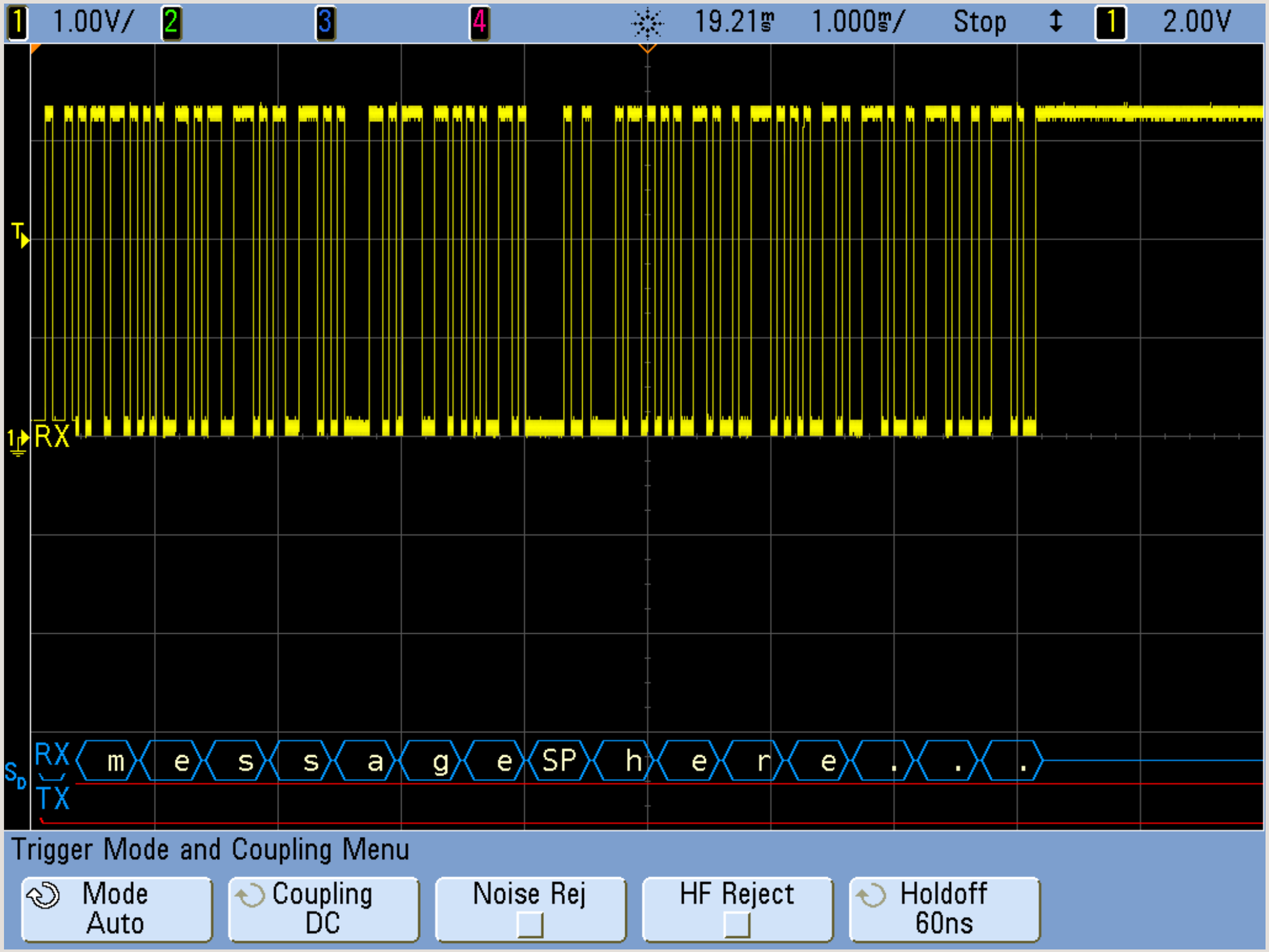


TP3: 2nd Stage Amp Output



TP5: Comparator Output

TP5: Comparator Output

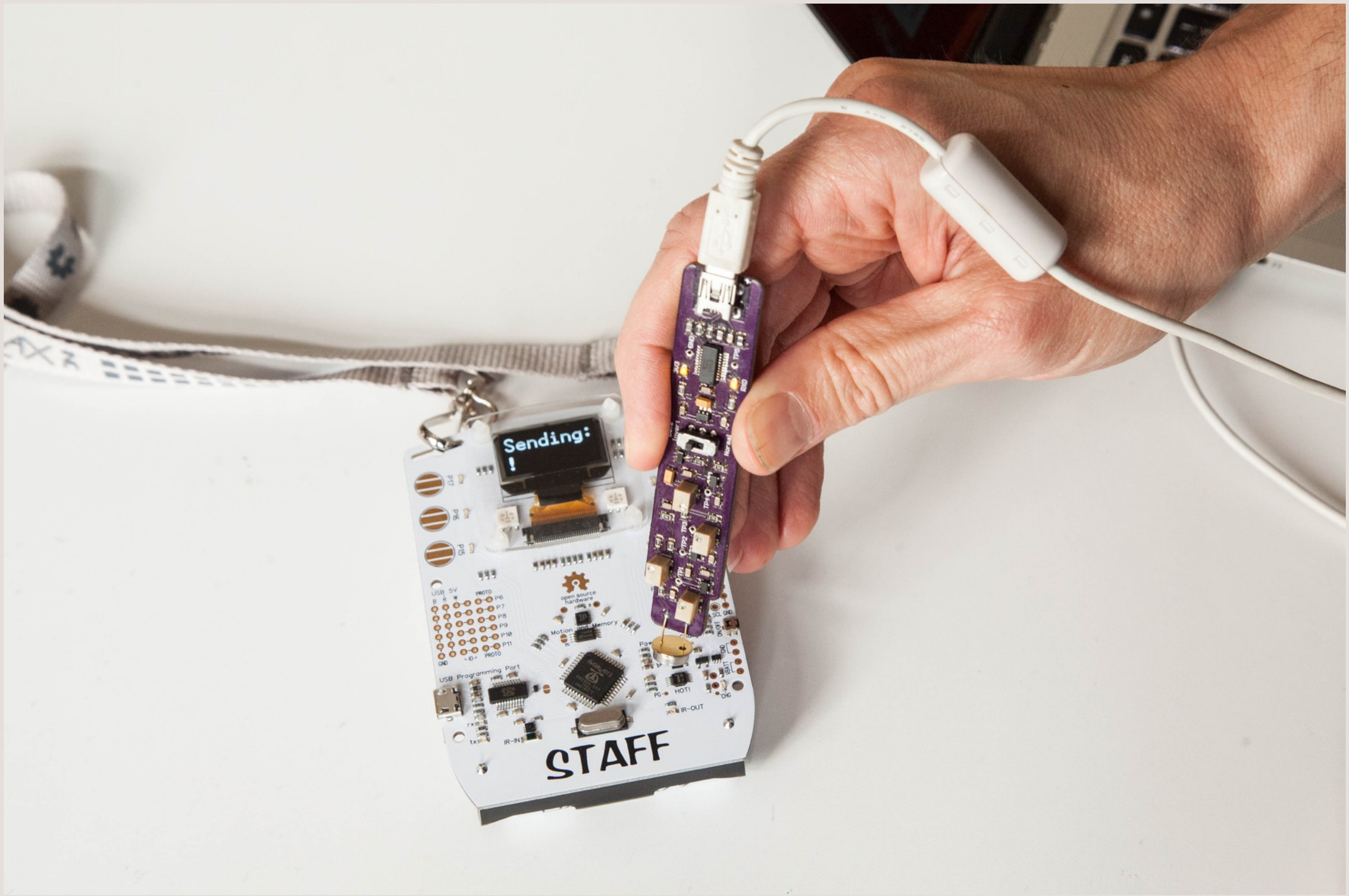


Calibration

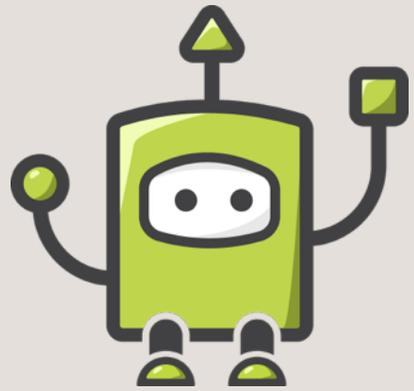
- Adjust settings for a particular target system
  - Reduce ambient noise
  - Increase receive distance
  - Change frequency response/bandwidth
  - Dependent on brightness and wavelength of transmitting signal
- Potentiometers
  - Gain adjustment (three stages)
    - Default setting @ mid-range -> 27.6MΩ
  - Threshold voltage adjustment (for comparator)
    - Set to 2.5V during production

Demonstrations

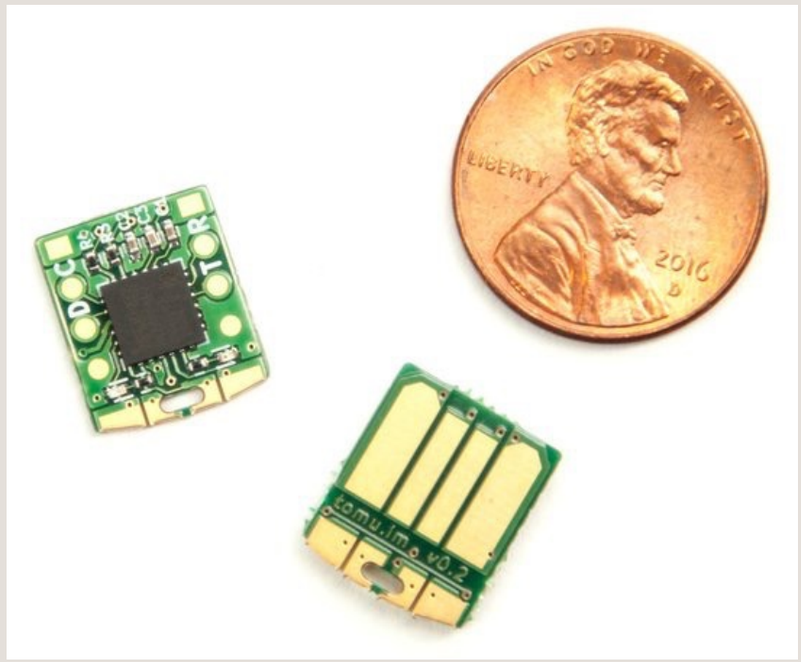
Parallax Electronic Badge

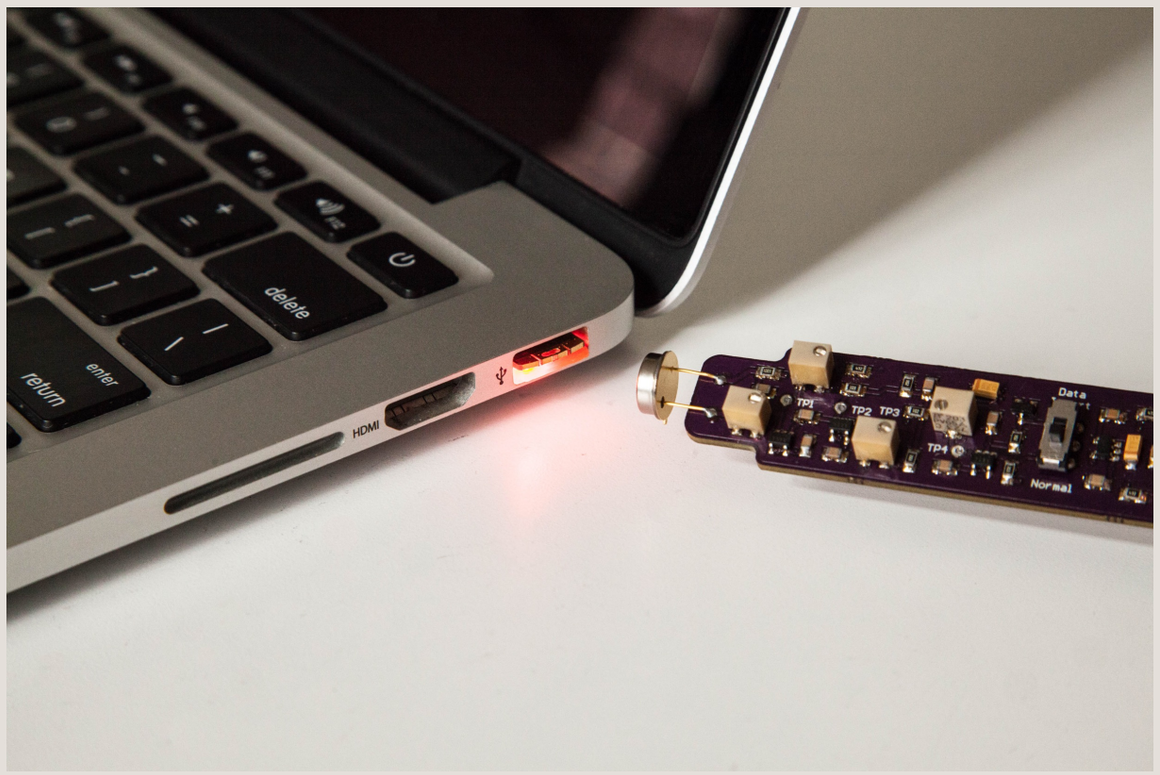


Tomu



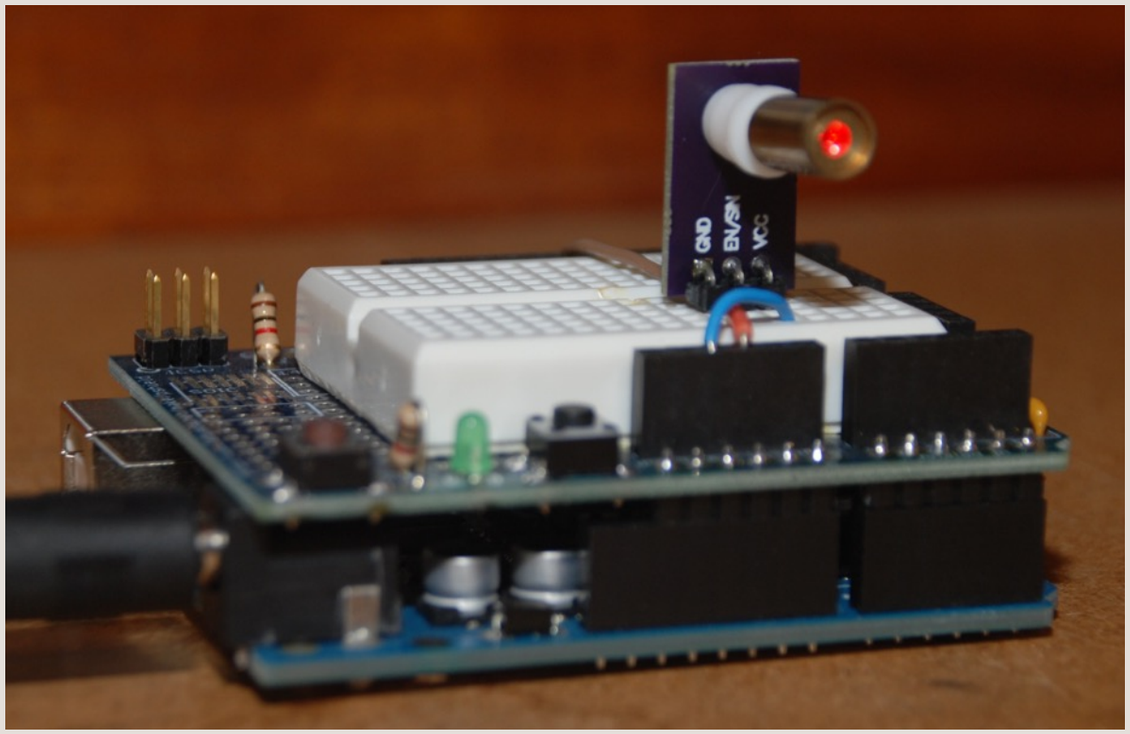
- Silicon Labs Happy Gecko EFM32HG309
- Total 12 components (incl. plastic case)
- 100% Open Source (w/ KiCad)
- http://tomu.im
- https://github.com/im-tomu/tomu-quickstart/tree/master/opticspy

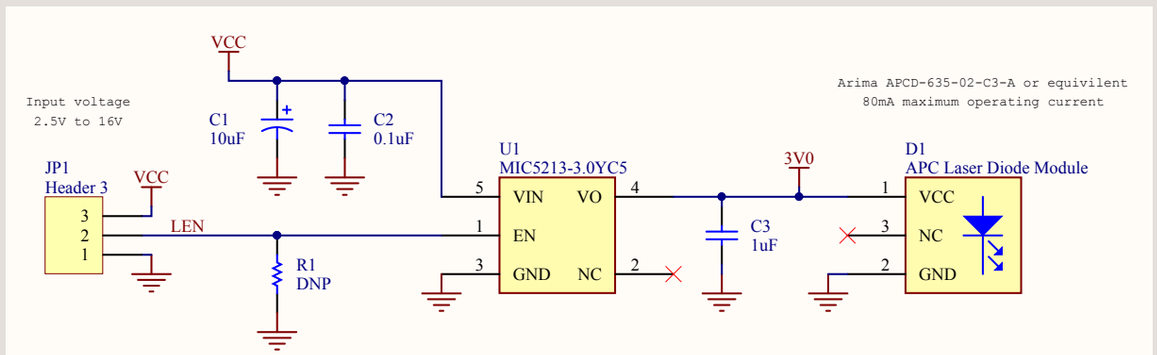


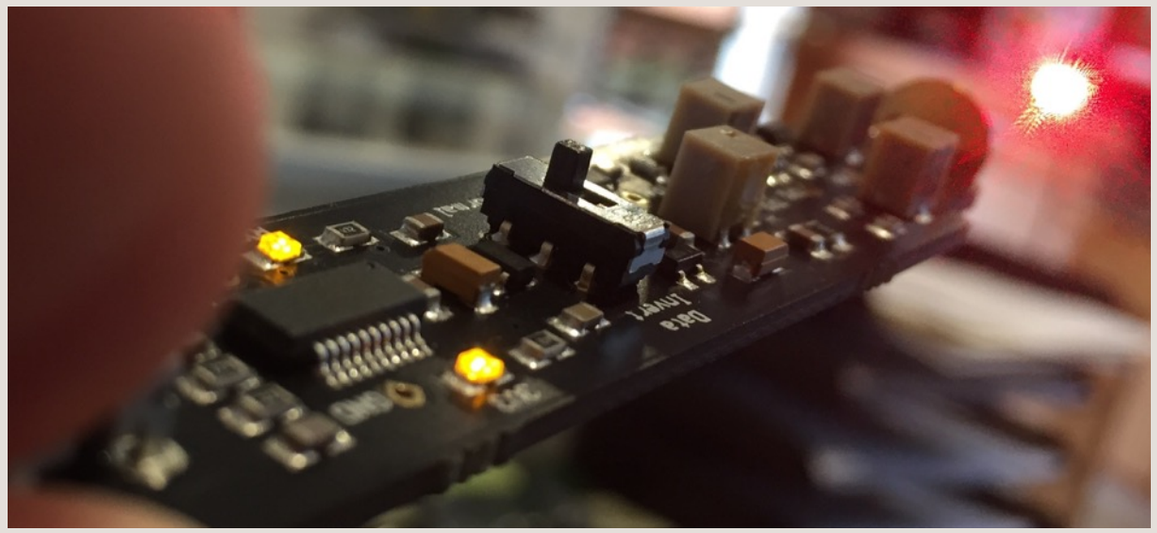


Arduino + LazOr!@

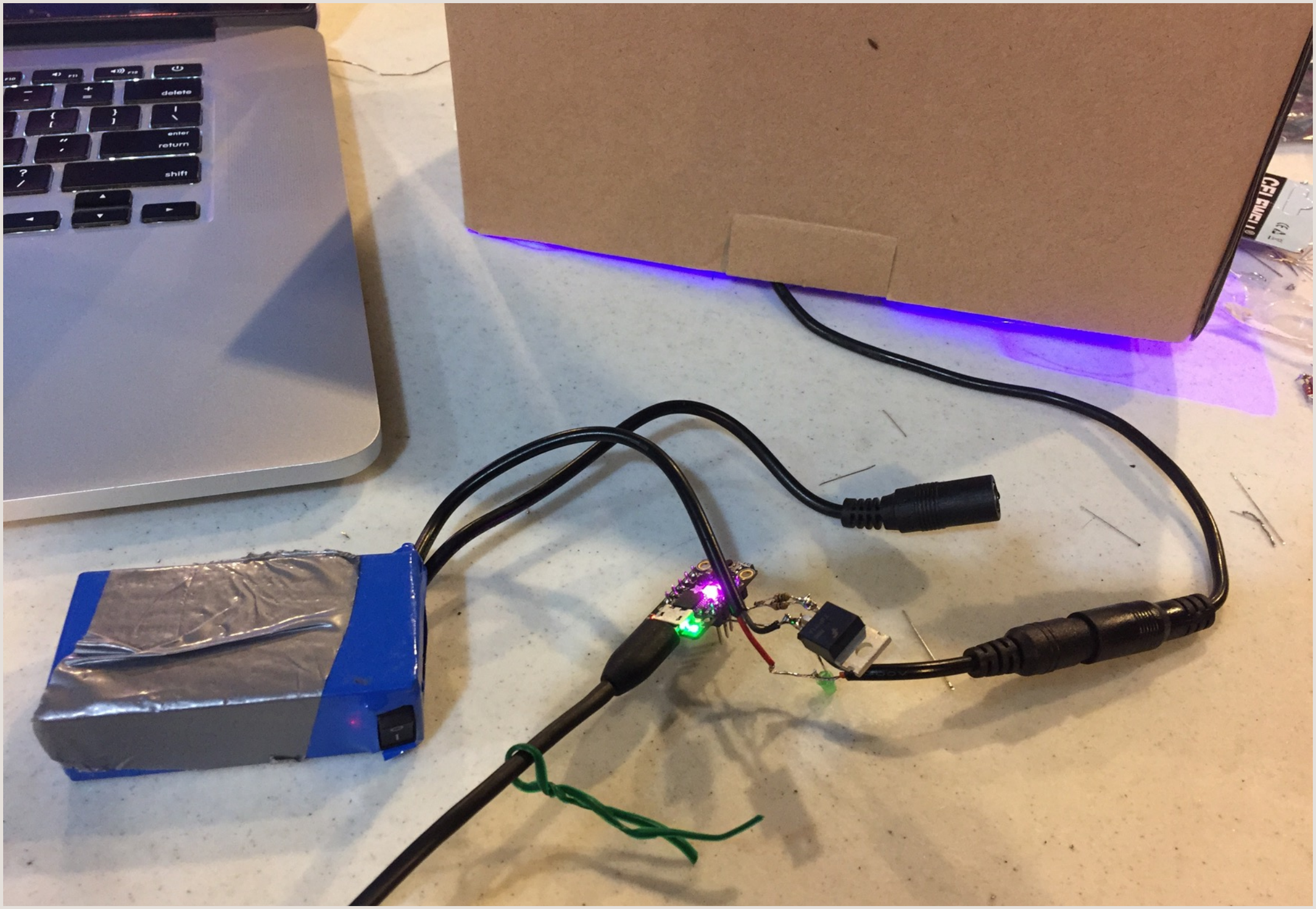
- Long-range data transmission w/ laser diode module
- Data sent to LDO Enable (EN) pin
- Distance limited by laser diffusion + output power
- oshpark.com/shared_projects/WV8fBzyW





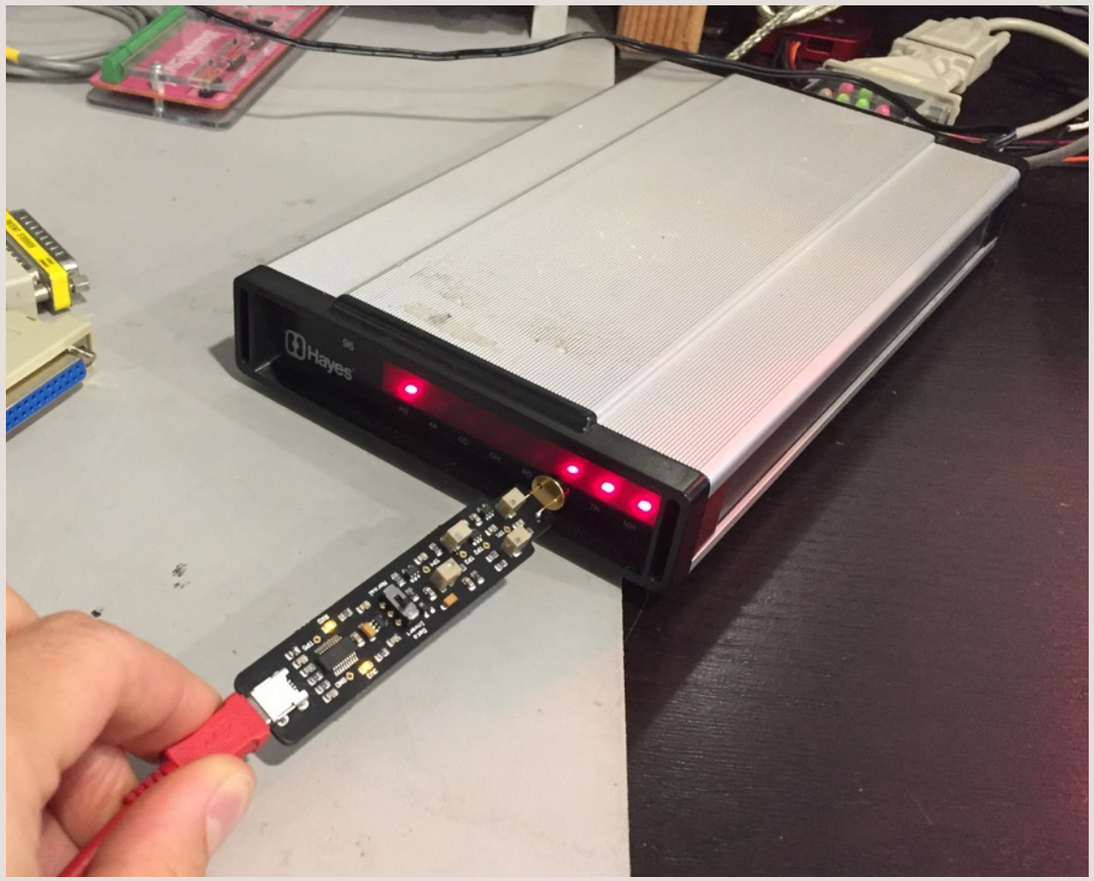


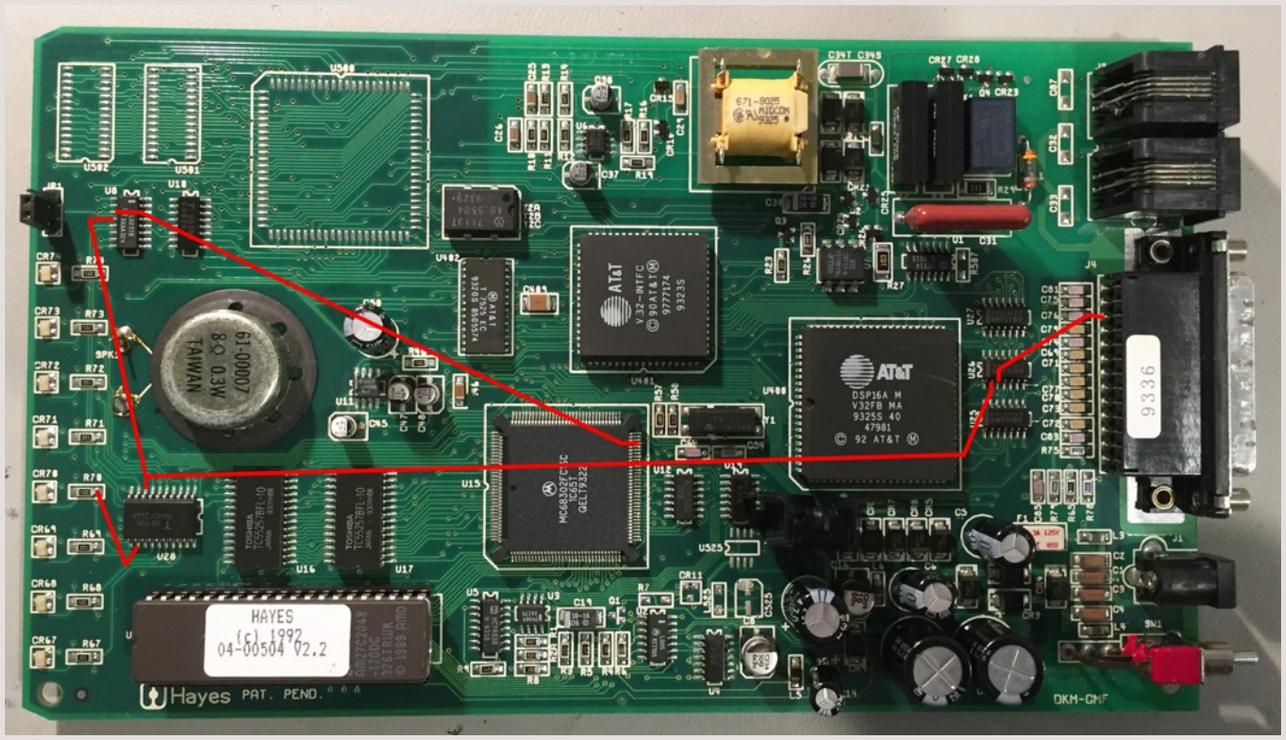
Arduino + LazOr!@



Hayes Smartmodem Optima

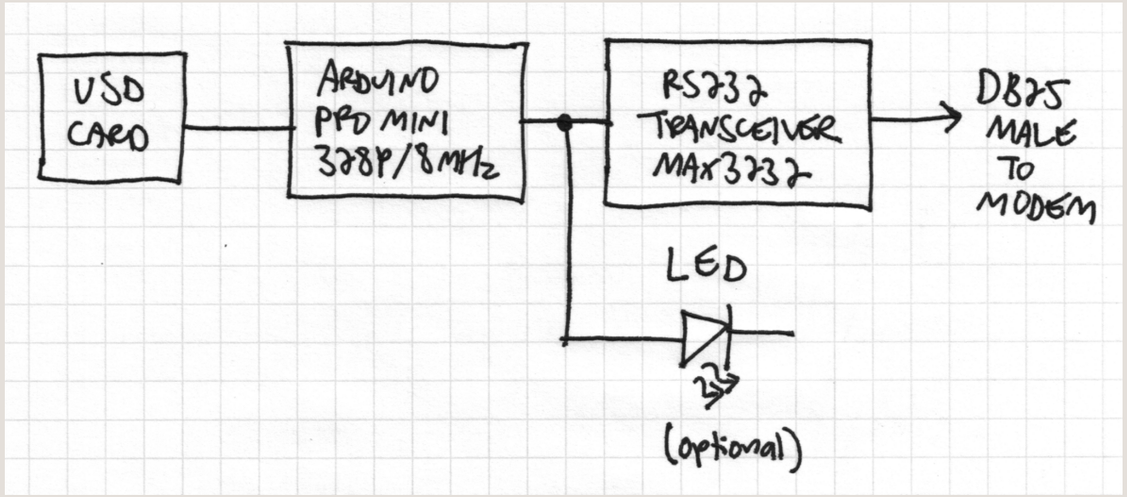
- Data leakage through SD (Send Data) LED
- Discovered by Loughry and Umphress 2002
- Indicator LEDs tied to serial port data lines

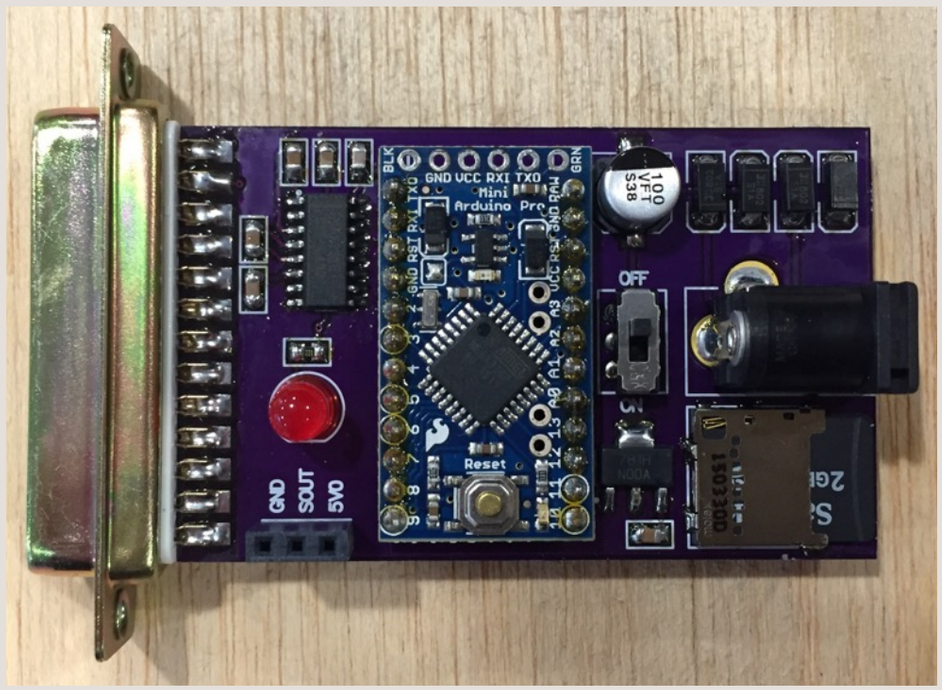


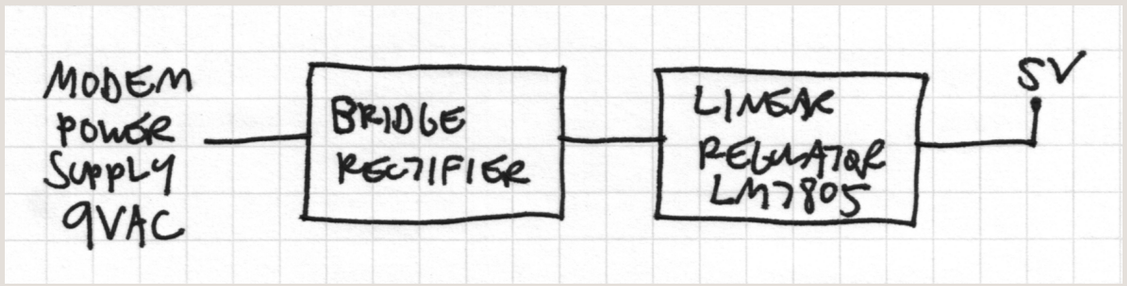


Hayes Smartmodem Optima

- uSD to Serial Interface
  - Read text file from card, send contents via serial
- DB25 connection for direct connection to modem
- Good for demonstrations, trolling, etc.
- oshpark.com/shared_projects/laP2t8DO



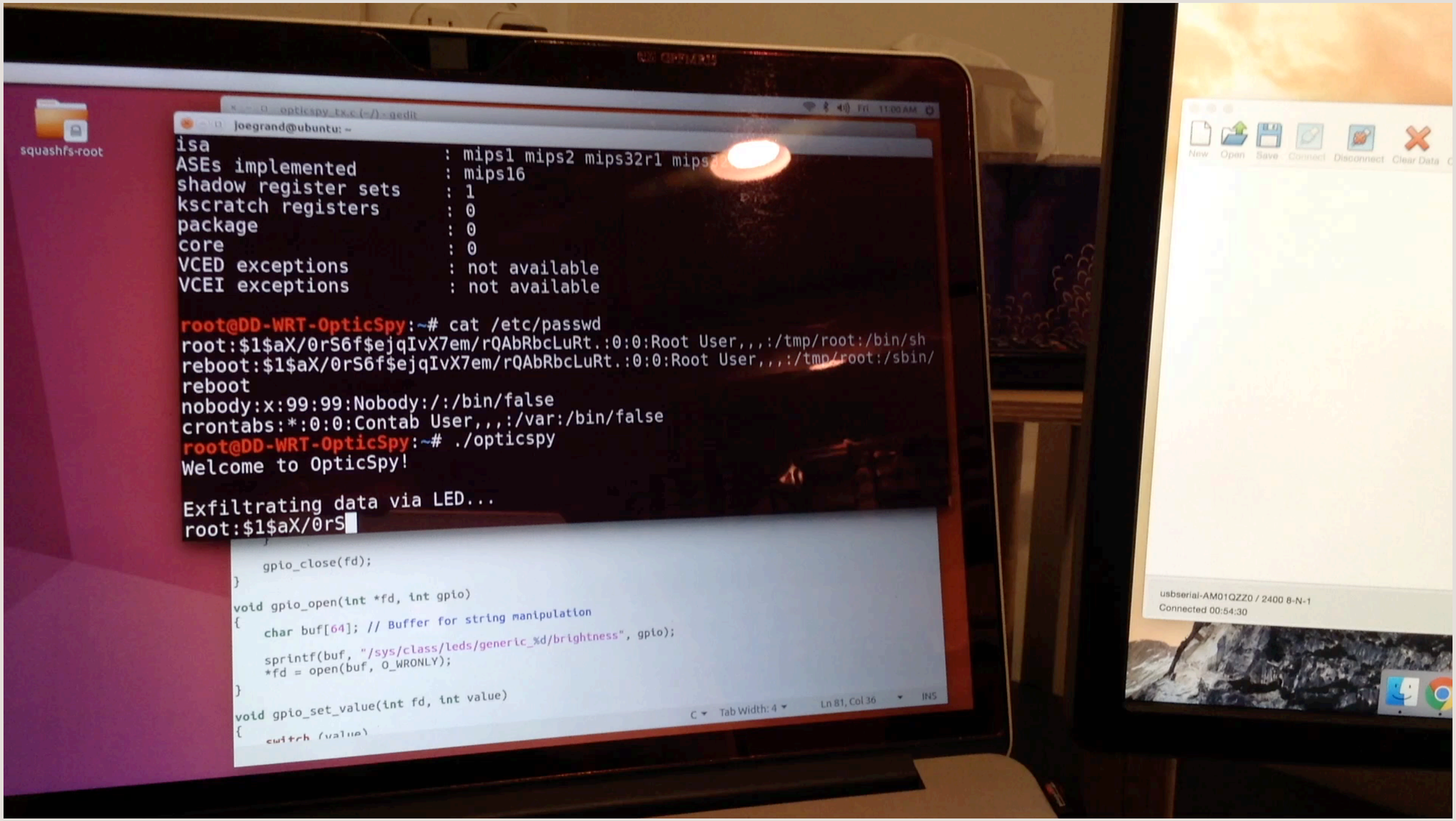




TP-Link TL-WR841N

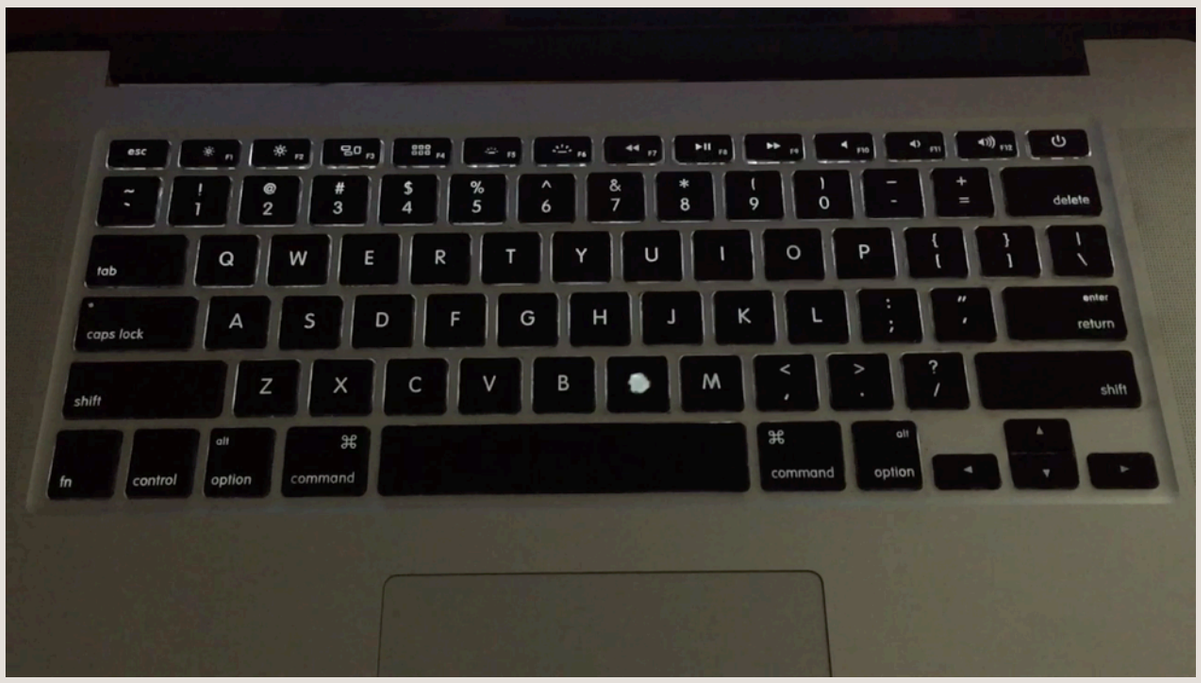
- Physically unmodified router w/ DD-WRT
- Cross compiled w/ toolchain-mips_24kc_gcc-7.2.0_musl
- Loaded onto the device with known administrator credentials (as proof of concept)

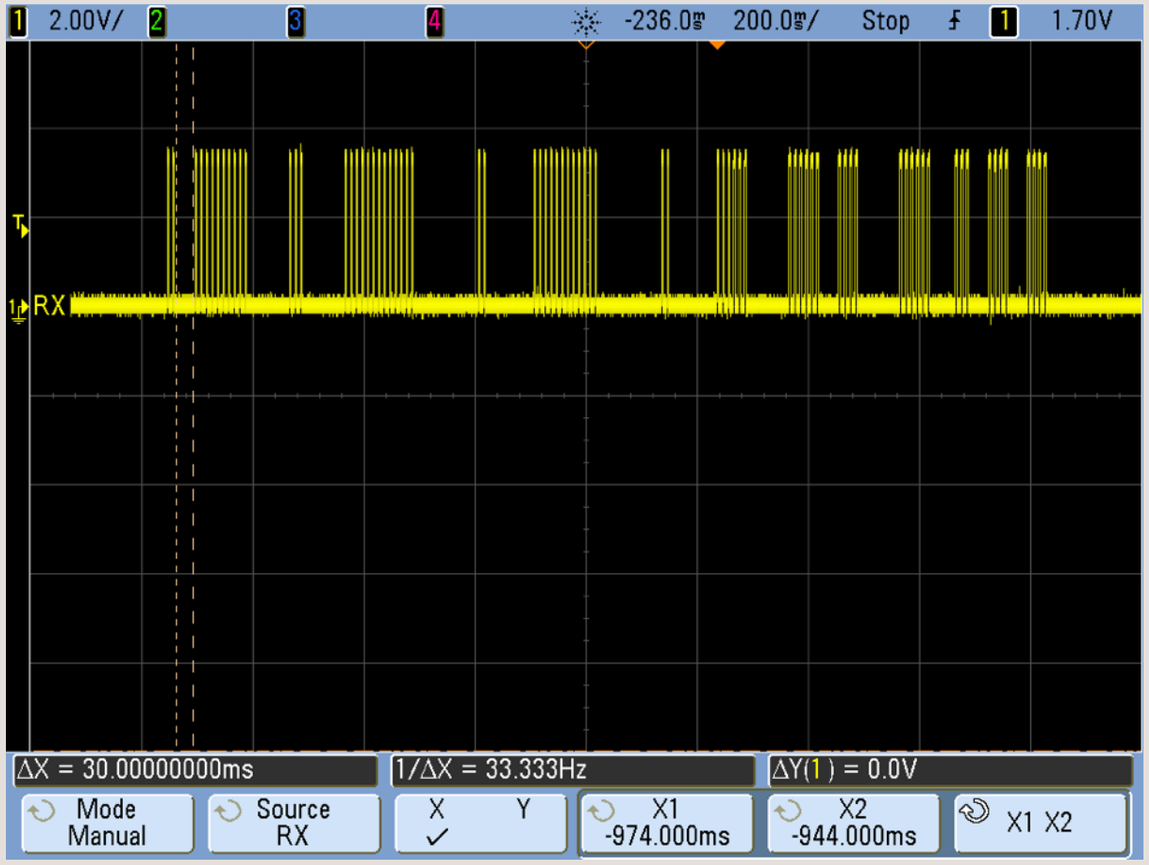
TP-Link TL-WR841N



MacBook Pro Keyboard

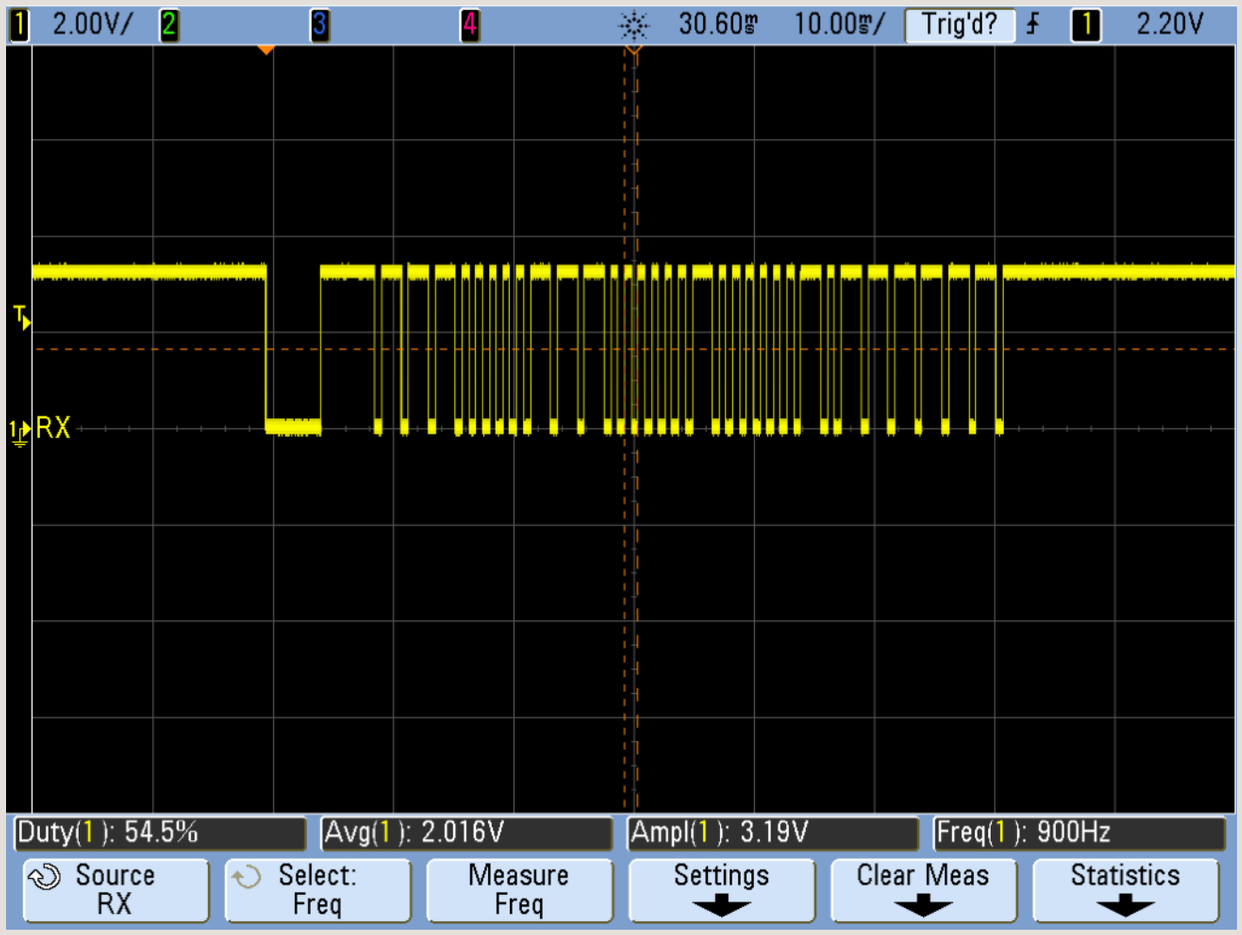
- Based on https://github.com/pirate/mac-keyboard-brightness
- Backlight LEDs @ 100Hz, 75% PWM :(
- Can decode manually or w/ MCU via TP5





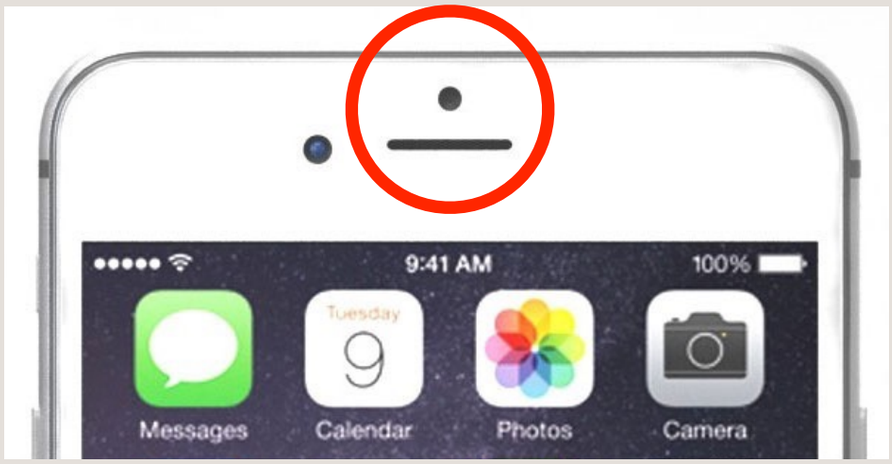
Samsung TV Remote

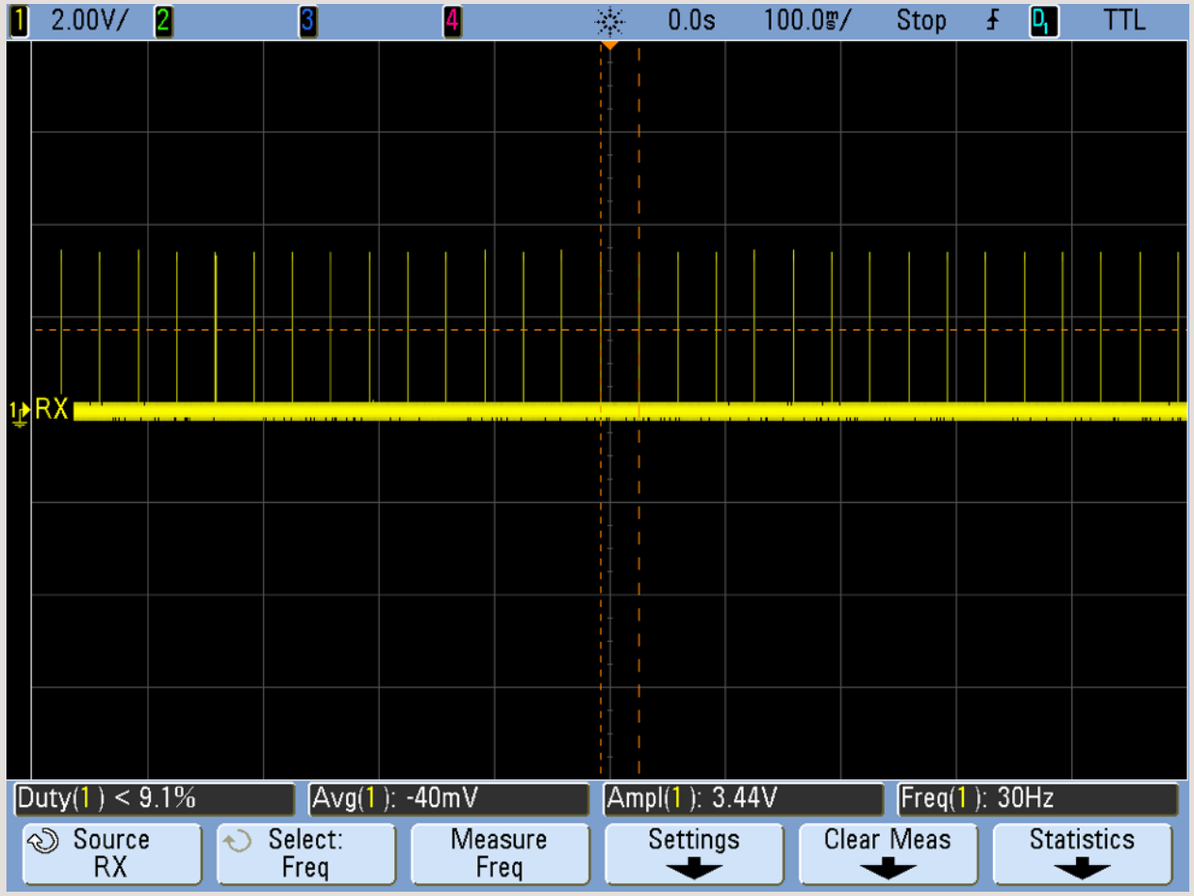
- 38kHz carrier
- Start: 4.5ms pulse burst, 4.5ms space
- Logic '1': ~544µs pulse, 1.706ms space
- Logic '0': ~544µs pulse, 580µs space
- Measure via TP5

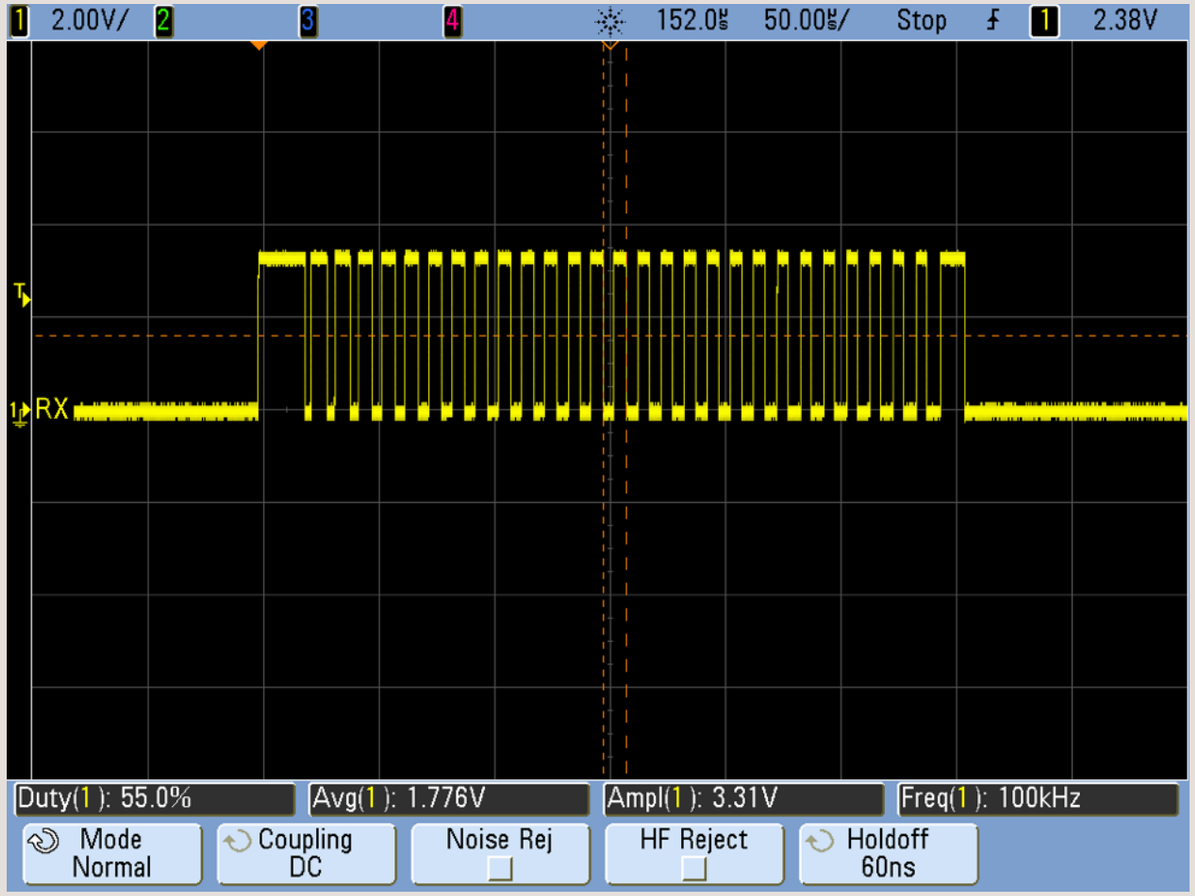


iPhone 6 Proximity Sensor

- ~313uS width @ 100kHz carrier
- 30Hz refresh rate
- Measure via TP5







Application ideas

- Search for optical covert channels in existing devices
- Discover optical networking/communications systems
- Add data transfer functionality to a project
- Receive/demodulate IR signals
- Measure the world around you

Limitations

- Data must be NRZ encoded in order to pass through USB-to-Serial interface
- Short receive range (up to ~4 inches) w/o additional optics
- Difficult to determine potentiometer settings

Future Work?

- More intelligence to handle non-NRZ data streams (on-board v. off-board)
- Automatic gain control (AGC) to replace potentiometers
- Compromise/communicate with a target device using an LED as an *input*

Other Things

- Photodiode Amplifiers: Op Amp Solutions, Jerald Graeme, McGraw-Hill, 1995
- Sound Camera: NYC Night Drive, Eric Archer, 2010
- The Photophone, Hack-a-Week, 2011
- PWM Laser Audio Transmitter, Tymkrs, 2011

Other Things

- IBM/Lenovo ThinkPad LED Control
  - www.reddit.com/r/thinkpad/comments/7n8eyu/thinkpad_led_control_under_gnulinux/
- Asus ROG Strix Z370 Gaming Mini-ITX Motherboard
  - Addressable AURA sync RGB LED lighting
  - www.asus.com/us/ROG-Republic-Of-Gamers/ROG-STRIX-Z370-I-GAMING/

Come into the Light

- grandideastudio.com/portfolio/opticspy
  *** Schematic, BOM, Gerber plots, test procedure, user manual, demonstration code

- oshpark.com/profiles/joegrand
  *** Bare boards

- crowdsupply.com/grand-idea-studio/opticspy
  *** Assembled units

The End.