b0bc3f0a440465caa518d0c4e152d350

Go Long!

Sending weird signals long distances over existing optical infrastructure

Ben Cartwright-Cox
2024 / 38c3

Hi

- I am Ben Cartwright-Cox (@benjojo@benjojo.co.uk)
- You might remember me from things like:
  - bgp.tools
  - "A deep dive into the world of DOS viruses" - 35C3
  - BGP Battleships
  - Some other blog bits like making {USB drivers, Class E, HDMI Magic boxes}

Hi

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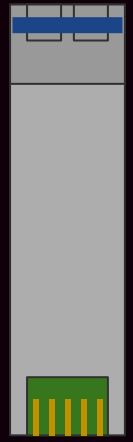
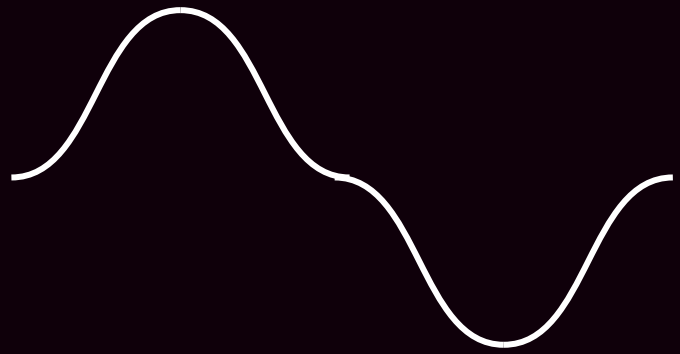
  - BGP Battleships
  - Some other blog bits like making {USB drivers, Class E, HDMI Magic boxes}
- I like knowing about how stuff works
  - It makes life more interesting, and I don't like taking any tech for granted
  - My rule of thumb; it's either really smart, or incredibly stupid
    - I'd like to know what one it is before I depend on it

The modern internet backbone is nearly all optical

Networking optical kit is a weird world





Device

- 1000baseKX
- 10000baseKR
- 25000baseCR
- Etc etc

Optic Type

- SFP
- SFP+
- XFP
- QSFP
- QSFP+
- OSFP

Transmission / Wavelength

- LR
- LX
- SR
- SX
- ER
- BX

- 850nm
- 1310nm
- 1510nm
- CWDM
- DWDM

Networking optical kit is a weird world (2)

9 µm

SMF/OS2

Single Mode

50 - 62 µm

Multi Mode

Average "boring" ISP network

- Uses a SFP+ Port on a switch
- With a vendor SFP+ optic
  - Or a 3rd party supplier, a lot of the optics are ultimately the same factories anyway!
  - Just juicy vendor ~~markup~~ support costs included
- The switch chip spits out a XGMII signal towards the optic
  - We will ignore what happens if you need to turn this into "BASE-T"
- The optic then does some stuff to turn that XGMII signal into laser light
- The opposite happens on the other end
- Data bits are exchanged

- Cat videos are exchanged or something

Some optics are surprisingly stupid

This thing is NOT thinking*

We will ignore weird things that have full CPUs in them

VDSL Modem in SFP

ARM Machine inside SFP [1]

GPON ONT inside SFP

[1] https://blog.benjojo.co.uk/post/smart-sfp-linux-inside

Some optics are surprisingly stupid

This thing is NOT thinking*

Some optics are surprisingly stupid

This thing is NOT thinking*

* There is a EEPROM to tell the switch what it is (and have the switch complain to you to buy vendor optics instead)

Some optics are surprisingly stupid

This thing is NOT thinking*

* **There is also** sometimes a tiny microcontroller to read out laser light level metrics and temperature for the switch

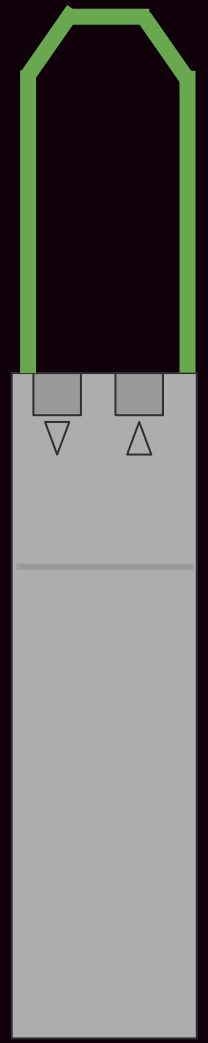
Average faster "boring" ISP network

- Uses a QSFP28 Port on a switch
- With a vendor QSFP28 optic
- Depending on the optic (100G is a mess) various fancy chips are used to convert [CK]R4 into something desirable, maybe even coherent for special use cases
- The opposite happens on the other end
- Data bits are exchanged

- Cat videos are exchanged *at higher speeds* or something

Some optics are surprisingly smart

- The fancy ones have to turn 4 "lanes" of 25GBaud data into one "normal" lane of "data", at 100GBaud speeds
- This (sometimes) requires advanced chips to exist inside the optics
  - Like, your intel laptop likely has a bigger process node than these optics
  - Most optics like this are 7nm/5nm or less
- These optics also consume considerably more power to run both the laser and the chip inside the optic to combine the feeds
- Depending on the type of optic (PLR4/ER/ZR/ZR+/SR/LR4/LR1/PSM/CWDM4) the complexity (and price) of the chips are better/worse



Other optic form factors are available

- XFP / CFP / Various QSFP forks / OSFP / X2 / Xenpack
  - All used in various places and ages of kit, but they are similar enough not to make a difference here

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- XFP / CFP / Various QSFP forks / OSFP / X2 / Xenpack
  - All used in various places and ages of kit, but they are similar enough not to make a difference here
- Home Theater stuff also uses some kind of optical transmission
  - SPDIF / TOSLINK

TOSLINK

- Two kinds of people use TOSLINK/SPDIF
  1. People who have ground loop issues (speaker mains hum)
  2. People who just want to seem cooler by using optical stuff
- Maxes out at ~10mbits/s, But really hangs around 3mbit/s for most setups
- The wavelength is more 700nm (aka red LEDs), and the cables have a super thick (1mm) plastic core

- Quoted max length for a cable is 10m

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- **Quoted max length for a cable is 10m (due to 1000µm core!)**

Networking optical kit is a weird world (2)

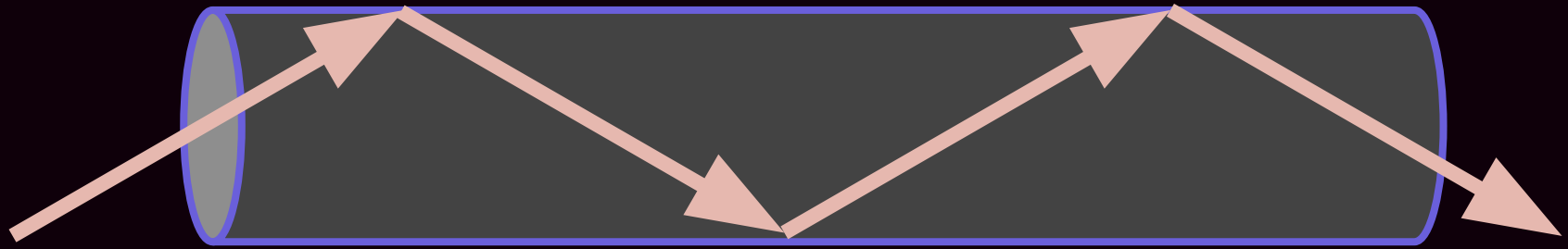
SMF/OS2

Single Mode
(9μm)

Multi Mode
(50μm~)

Networking optical kit is a weird world (3)

Networking optical kit is a weird world (3)



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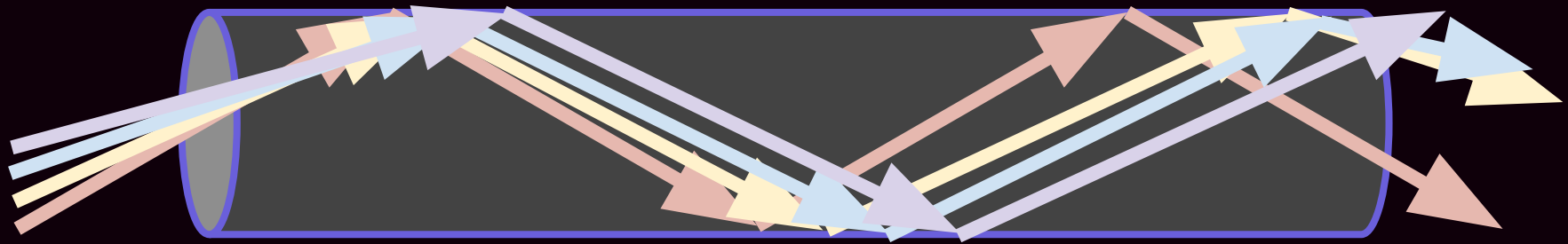

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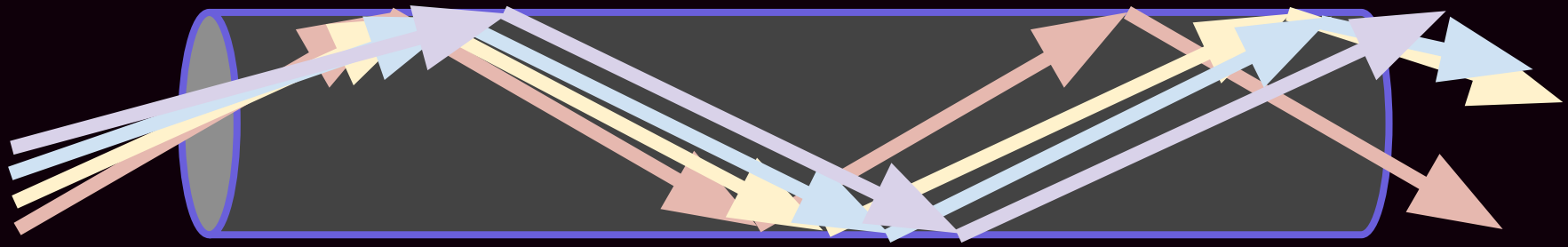

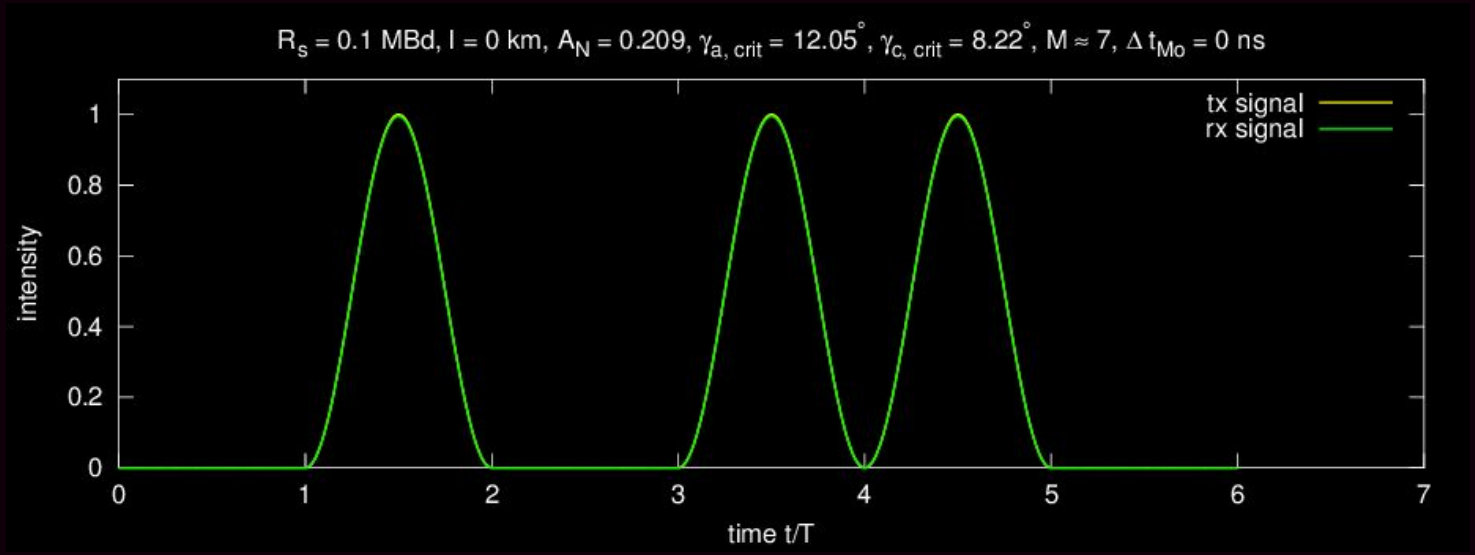

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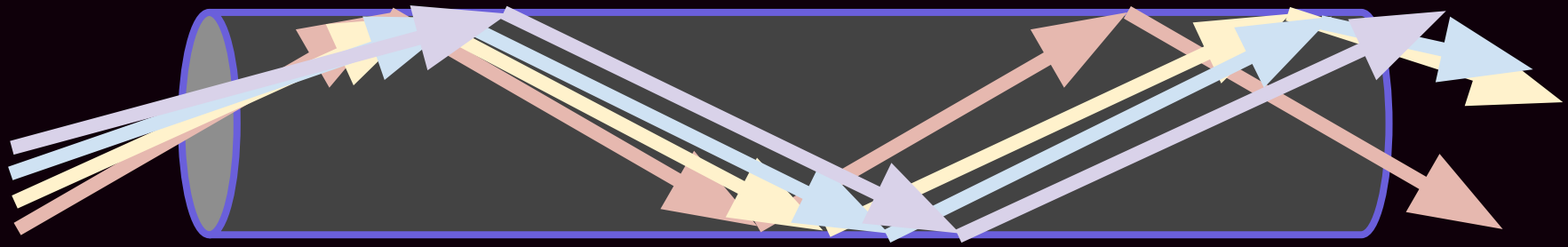

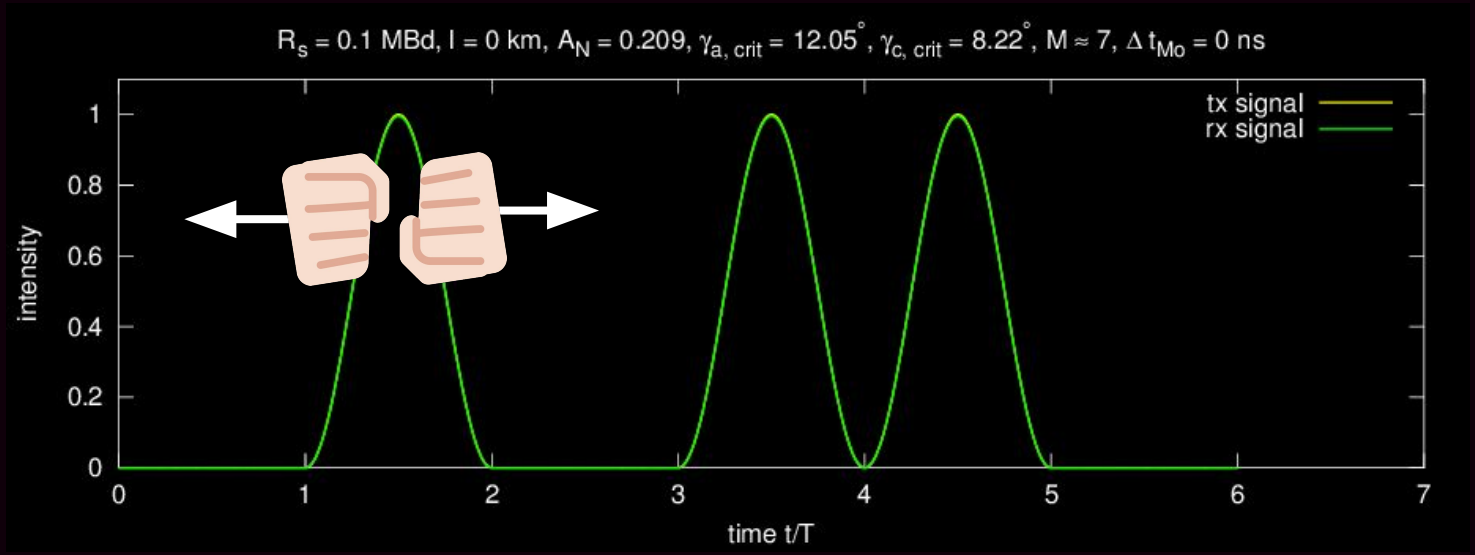

[1] https://webdemo.inue.uni-stuttgart.de/webdemos/02_lectures/uebertragungstechnik_2/modal_dispersion/index.php?id=3#

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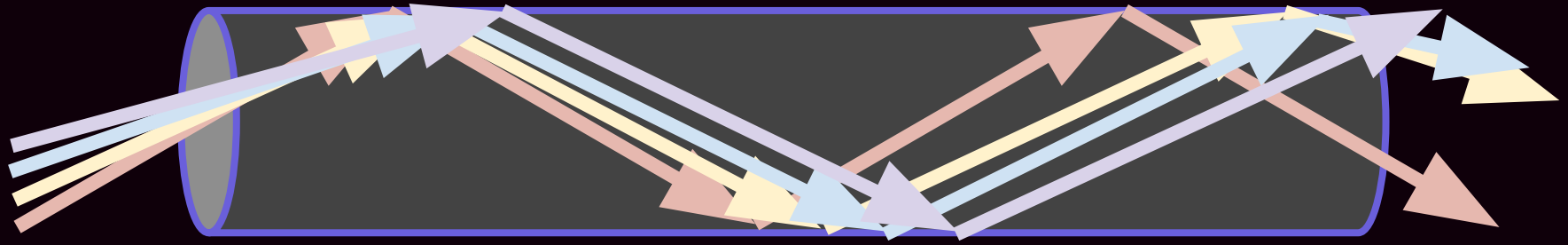

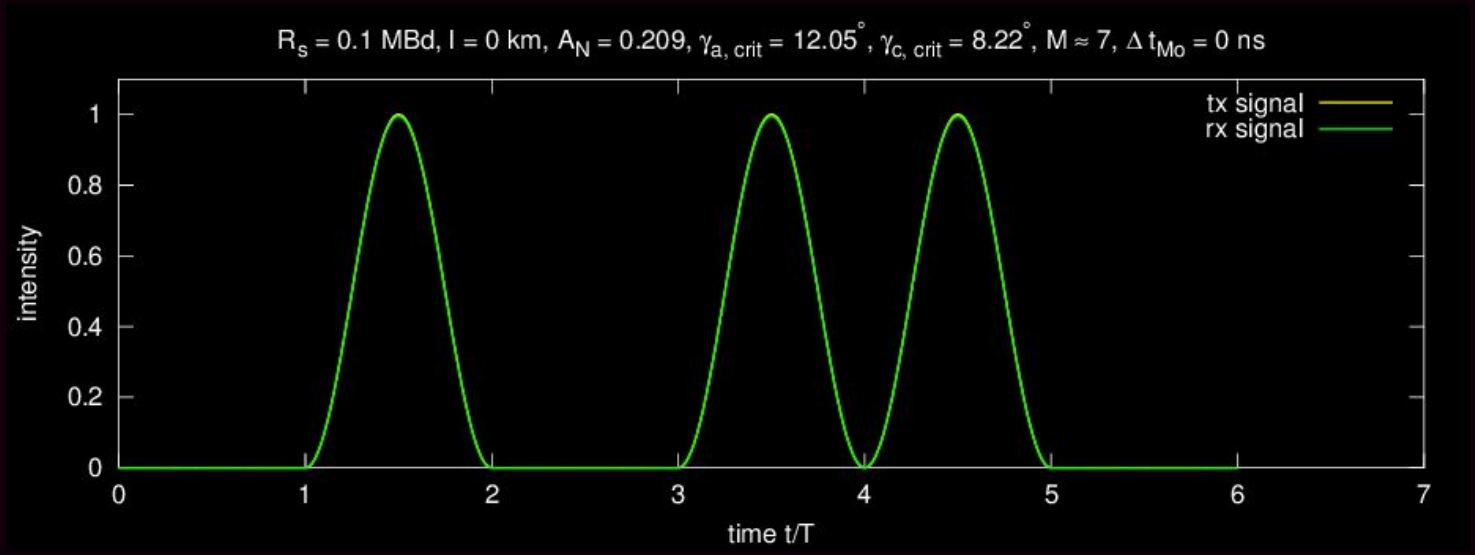

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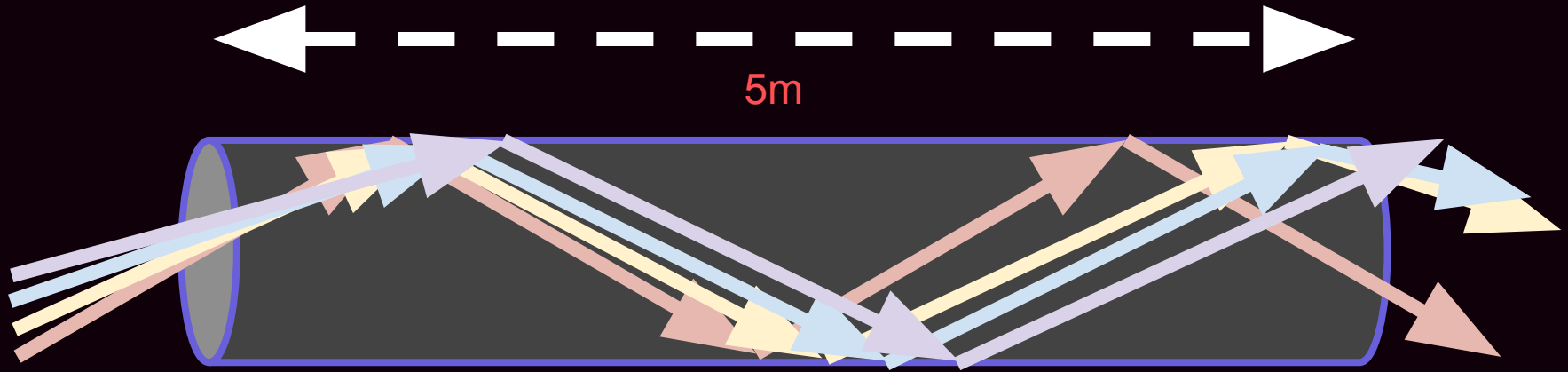

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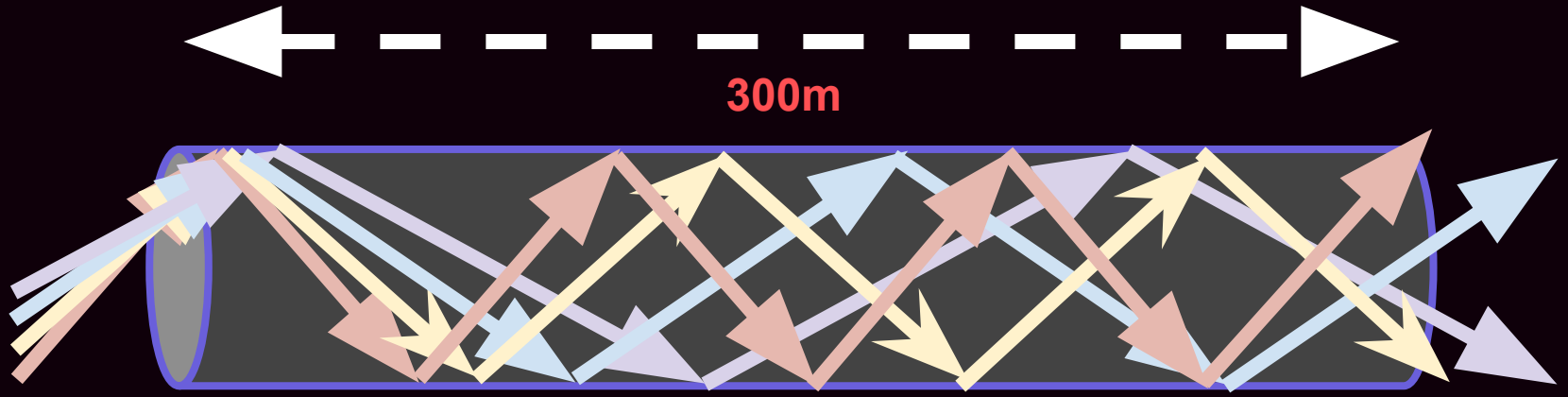

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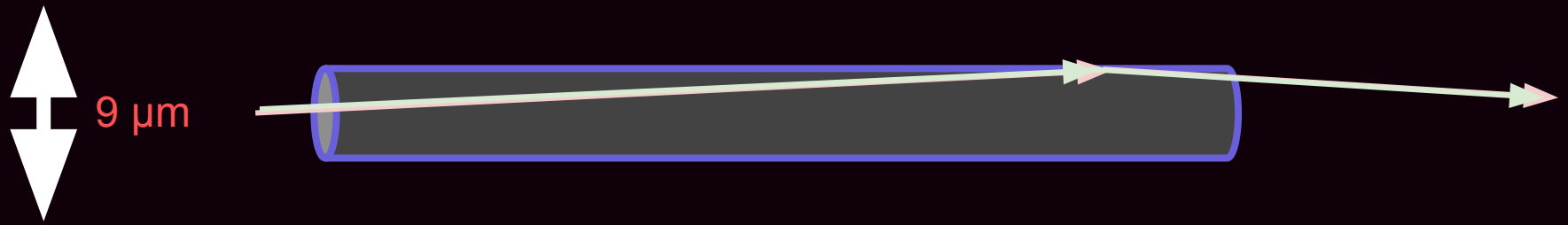


So I was thinking

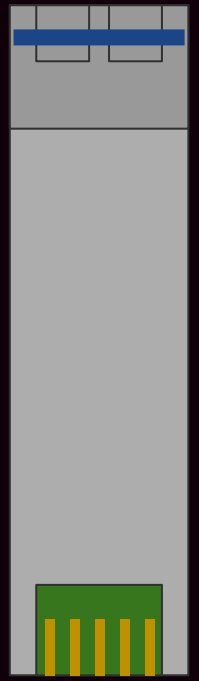
So I was thinking

So I was thinking

Too stupid to care

So I was thinking

+



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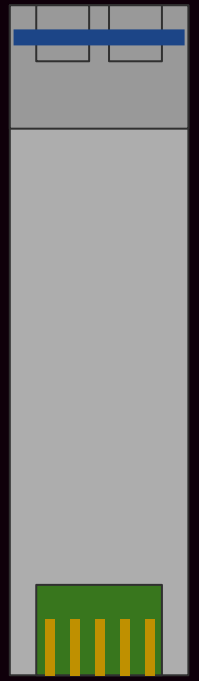
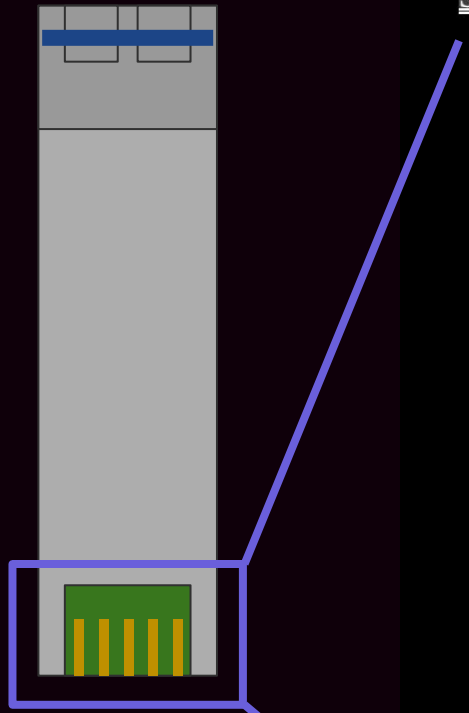


10km TOSLINK?

We are going to need to do some things



Small Form-factor Pluggable (SFP) Transceiver MultiSource Agreement (MSA)

	Top of Board		Bottom of Board (as viewed thru top of board)
20	VeeT	1	VeeT
19	TD-	2	TxFault
18	TD+	3	Tx Disable
17	VeeT	4	MOD-DEF(2)
16	VccT	5	MOD-DEF(1)
15	VccR	6	MOD-DEF(0)
14	VeeR	7	Rate Select
13	RD+	8	LOS
12	RD-	9	VeeR
11	VeeR	10	VeeR

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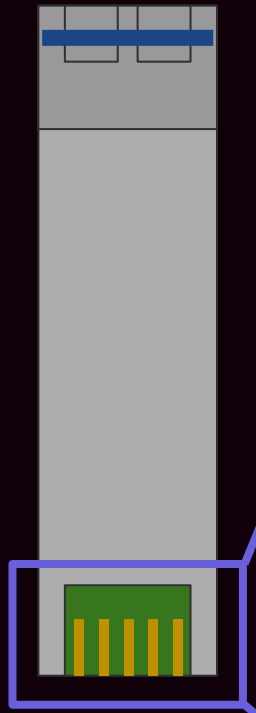

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12	RD-	9	VeeR
11	VeeR	10	VeeR

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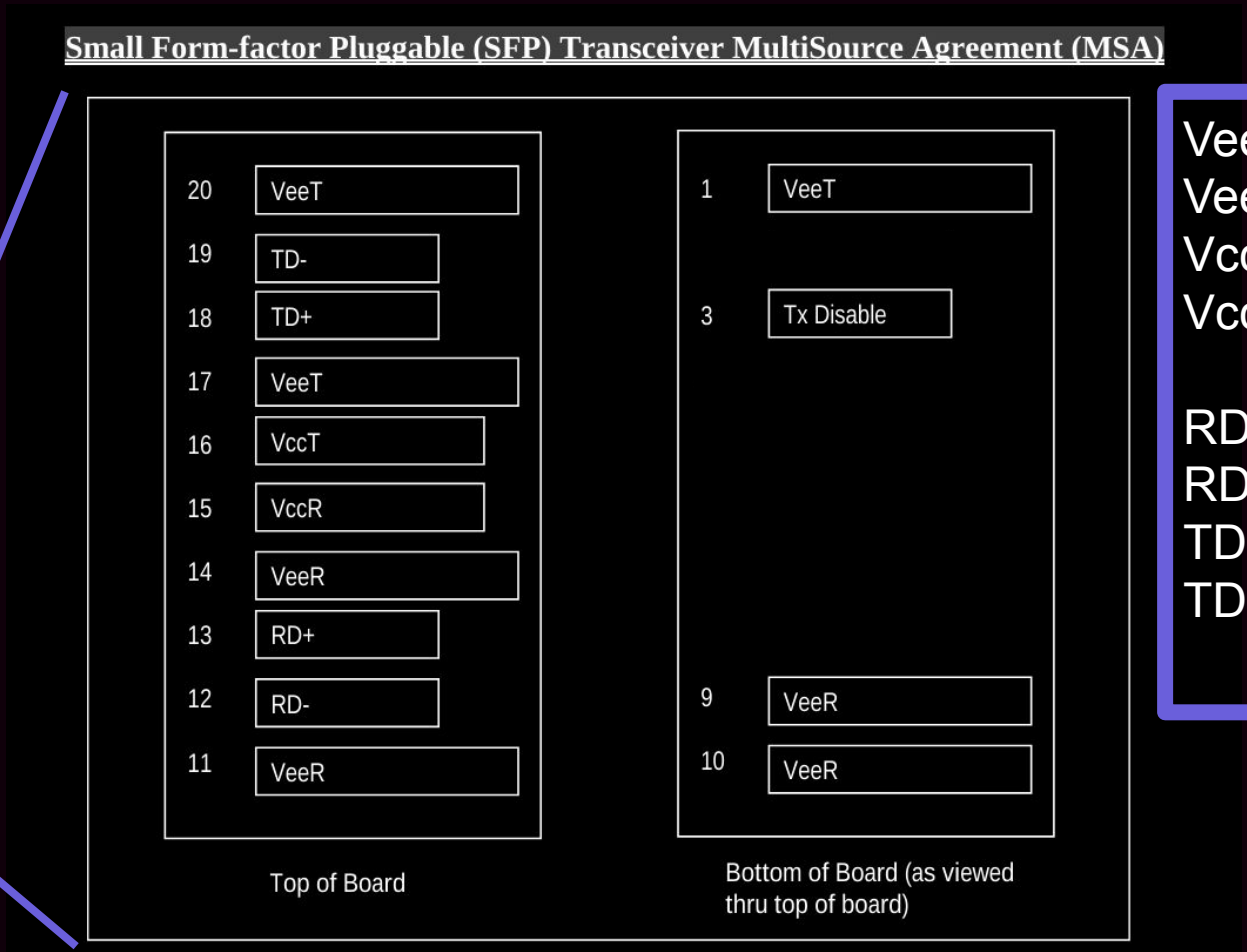

VeeT: TX Ground
VeeR: RX Ground
VccT: Tx Power
VccR: Rx Power

RD- : RX Signal
RD+ : RX Signal
TD-: TX Signal
TD+: TX Signal

[1] https://wlcx.cc/

Cheating a bit

A friend[1] made some Osmocom SFP Experimenter boards, They come with:

- A 5v to 3.3v power supply
- SFP Connecter + Cage
- Wired up extra pins for various aux signals we want
- LEDs to tell you when you have upset the optic
- Exposed pads to inject your signal
- A pair of line drivers to make the signal friendly to optics

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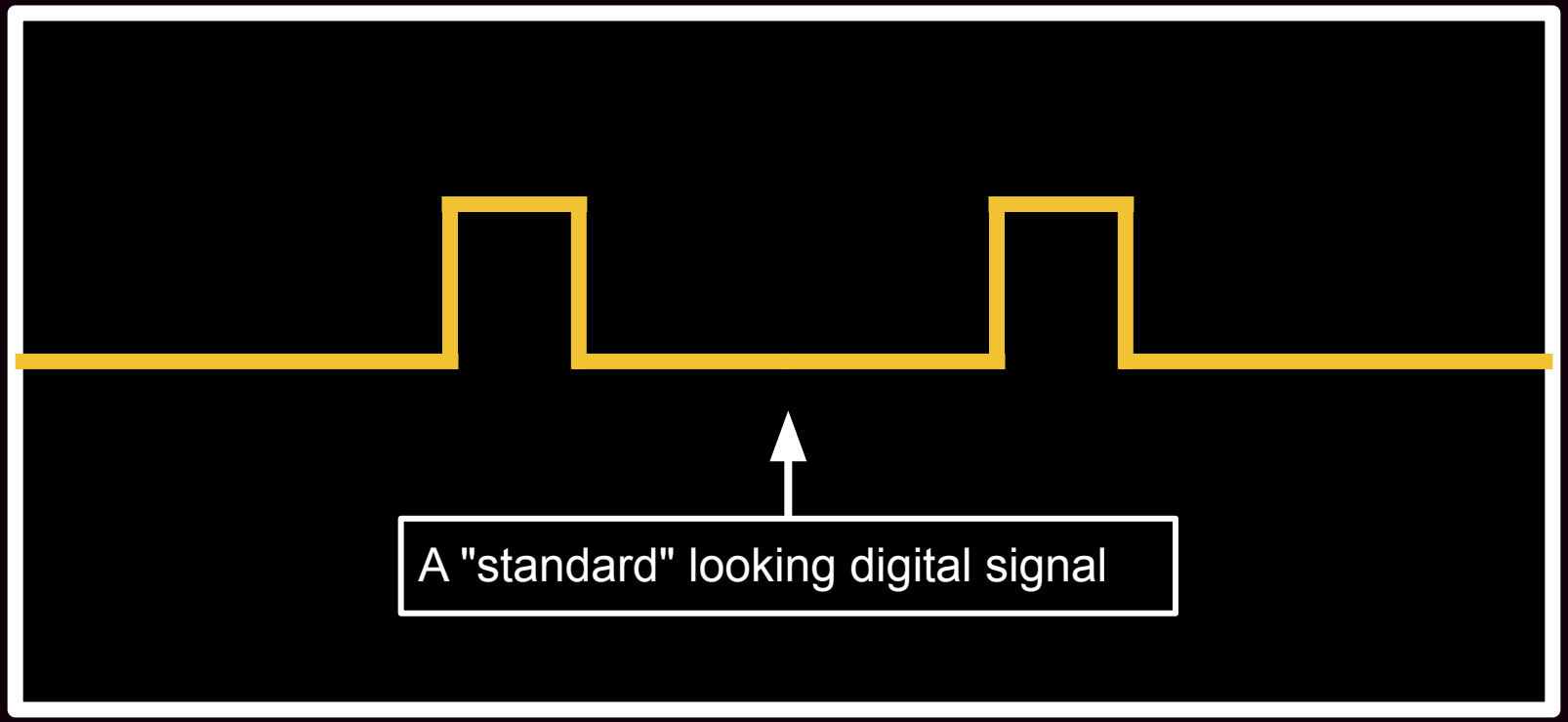
Line drivers make things wobble just right



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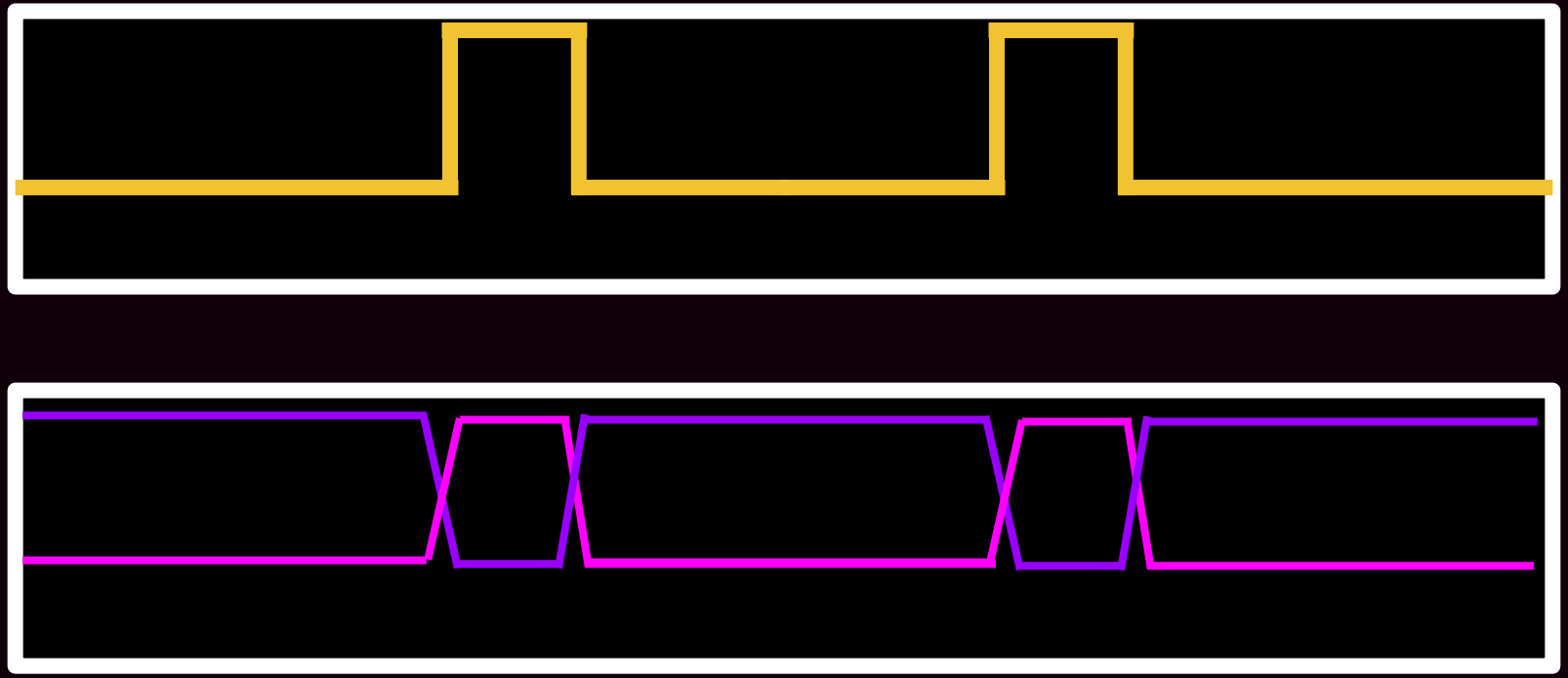
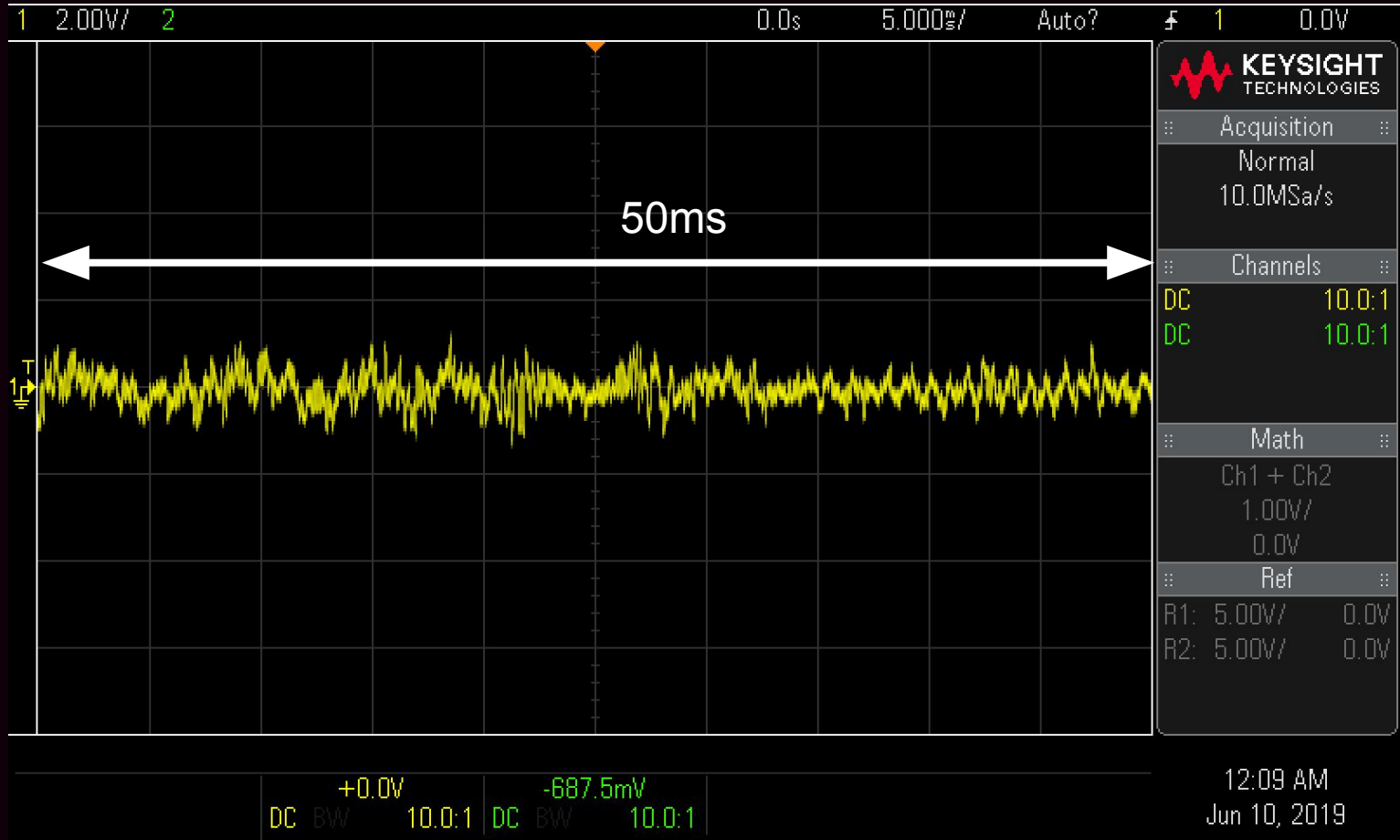
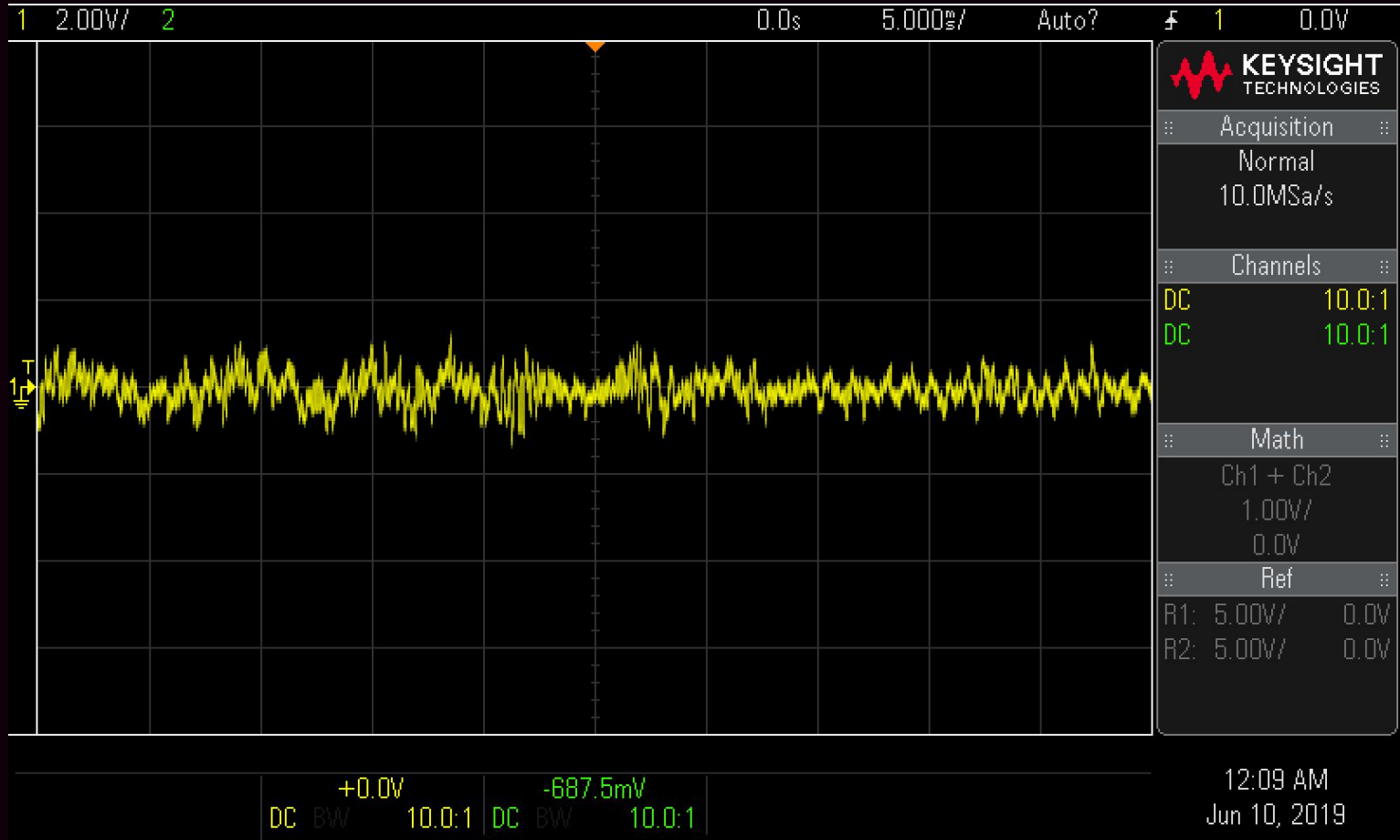


Line drivers make things wobble just right

Audio In


1 2.00V/ 2
0.0s
5.000ms/
Auto?
1 0.0V
KEYSIGHT TECHNOLOGIES
Acquisition
Normal
10.0MSa/s
Channels
DC 10.0:1
DC 10.0:1
Math
Ch1 + Ch2
1.00V/
0.0V
Ref
R1: 5.00V/ 0.0V
R2: 5.00V/ 0.0V
50ms
+0.0V
DC BW 10.0:1
-687.5mV
DC BW 10.0:1
12:09 AM
Jun 10, 2019

Audio In


1 2.00V/ 2
0.0s
5.000ms/
Auto?
1 0.0V
KEYSIGHT TECHNOLOGIES
Acquisition
Normal
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Channels
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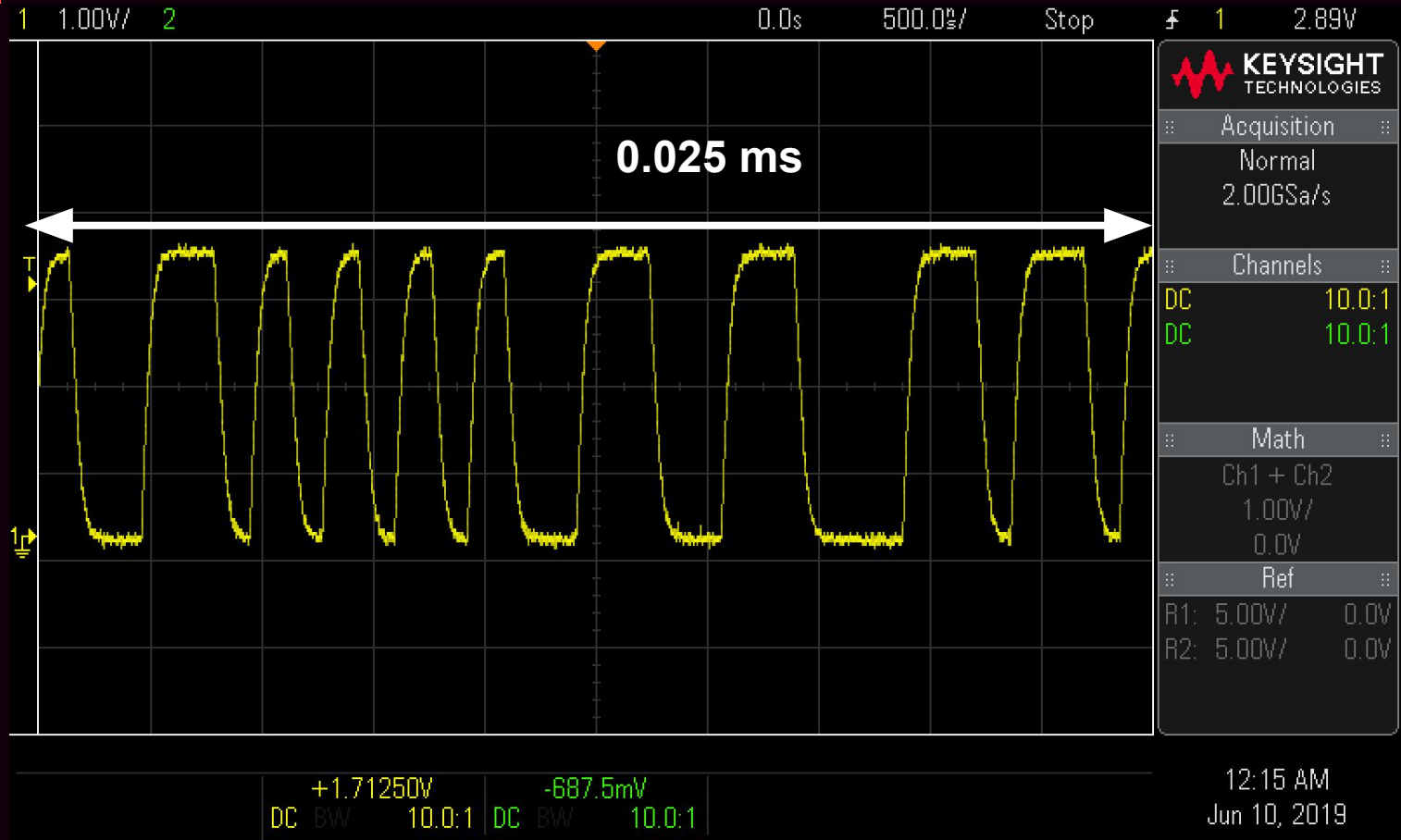
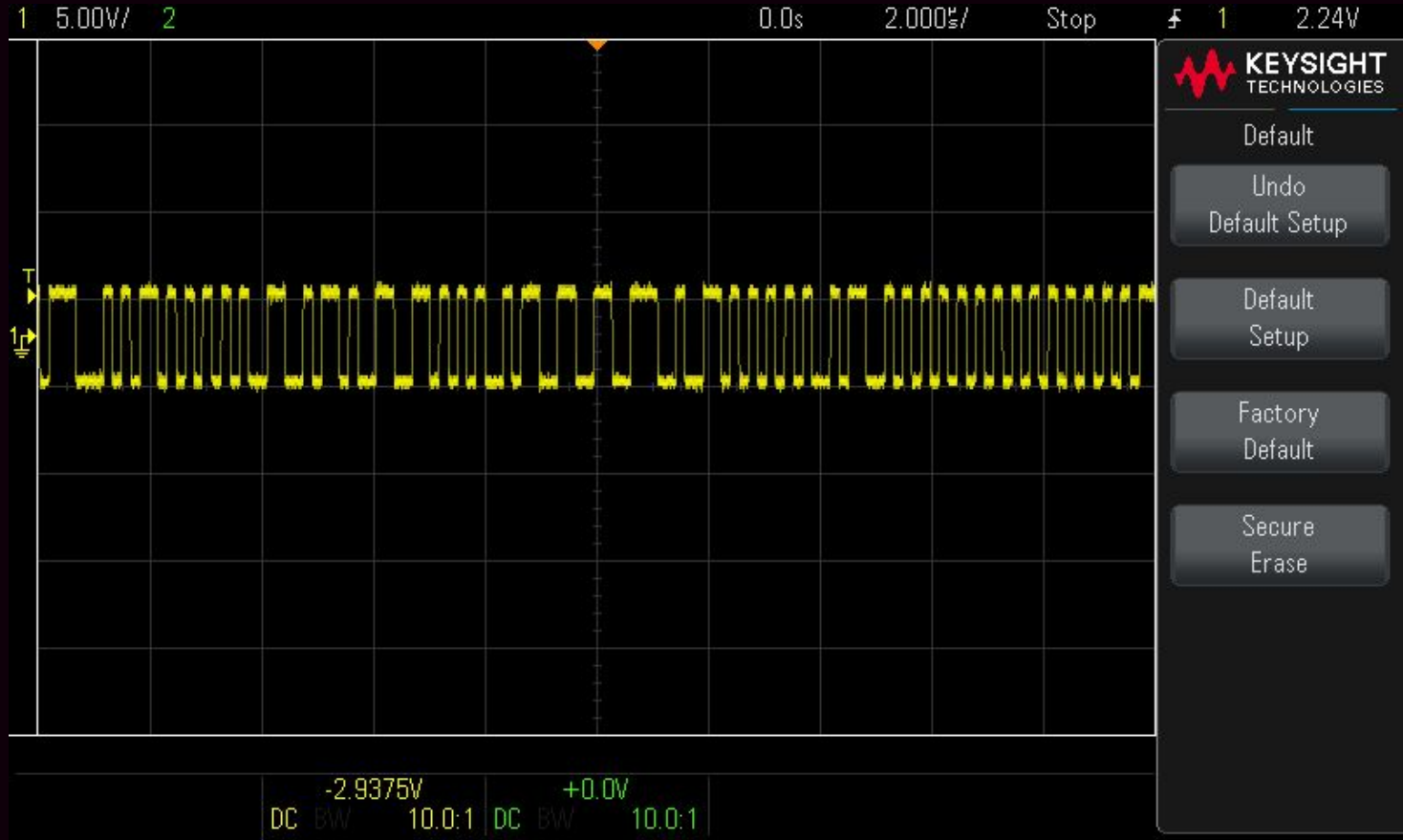
+0.0V
DC BW 10.0:1
-687.5mV
DC BW 10.0:1
12:09 AM
Jun 10, 2019

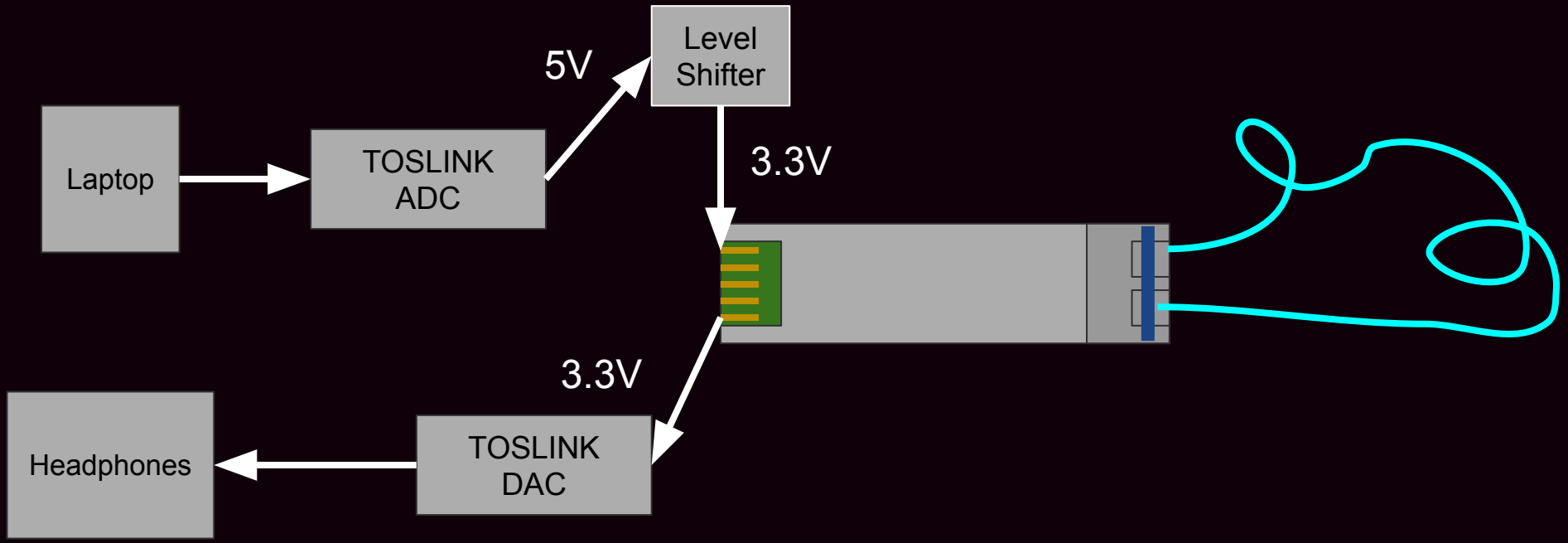
SPDIF Out


1 1.00V/ 2
0.0s
500.0%/
Stop
1 2.89V
0.025 ms
KEYSIGHT TECHNOLOGIES
Acquisition
Normal
2.00GSa/s
Channels
DC 10.0:1
DC 10.0:1
Math
Ch1 + Ch2
1.00V/
0.0V
Ref
R1: 5.00V/ 0.0V
R2: 5.00V/ 0.0V
+1.71250V
DC BW 10.0:1
-687.5mV
DC BW 10.0:1
12:15 AM
Jun 10, 2019

About 2Mhz~ of data

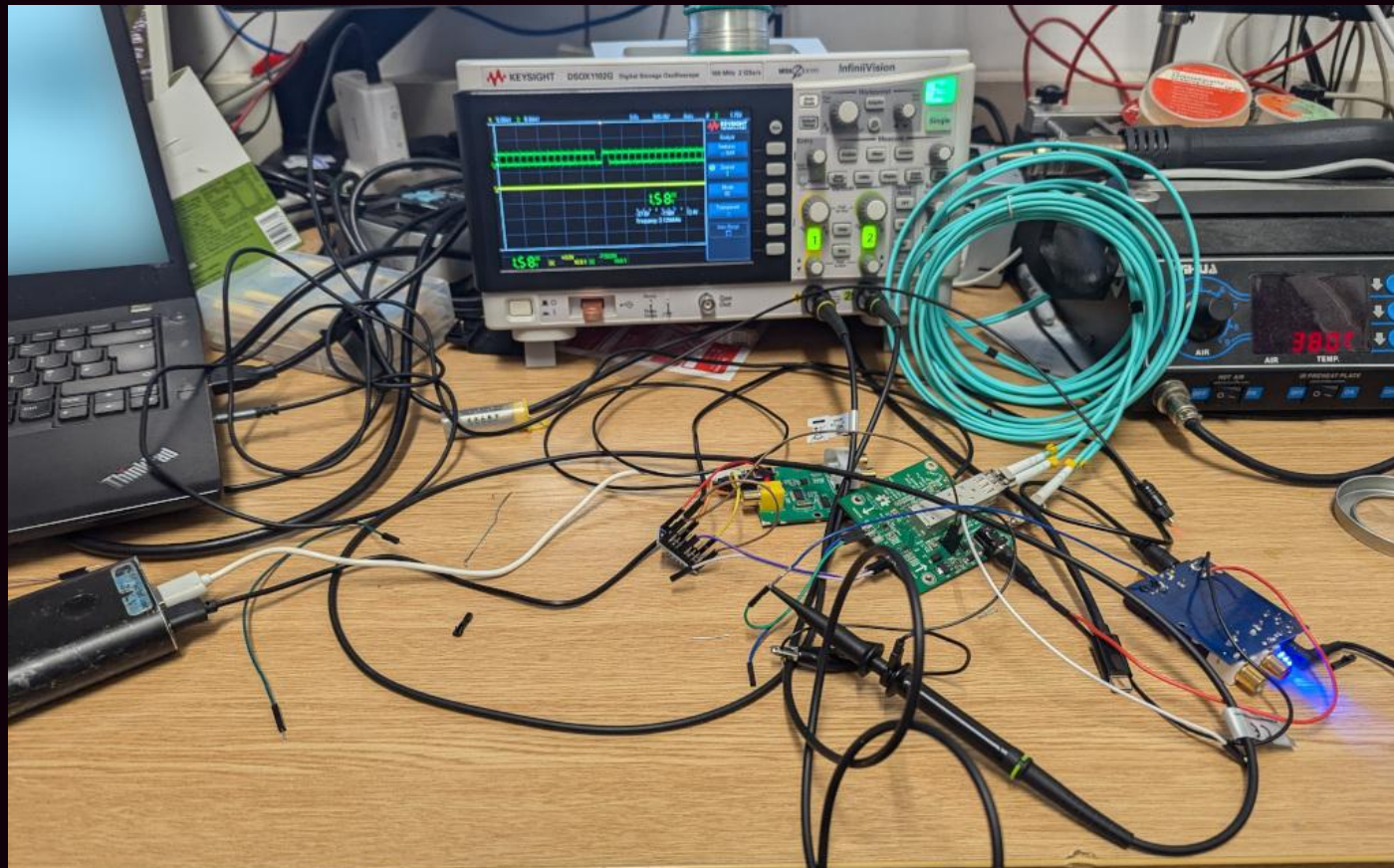


POC Setup


Laptop
TOSLINK ADC
5V
Level Shifter
3.3V
3.3V
TOSLINK DAC
Headphones

Working POC

- Not airport friendly

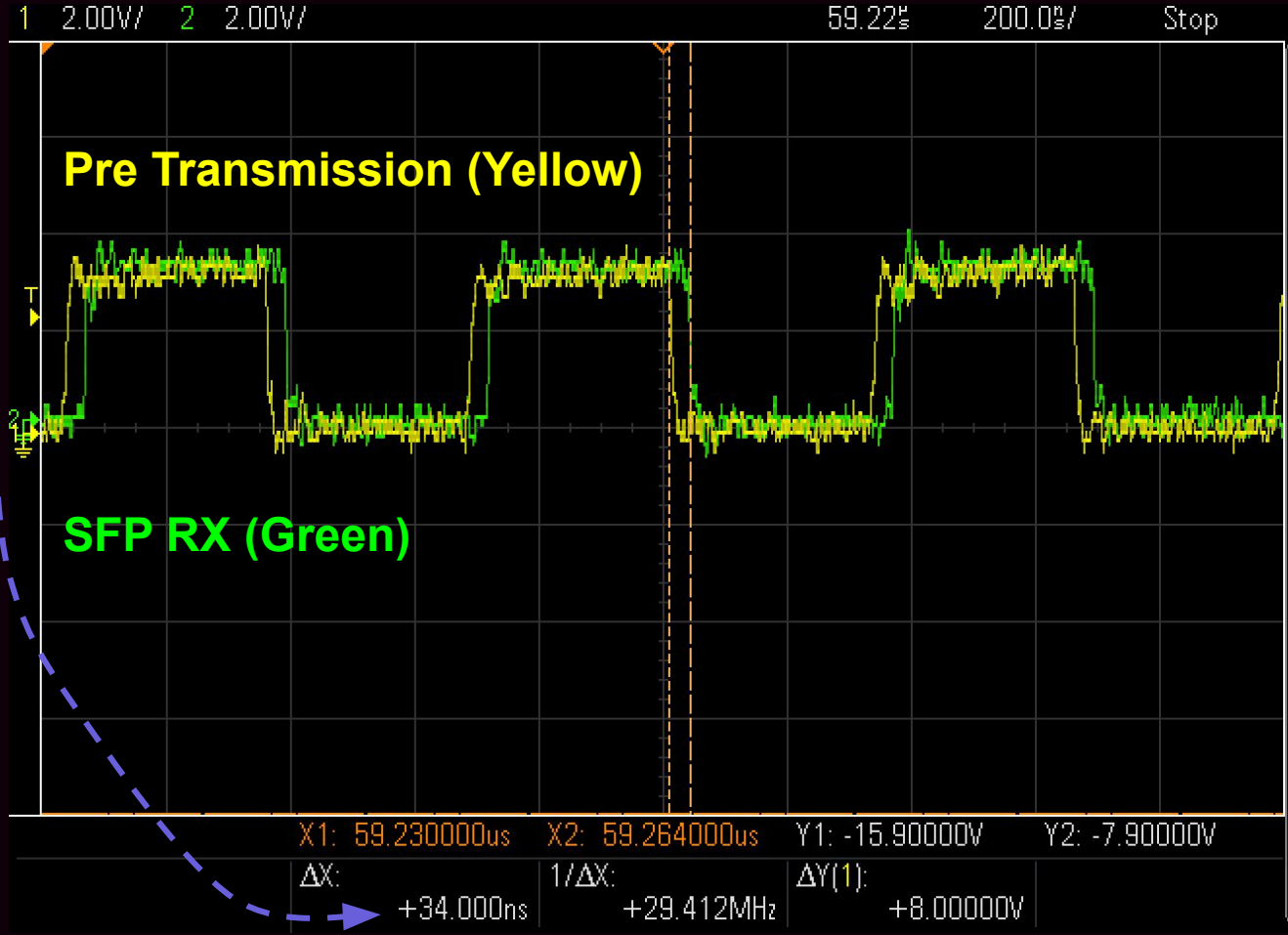


Latency

Adds about 34ns~

34 nanoseconds / 200000 km per second is about 680cm.

Not bad! Given the patch lead is at least 500 cm



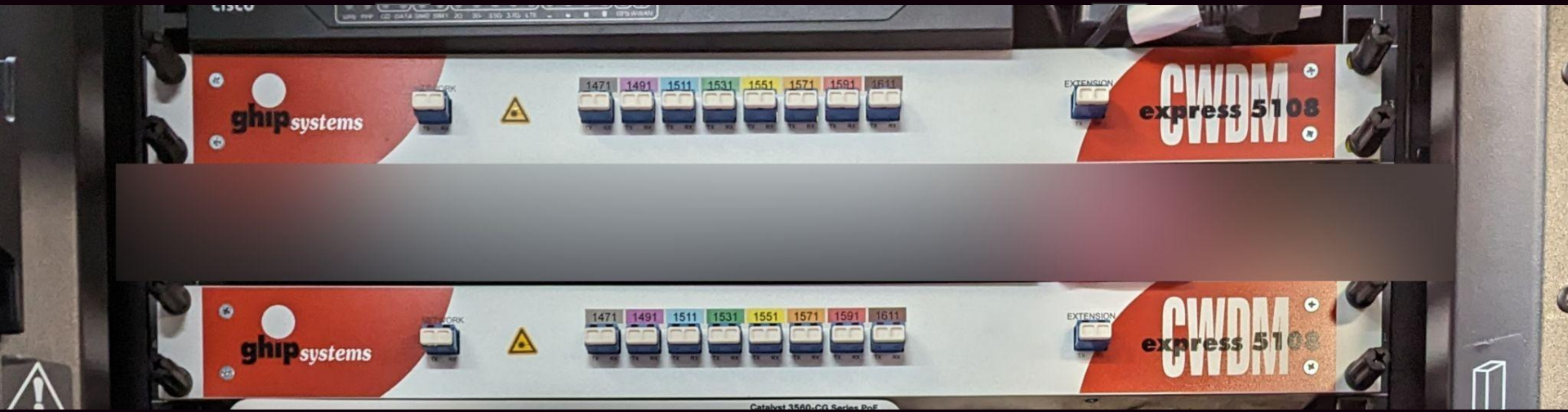
But what if we could go long haul?

About 650 meters~
IPH
Telehouse
Poplar Riverside
Leven
oad Green
Abbott Rd
Dee St
Ada Gardens
B125
Oban St
Blair St
Portree St
Lantick Rd
E India Dock Rd
Newham W
Village Ave
Bow Creek
Bow Creek Ecology Park
Orchard Wharf
Limmo Peninsula Ecological Park
River Lea
Hope St
Lookout Ln
Docklands Central
Switch
lon East

Coarse Wavelength Division Multiplexing

CWDM Channel from Jump Networks ~1km ish

- Thanks for James Rice for being trusting enough to be the 1st test case!
- IP-House <-> Telehouse North (London)
- Optical loopback on the telehouse side



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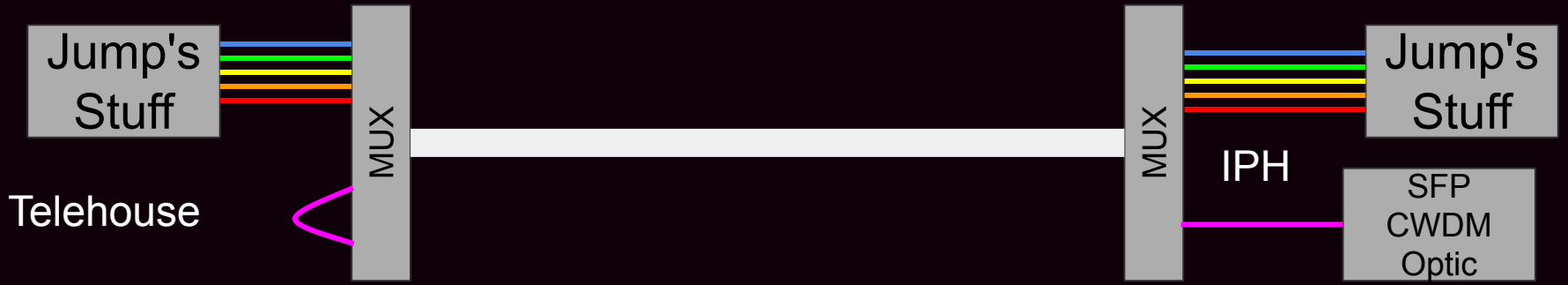
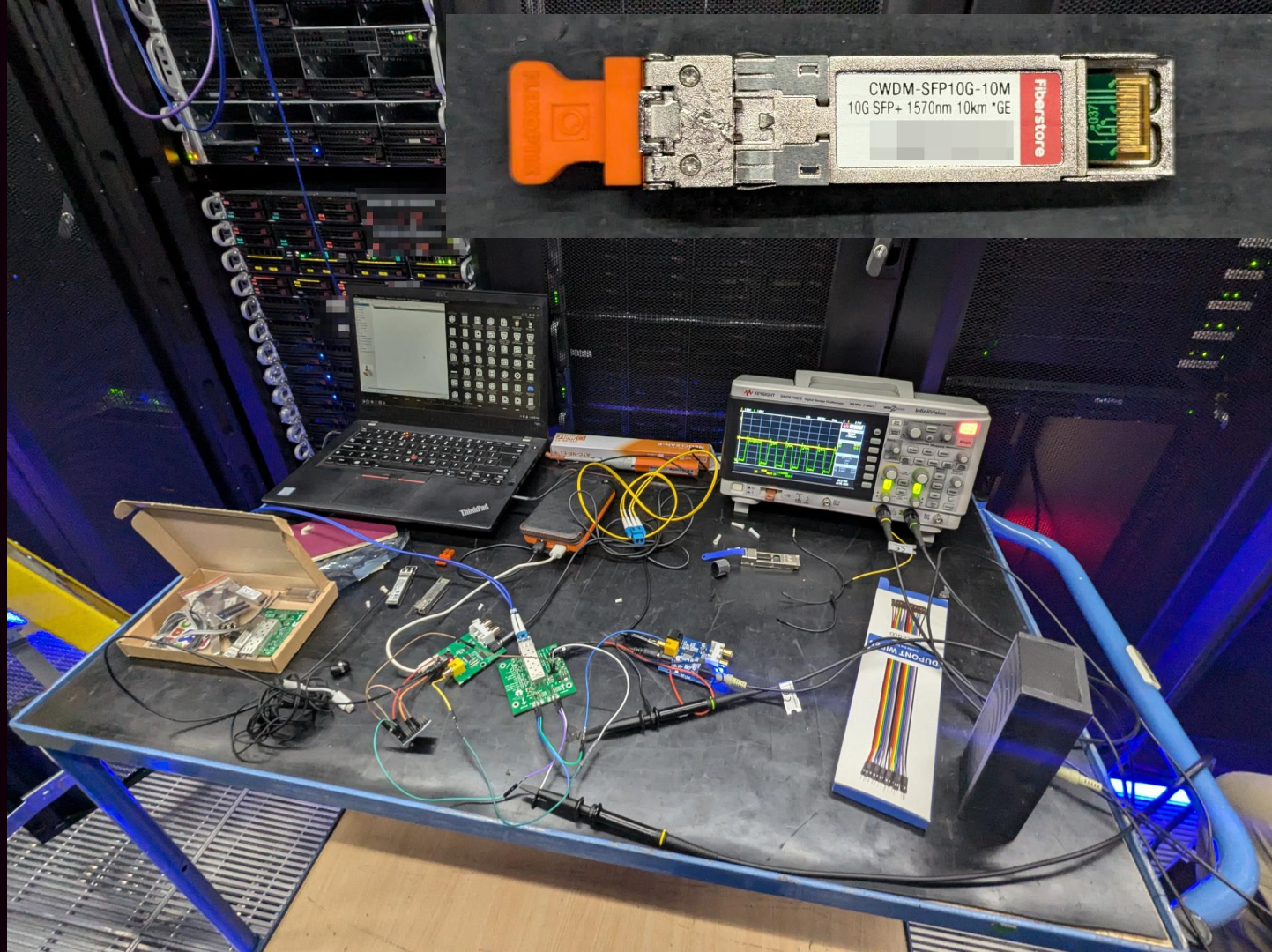


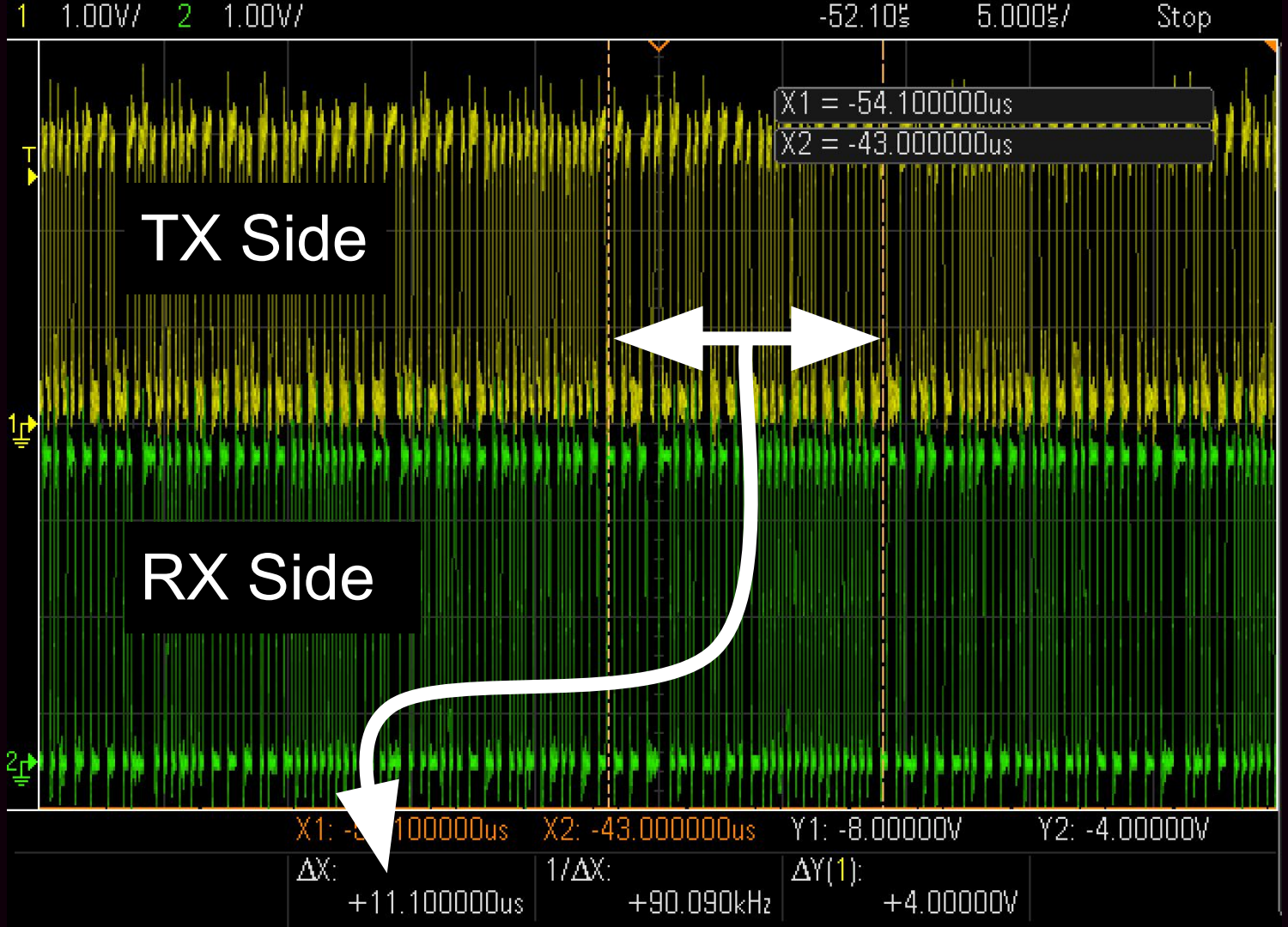
It worked!

- Portable speaker was fighting against the data hall noise!
- Did not destroy the CWDM optic!



Latency

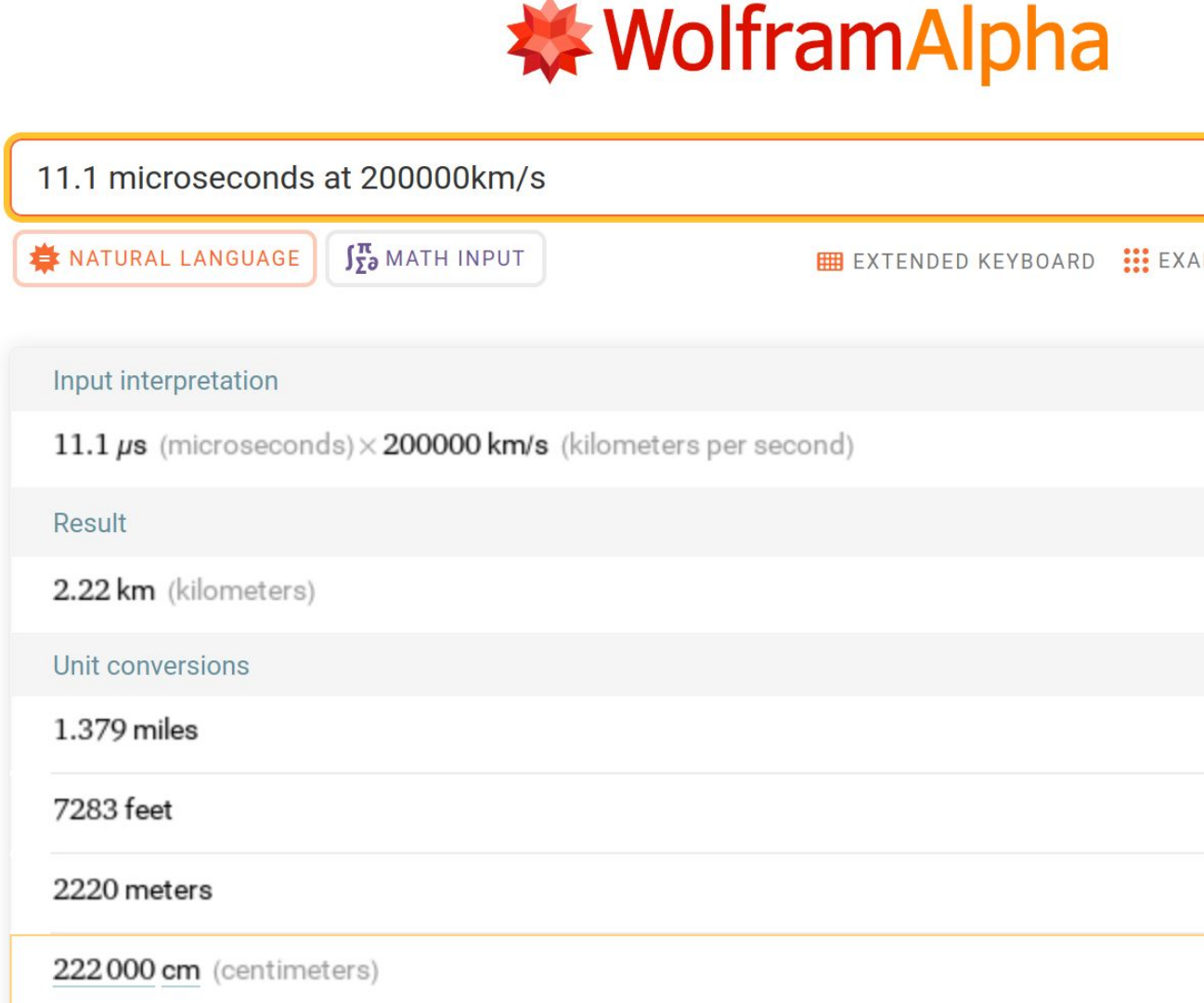
Harder this time on the scope because *11µs* requires you to zoom out a lot to find the offset



11μs = 2.2km

- Double what a very rough google maps estimate gave

- Building cabling on both sides likely add up a lot
- This is more like the distance if added a lap of both DC buildings (in 2D)



About 650 meters~
IPH
Telehouse
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Dee St
Ada Gardens
B125
Oban St
Blair St
Portree St
Lantick Rd
E India Dock Rd
Newham W
Village Ave
Bow Creek
Bow Creek Ecology Park
Orchard Wharf
Limmo Peninsula Ecological Park
River Lea
Hope St
Lookout Ln
Docklands Central
Switch
lon East

Telehouse London
Data Centres
Rosemary Dr
Oregano Dr

But what if we could go longer haul?

Longer haul options

- Typically, if you were doing 1G/10G you would be doing DWDM at this point
- DWDM is like CWDM, but uh, **D**enser!
- 8 channels to 32/64~ channels.
- Optics are more expensive because they have cooler/hotter physics inside to adjust their wavelength and are more precise in what wavelength they emit

Longer haul options

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- DWDM is like CWDM, but uh, Denser!
- 8 channels to 32/64~ channels.
- Optics are more expensive because they have cooler/hotter physics inside to adjust their wavelength and are more precise in what wavelength they emit
- DWDM also amplifies well with fiber amplifiers
    - Side note, The physics involved with EDFA amplifiers are bizarre and feel like a bug in physics

Other Longer Haul options

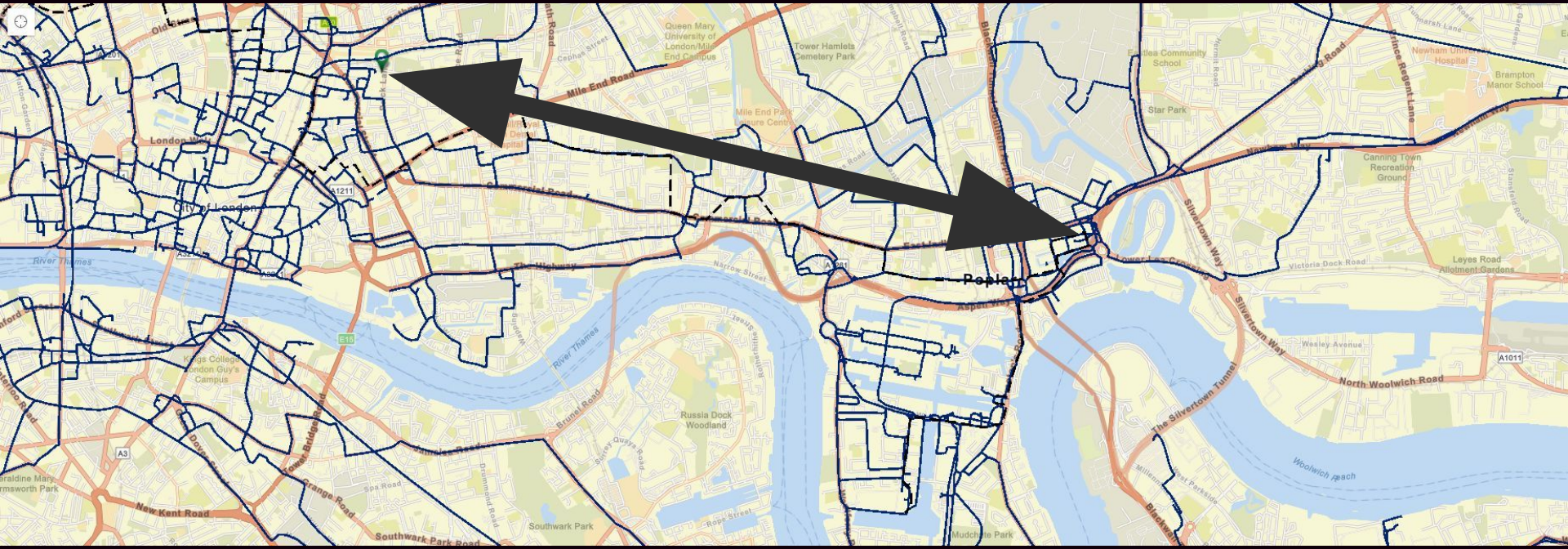
- Most times, you don't want your customers to use your multiplexer directly
  - You probably don't trust them to have the right transmission color/power and risking your other channels if they are too bright
- This is where you use a *transponder*, a transponder is something that basically copies and pastes a signal from one SFP to another
- The idea is that you have your customer connect at 1310nm LR/LX/etc, and you install the magic DWDM/Weird optic on your side!

- My weird signals work fine in transponders, as they are simple devices

Incompatible long haul options

- There are "muxponders" and other fancy "line systems" that do a lot more processing with the input signal
- These things achieve amazing density, by mostly understanding the signals coming in (Ethernet/FiberChannel/Infiniband/etc) and merging into a more denser high speed data streams.
- A Muxsponders understands ethernet etc directly, it "sees" your ethernet frames and packs them into time slots
- For example, a muxponder can have a number of 10G ethernet inputs, and output a single 200GBit/s (or faster) "beam"
- **You cannot send TOSLINK over these, sadly (for me) these are common with a lot of carriers (and their use is growing)**

DWDM TOSLINK



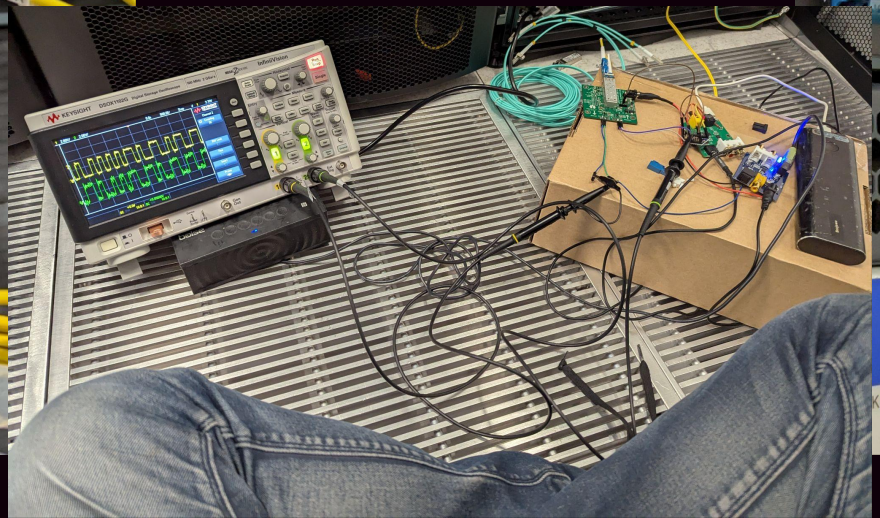
Physical distance is about ~6km from Interxion LON1 <-> Telehouse North

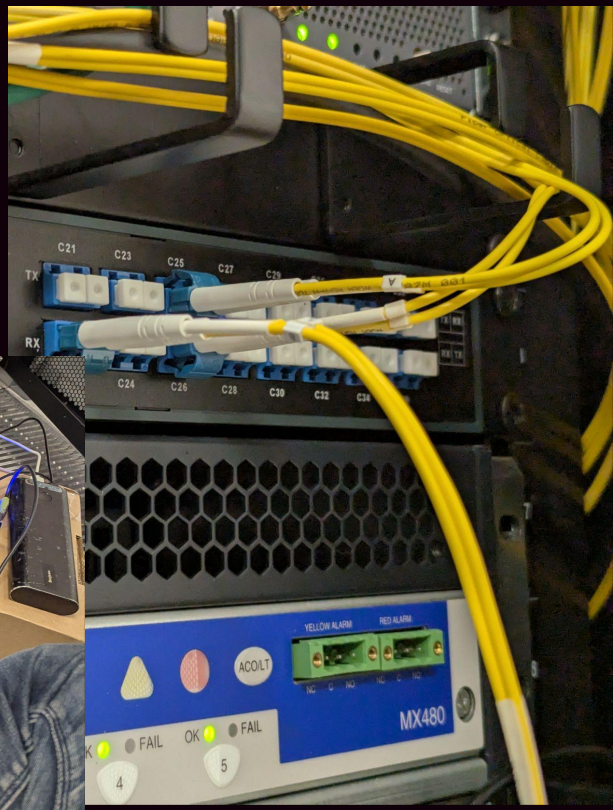
(Thank you to VeloxServ for letting me borrow a channel)

DWDM Setup

Telehouse (with loop)

Interxion



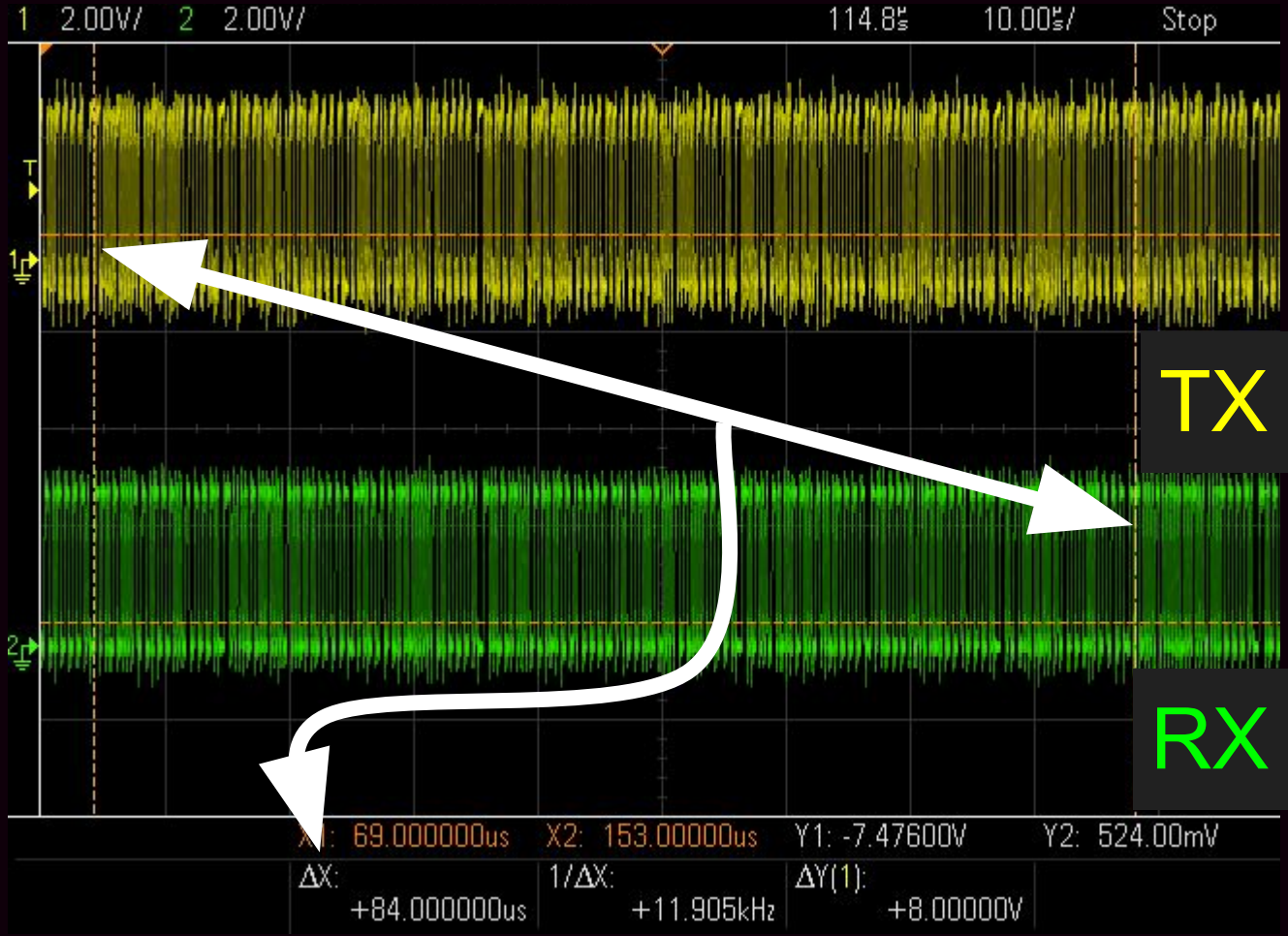


DWDM works!

- Round Trip ~84µs
- About 16.8KM of glass tube then

- With 10 db of optical attenuation to avoid blowing the optic up

(Thank you to Brandon Butterworth for lending me the optics)



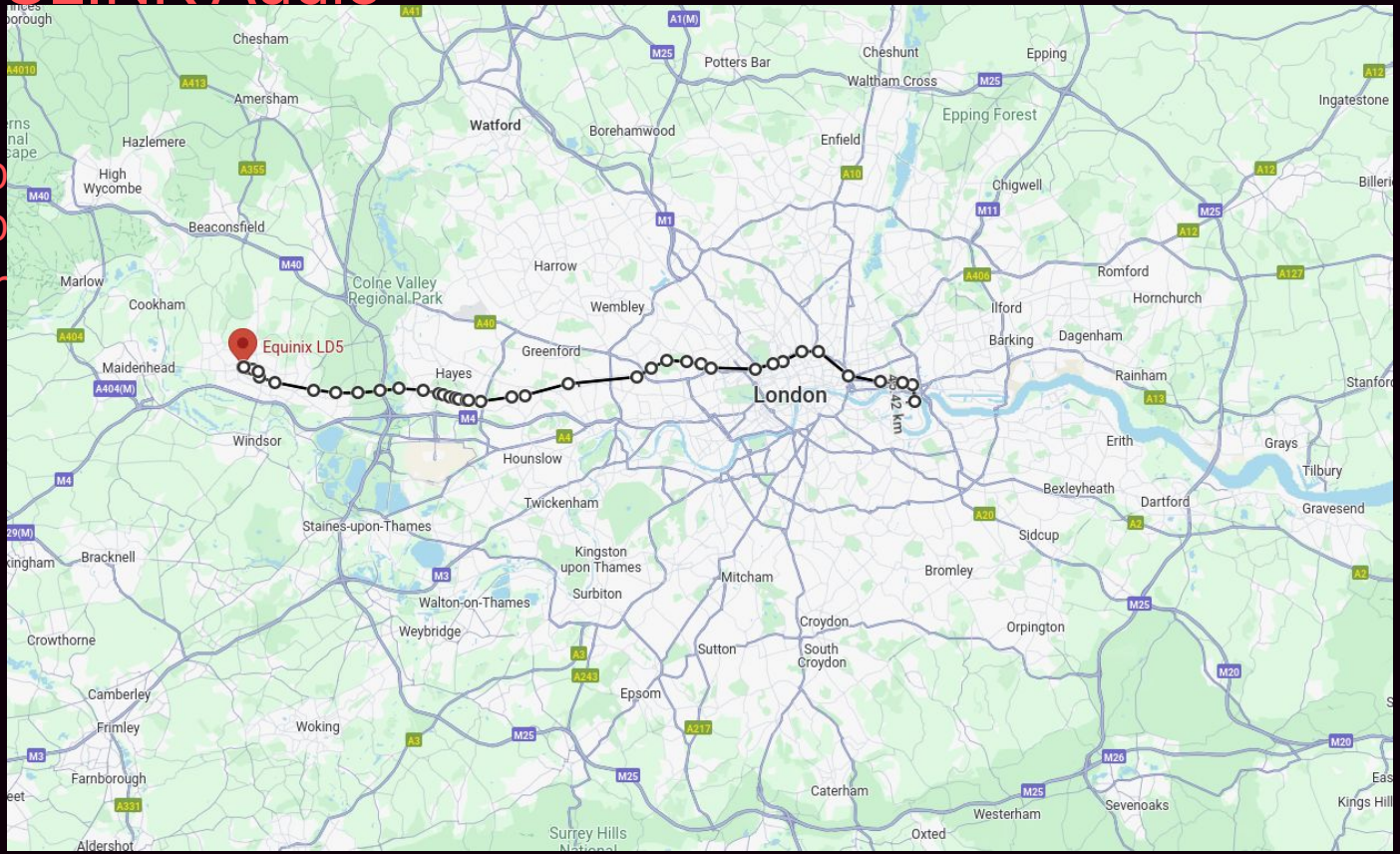
But what if we could go longer haul?

Inter-city TOSLINK Audio

- LONAP (❤️) had a spare DWDM between:
  - Equinix "LD"6 (Actually Slough, not London)
  - Equinix LD8 (London Docklands)
- This is not only intercity, but it's so far that it has to be amplified!
- Estimated to be 73 kilometers one way

Inter-city TOSLINK Audio

- LONAP (❤️)
  - Equinix LD
  - Equinix LD
- This is not or
- Estimated to



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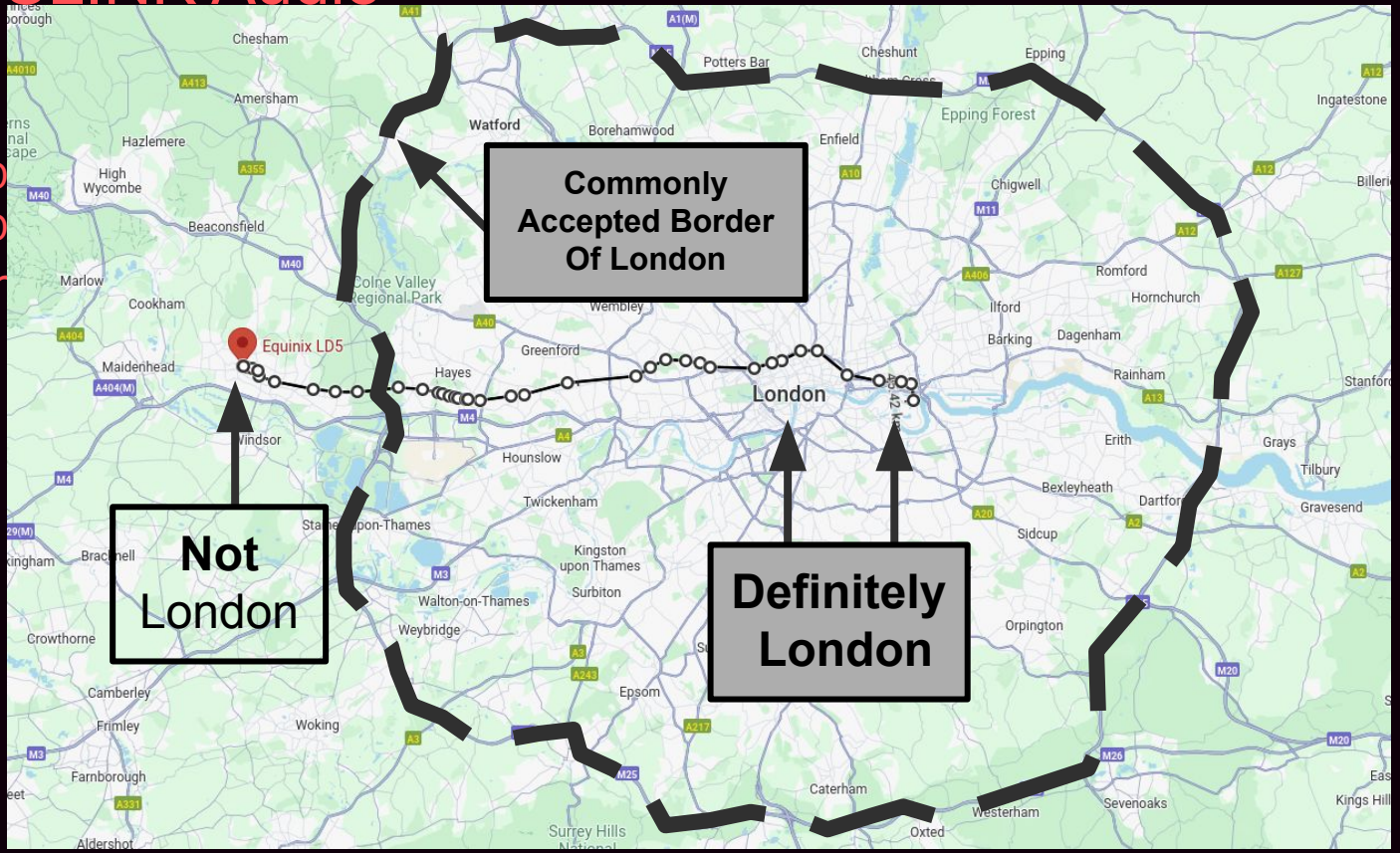
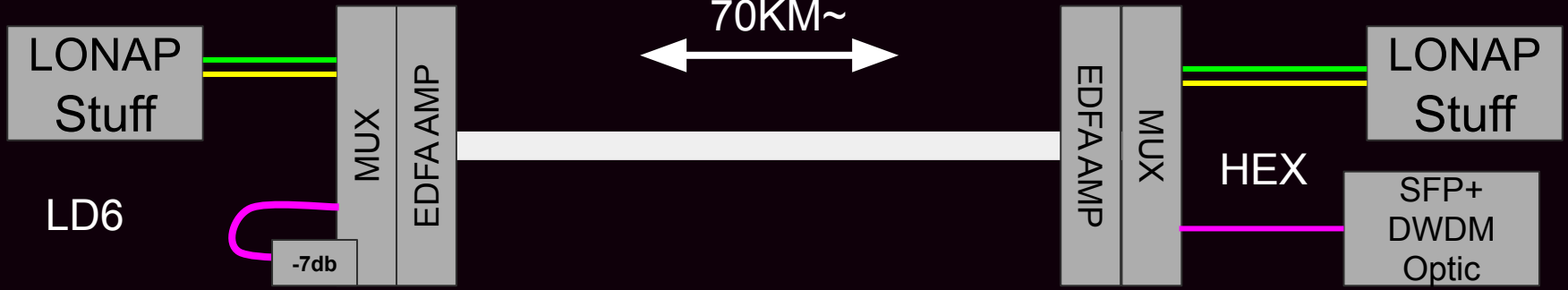


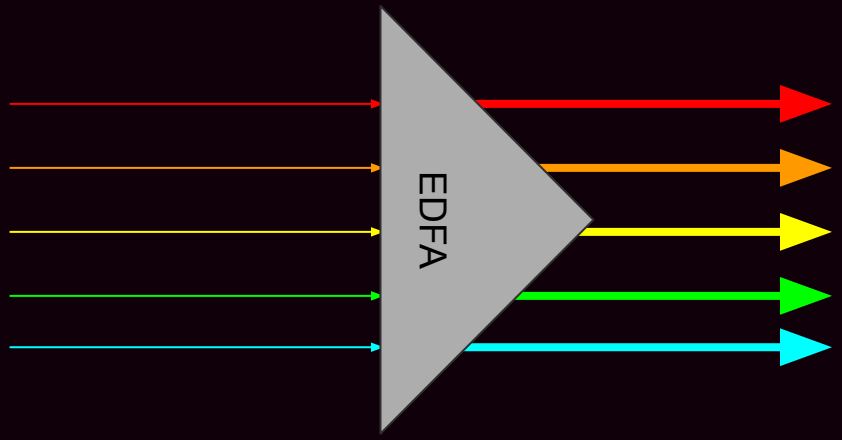

LONAP Stuff
LD6
-7db
MUX
EDFA AMP
70KM~
EDFA AMP
MUX
HEX
LONAP Stuff
SFP+ DWDM Optic

Inter-city TOSLINK Audio

- Used a spare DWDM SFP+, Plugged into a SmartOptics DCP-M40-C-ZR+
- Amplified, and DWDM Mux'd, a loop (with attenuator) was installed on one side so I didn't have to be in Slough for any longer than needed

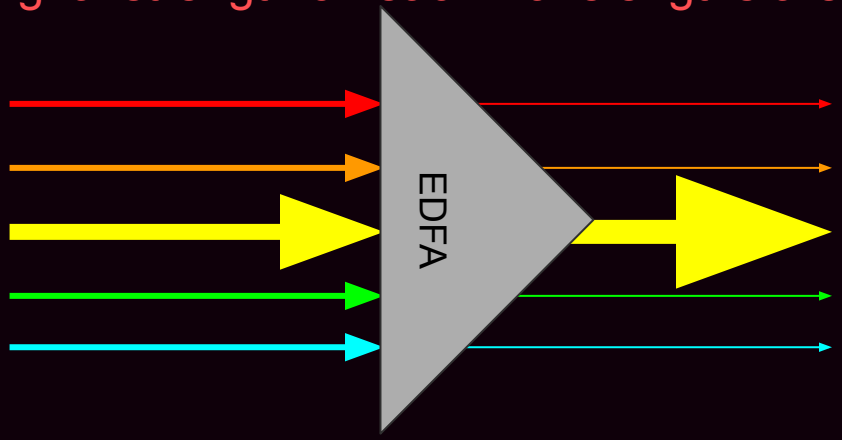
Why put attenuator on the loop?

- Erbium-Doped Fiber Amplifiers (EDFA) are magic, but they do have their limits



Why put attenuator on the loop?

- Erbium-Doped Fiber Amplifiers (EDFA) are magic, but they do have their limits
- But if the input signal strength on each wavelengths are not mostly the same:



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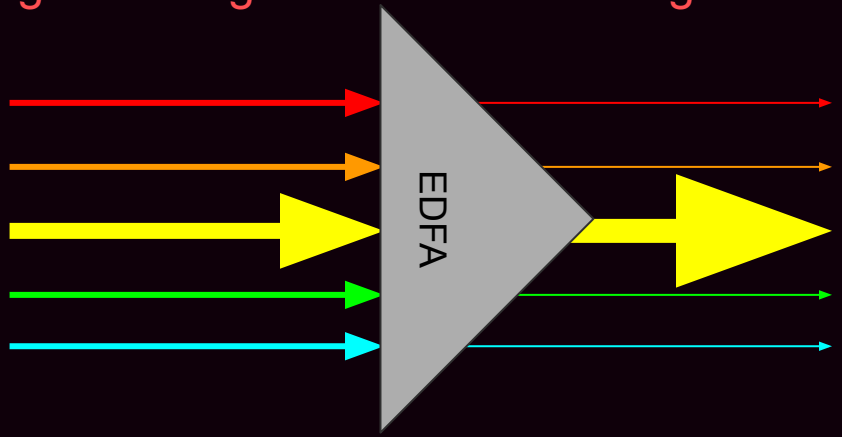
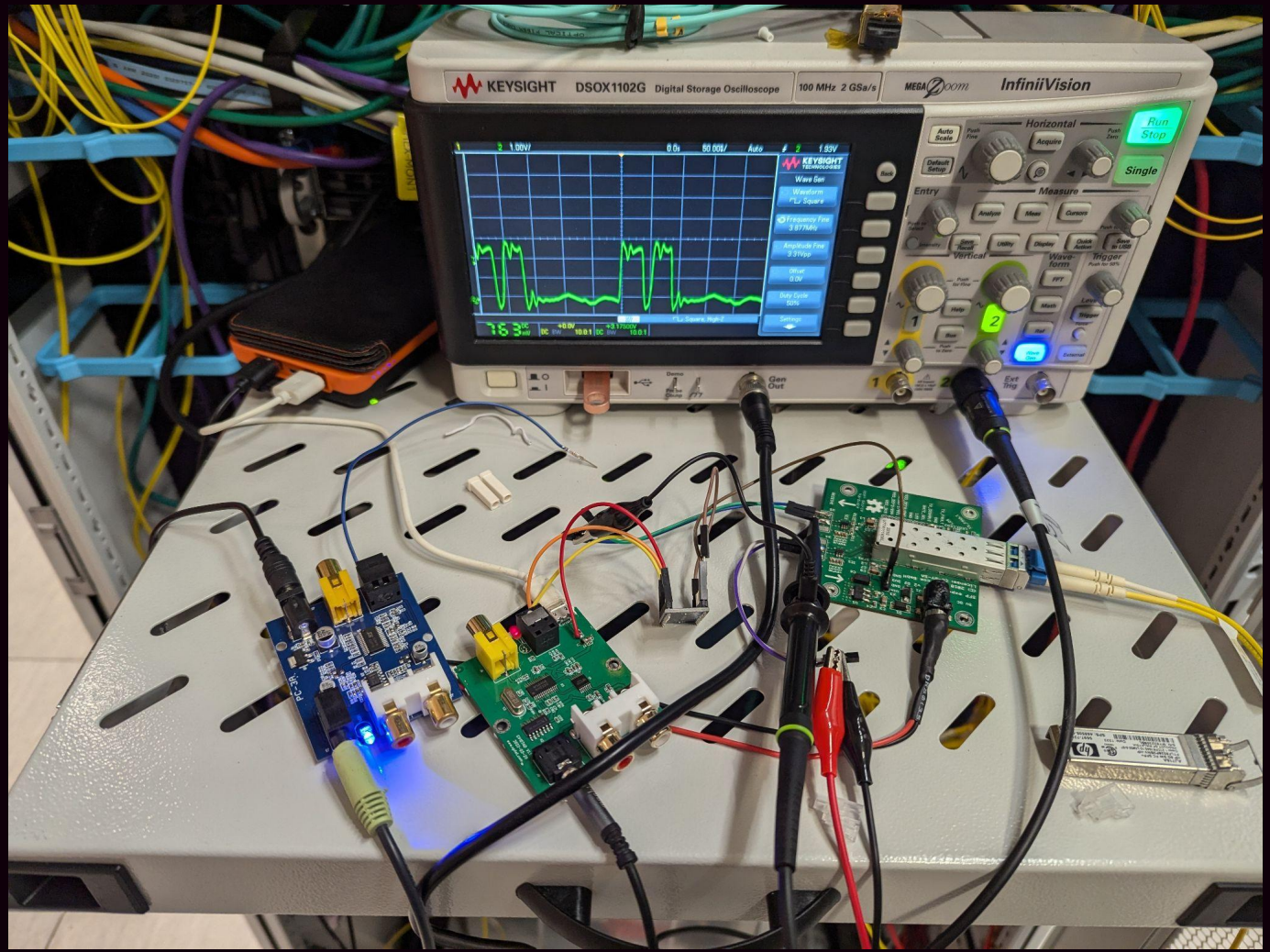


The mux+amp amplifies the signal on the way out as well, so if you have a loopback the input is much brighter than most optics can be

The mux gives some cool stats too

```
admin@hex-eqs-somuxc>show linkview

chassis-1

  Local system                                          Fiber            Remote system
  ================================================  ===============  ===================================
                                              Power  Loss             Power
  Hostname        Interface     Status  Alarm  [dBm]  [dB]  Direction  [dBm]  Interface     Hostname
  --------------  ------------  ------  -----  -----  ----  ---------  -----  ------------  --------------
  hex-eqs-somuxc  if-1/line-tx  up      ok       6.5  21.0    >>>>>    -14.5  if-1/line-rx  eqs-hex-somuxc
  hex-eqs-somuxc  if-1/line-rx  up      ok     -13.8  19.7    <<<<<      5.9  if-1/line-tx  eqs-hex-somuxc

admin@hex-eqs-somuxc>show interface

              Status             Rx power  Tx power            Expected
  Interface   [Rx/Tx]    Alarm   [dBm]     [dBm]     Format    wavelength[nm]  Description
  ----------  ---------  ------  --------  --------  --------  --------------  ------------
  if-1/line   up/up      ok         -13.8       6.5  wdm       n/a
  if-1/9210   up/up      ok          -7.5      -0.7  Coherent  1560.61
  if-1/9220   up/up      ok          -8.3      -0.6  Coherent  1559.79
  if-1/9230   idle/idle  ok         -99.0     -99.0  n/a       1558.98
…
  if-1/9590   up/up      ok           1.3      -2.3  1-32G     1530.33
```

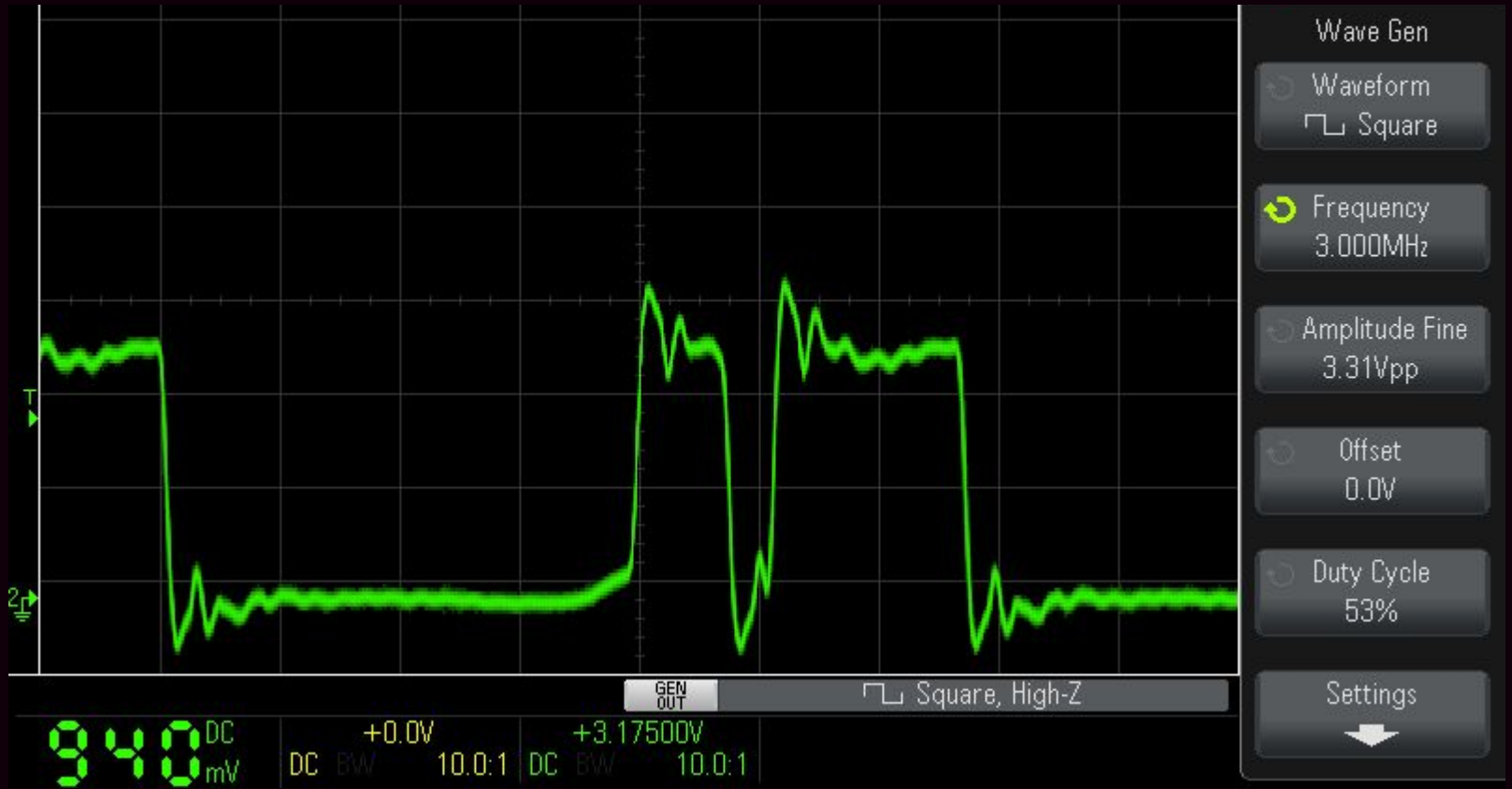
Rigged up


KEYSIGHT
DSOX1102G
Digital Storage Oscilloscope
100 MHz 2 GSa/s
InfiniiVision
Horizontal
Run
Stop
Single
Entry
Measure
Vertical
Trigger

It didn't work!

- Built the setup up using MultiMode optics for testing and confirmed that worked
- Swapped in the DWDM optic, and that didn't work
- DWDM optic + loop confirmed working by using a 1G USB SFP NIC
- Turns out this DWDM optic has a much higher bar for input/output speed!

Square wave via a FS.COM DWDM-SFP10G-80



3MHz min?!

- Tested with the scopes wave generator, the optic will only start working at 3mhz!
- Except the square is not very square at 3 mhz

My signal is very out of spec anyway

Stable at 6.5MHz (ish)

Our TOSLINK signal is 2.2MHz, but the square wave only really becomes square at 6.5MHz

it's all I had for DWDM C59,

Trip failed :(

Why?

- Finding the internal chips inside these optics is very hard
- Even if you know the IC part numbers, getting the datasheet is harder
- I made a guess this is some kind of signal processing for the longer distance?
  - LX/SR/CWDM optics start working at 150KHz, so unclear why so much for this DWDM optic
- This optic was also a 10G DWDM, maybe a 1G optic would work?
- I sent some emails to a number of optics vendors asking about this behaviour

AaAAAaaaAAa Retimers?!

- Finding the internal chips inside these optics is very hard
- Even if you know the IC part numbers, getting the datasheet is harder

Another piece of Information that might be helpful for you: **Make sure that the transceiver you want to use does not contain a clock and data recovery IC, sometimes also referred to as an eyeopener or retimer**. Those only can handle specific data rates and even the multirate ones likely won't be capable of dealing with your application. The good news is, **that most of the low data rate transceivers don't have those chips**, they rely only on limiting amplifiers for the RX path and Laser diode drivers for the TX path. These can handle non standard data rates. The long distance Transceivers for multi gigabit applications are more likely to have those ICs and should thus be avoided.

FLEXOPTIX, Thank you to Gert & Thomas

New day, New optics

- Acquired a *brand new* 1G DWDM optic
- Also a pile of 2nd hand DWDM optics that other people no longer needed
- Armed with better testing equipment at home so I can test at short distances before I go to the data center
- Will it work?

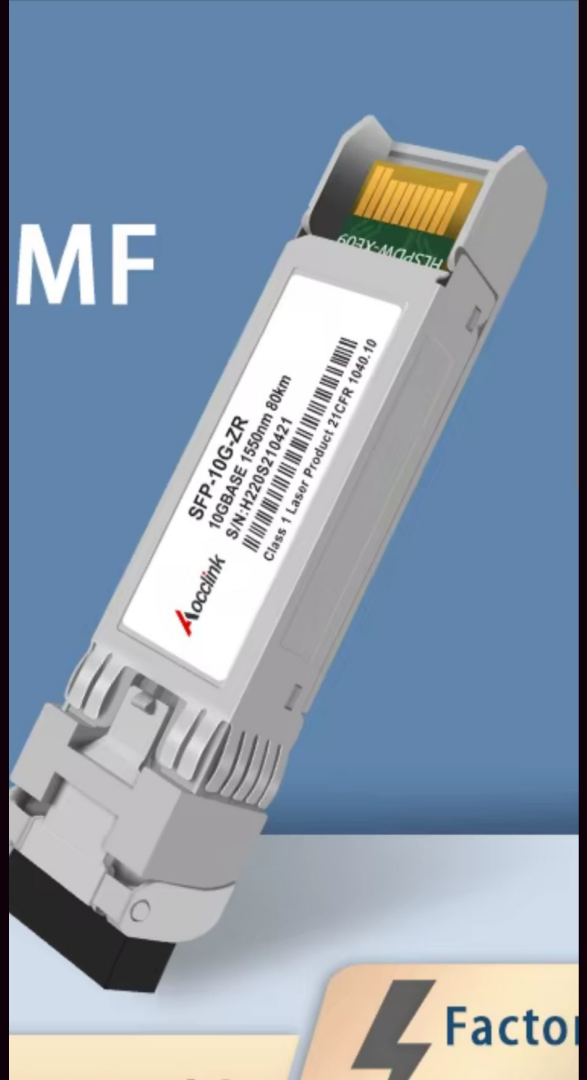
Suspect optics

Suspect optics

"HLSPDW-**XE**09" is suspect

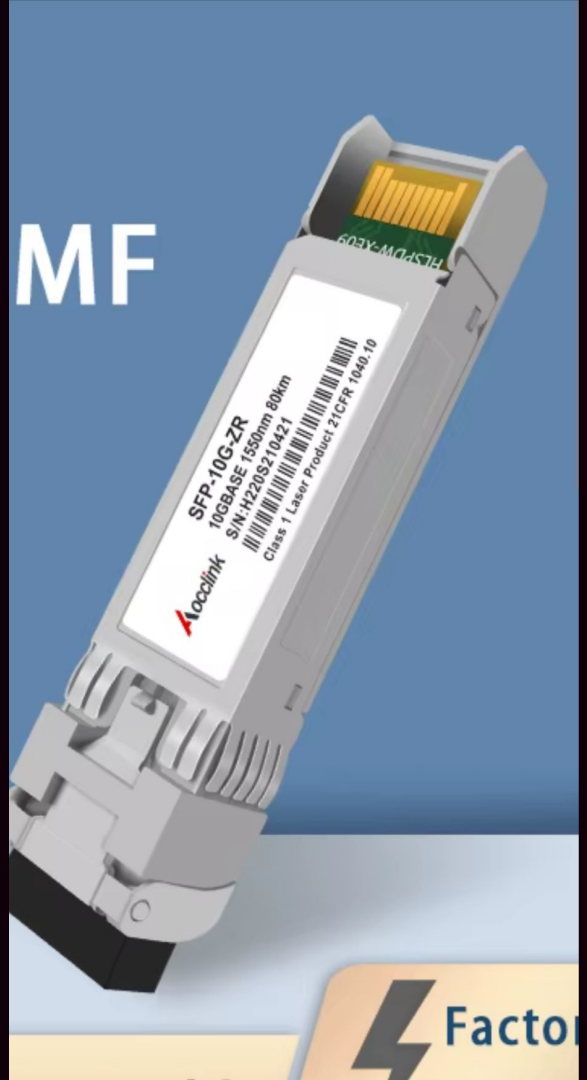
Tweaked 10G Optics

- Searching for HLSPDW-XE09 brings up a load of 10G DWDM optics from other vendors



Tweaked 10G Optics

- Searching for HLSPDW-XE09 brings up a load of 10G DWDM optics from other vendors
- My optic behaves exactly like the 10G DWDM one
- Mine is almost certainly a 10G DWDM optic with it's EEPROM reprogrammed to be "1G"



Wait, The optics have a EEPROM?

```
eeprom: 0000: 03 04 07 20 00 00 00 00  00 01 00 06 67 00 0a 64  ... .... ....g..d
        0010: 00 00 00 00 51 53 46 50  54 45 4b 20 20 20 20 20  ....QSFP TEK
        0020: 20 20 20 20 00 00 0b 40  51 54 2d 53 46 50 2b 2d      ...@ QT-SFP+-
        0030: 4c 52 20 20 20 20 20 20  42 20 20 20 05 1e 00 c9  LR      B   ....
        0040: 00 1a 00 00 51 54 38 32  33 31 31 31 34 30 36 36  ....QT82 31114066
        0050: 20 20 20 20 32 33 31 31  31 35 20 20 68 f0 03 07      2311 15  h...
        0060: 00 00 08 8e a9 66 96 16  47 ca 48 cb d8 36 e2 ef  .....f.. G.H..6..
        0070: 07 13 c6 00 00 00 00 00  00 00 00 00 2e de f1 c5  ........ ........
        0080: 5a 00 d3 00 55 00 d8 00  8d cc 74 04 87 5a 7a 76  Z...U... ..t..Zzv
        0090: c3 50 13 88 9c 40 27 10  45 77 04 eb 2b d4 07 cb  .P...@'. Ew..+...
        00a0: 37 2d 00 c8 2b d4 01 3c  00 00 00 00 00 00 00 00  7-..+..< ........
        00b0: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ........ ........
              00 00 00 3f 80 00 00 00  00 00 00 01 00 00 00 00  ....?... ........
              00 00 00 01 00 00 00 01  00 00 00 00 00 00 00 64  ........ .......d
              7 2c 7f 28 40 bf 1a 85  11 a9 00 00 00 00 08 00  ',.(@... ........
              0 00 00 40 00 00 08 00  00 00 00 00 00 00 00 00  ...@.... ........
```

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```
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        0010: 00 00 00 00 51 53 46 50  54 45 4b 20 20 20 20 20  ....QSFP TEK      (Vendor)
        0020: 20 20 20 20 00 00 0b 40  51 54 2d 53 46 50 2b 2d      ...@ QT-SFP+- (Part)
        0030: 4c 52 20 20 20 20 20 20  42 20 20 20 05 1e 00 c9  LR      B   ....
        0040: 00 1a 00 00 51 54 38 32  33 31 31 31 34 30 36 36  ....QT82 31114066 (Serial)
        0050: 20 20 20 20 32 33 31 31  31 35 20 20 68 f0 03 07      2311 15  h... (Date)
        0060: 00 00 08 8e a9 66 96 16  47 ca 48 cb d8 36 e2 ef  .....f.. G.H..6..
        0070: 07 13 c6 00 00 00 00 00  00 00 00 00 2e de f1 c5  ........ ........
        0080: 5a 00 d3 00 55 00 d8 00  8d cc 74 04 87 5a 7a 76  Z...U... ..t..Zzv
        0090: c3 50 13 88 9c 40 27 10  45 77 04 eb 2b d4 07 cb  .P...@'. Ew..+...
        00a0: 37 2d 00 c8 2b d4 01 3c  00 00 00 00 00 00 00 00  7-..+..< ........
        00b0: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ........ ........
              00 00 00 3f 80 00 00 00  00 00 00 00 01 00 00 00  ....?... ........
              00 00 00 01 00 00 00 01  00 00 00 00 00 00 00 64  ........ .......d
              7 2c 7f 28 40 bf 1a 85  11 a9 00 00 00 00 08 00  ',.(@... ........
              0 00 00 40 00 00 08 00  00 00 00 00 00 00 00 00  ...@.... ........
```
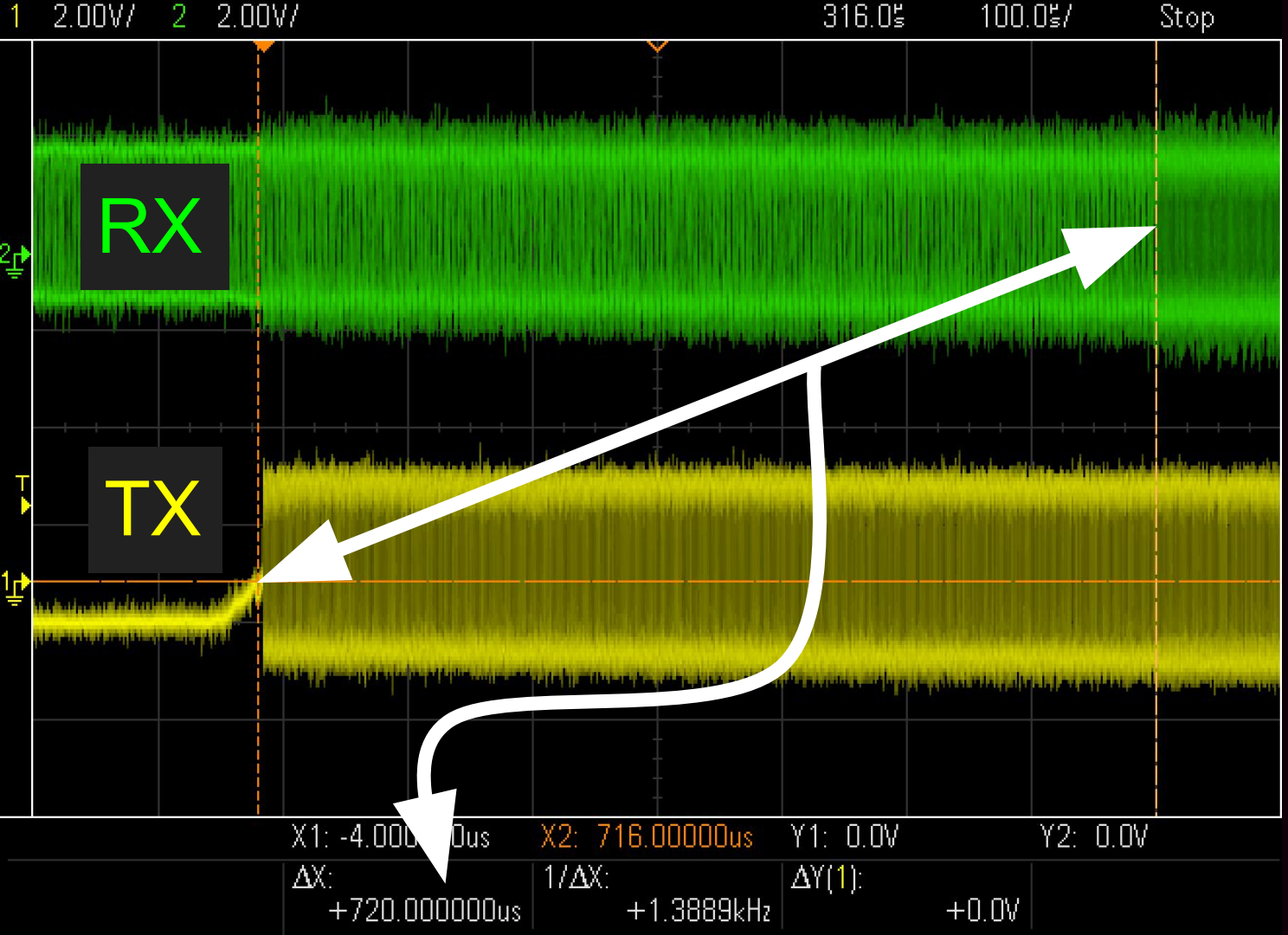
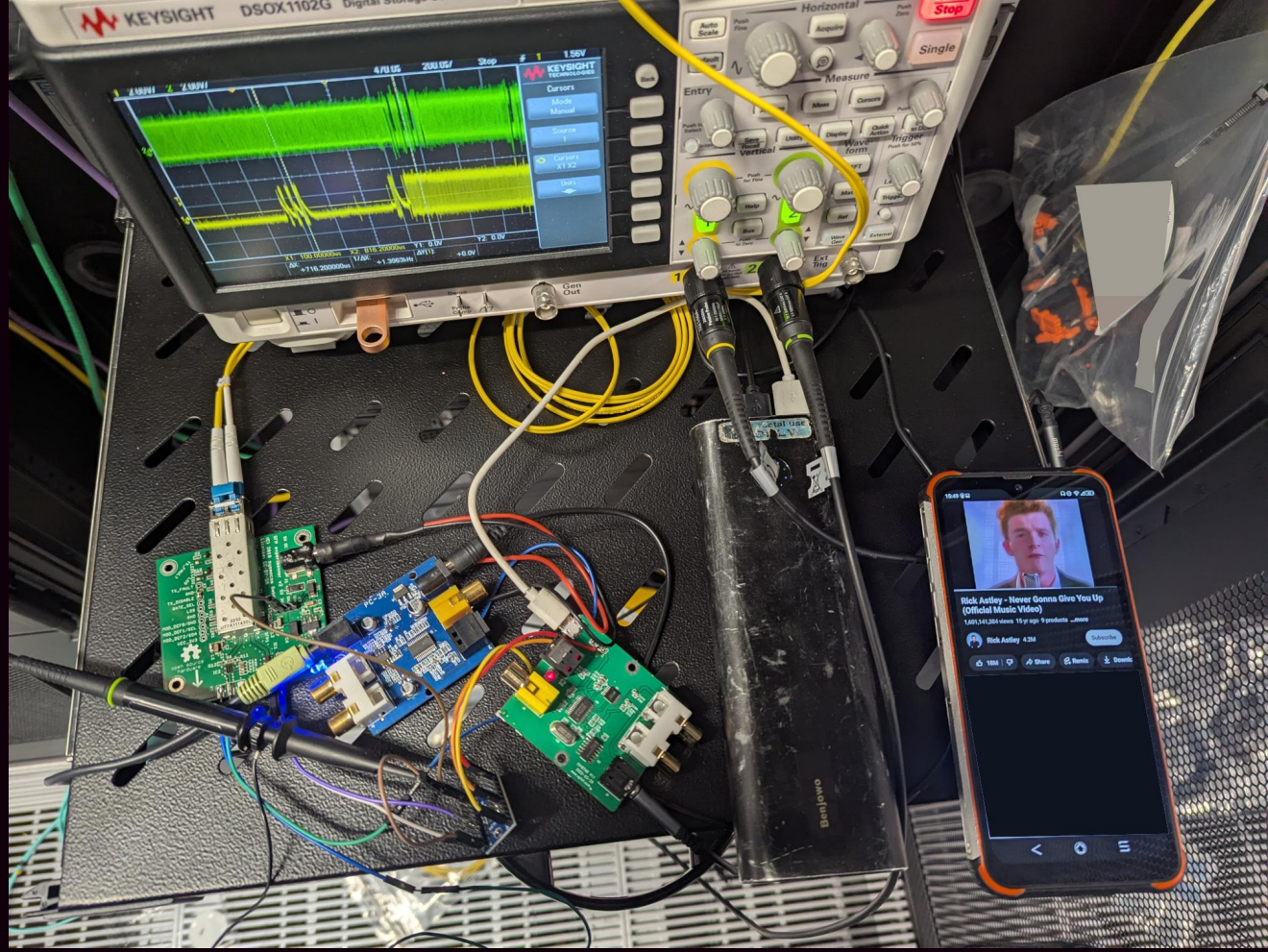

140 km: Round 2

- Armed with a old 1G DWDM optic on a different channel, since it seems that brand new DWDM 1G optics are not being made anymore!



- Harder to measure latency this time by matching bits
- Instead measure "strope time"
- 720µs round trip
- ~143.2km

140 km: Round 2



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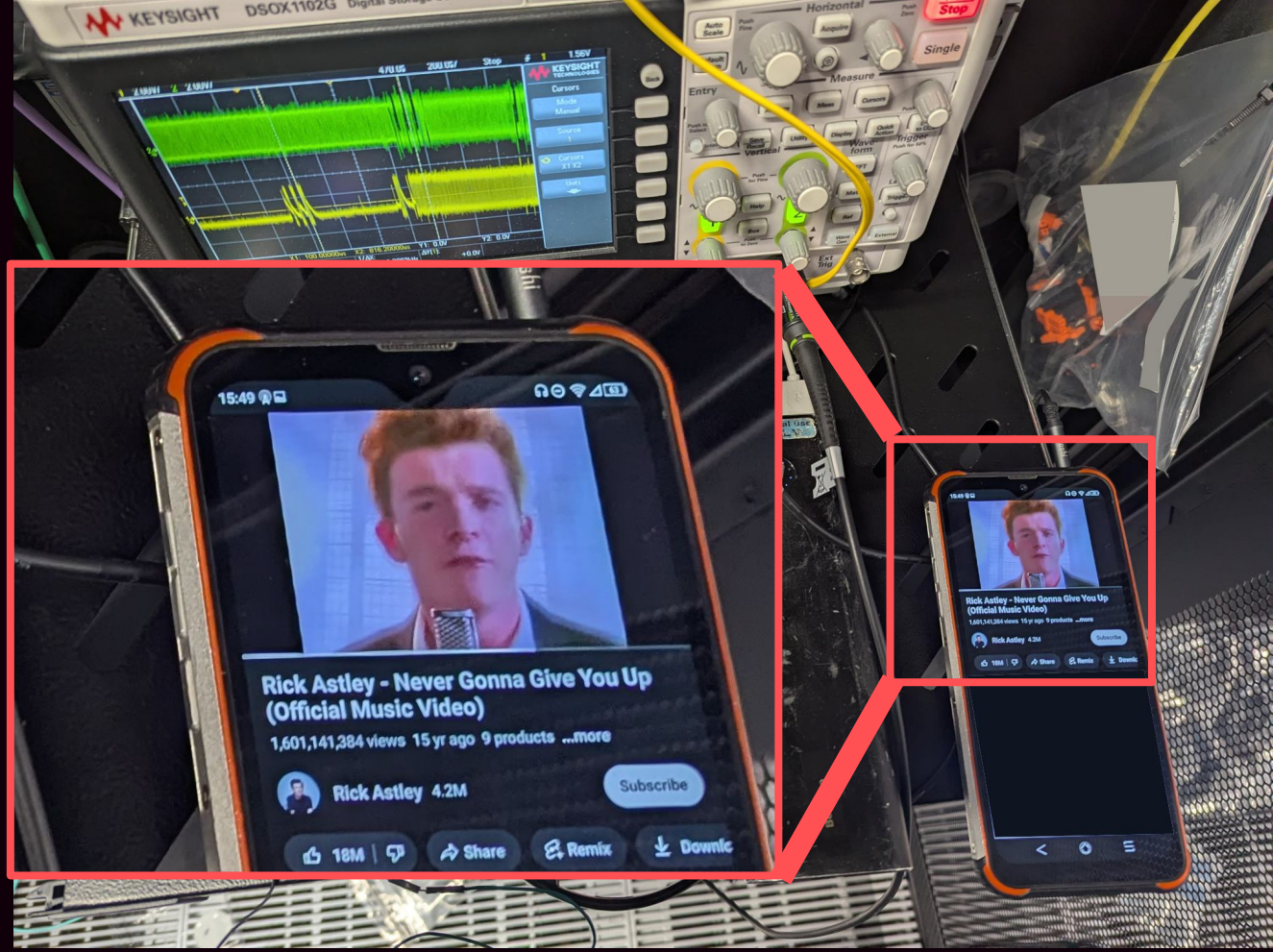

Future (pointless) innovation

- If the SFP pluggable didn't have a LVDS in it, it would be nice to drive the laser directly, send "raw" audio in its full glory (and probably damage the laser)
  - I hear this is sorta how "RF over Fiber" works
  - A friend also suggested YOLO-ing a FM signal might work, I didn't get to test this, but I bet it does

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- It is tempting to attach a "dialup" modem to both sides
  - This would create the greatest waste of a 100 GHz optical channel, in that it gives a final output bandwidth of ~40 kbit/s
  - And ***extremely*** confuse some intelligence agency I assume

To conclude

- Yes, you can send "low" speed signals over SFP optics
  - Sometimes, Most optics start working at 150 KHz, the retimers don't like working below 6 MHz for some optics
- You can even send them very far

To conclude

- Yes, you can send "low" speed signals over SFP optics
  - Sometimes, Most optics start working at 150 KHz, the retimers don't like working below 6 MHz for some optics
- You can even send them very far
- There is likely not a good reason to do this. There are better IP solutions now
  - But knowing how things work is important! Knowing something is possible is useful to build bigger, better, ***more horrifying*** solutions or workarounds to problems
- I know far more about optical transmission, and general inner optics workings now
  - Maybe you do too!

Questions?

Shy? Ask me here instead:

Email 38c3@benjojo.co.uk

Fedi @benjojo@benjojo.co.uk