Improving light coupling into instruments with integrated photonic circuits and low temperature detectors:

Or does it make sense to include optical integrating in the RDC work package?

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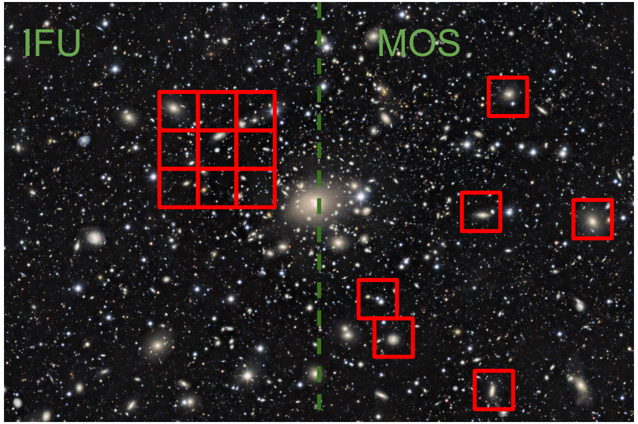
Motivation

Objective: Make spectrometer to advance capability of determining atmospheric composition/habitability on exoplanets

Method: Make a medium resolution spectrograph for use in multi-object or integral field spectroscopy at next generation extremely large telescopes (>30 m) with wavefront control/single mode fiber injection.

Innovation: Use photonic circuits integrated with low temperature detector (i.e. MKIDs, TES, ~~SNSPDs~~) instead of bulk optics and conventional semiconductor photodetectors as the spectrometer

Advantage: Significant reduction of size weight cost of instrument, and potential decrease in measurement time.



Collaboration and Funding

Got small amounts of funding.

- Found Industry partner (Small Business Technology Transfer) STTR funding from NASA
- Later got a grad student on NSF fellowship
- NSF EArly-concept Grants for Exploratory Research (EAGER) funding.

UCSB

ULTRA-LOW LOSS
TECHNOLOGIES

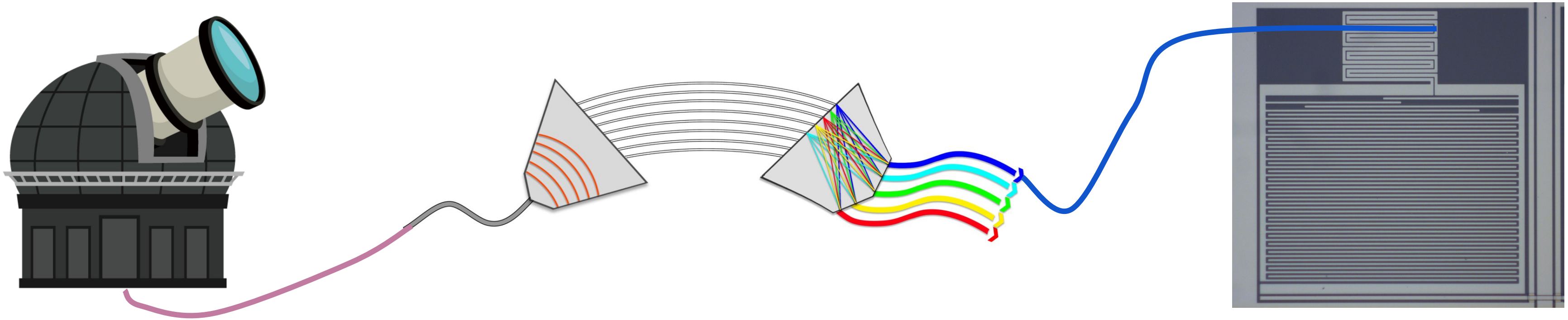
NSF

NASA

Specification Goals

Photonic circuit disperse light, then photon detection by MKIDs!

- $R=\lambda/\Delta\lambda \sim 5000$
- Bandwidth: 400 nm - 800 nm
- Fiber to MKID throughput: 60%
- Number of detector channels: 1024
- Operation temperature: ~100 mK
- Integrated MKID + Waveguide Chip ~10 cm^2



Current State of the Art

Compare to Dark Energy Spectroscopic Instrument (DESI)

10 spectrographs each illuminated by 500 multimode fibers

CCD detectors at ~140K

Bandwidth	360 nm - 980 nm
R = $\lambda/\Delta\lambda$	2000 - 5000
Throughput	60% - 78%

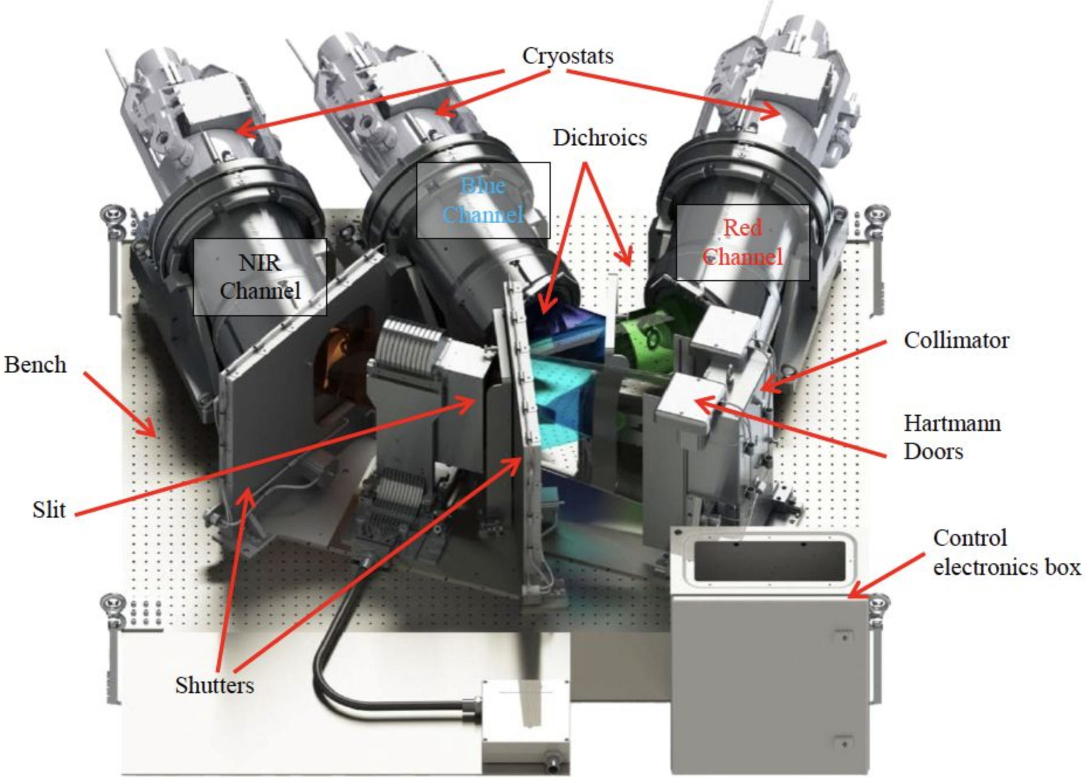
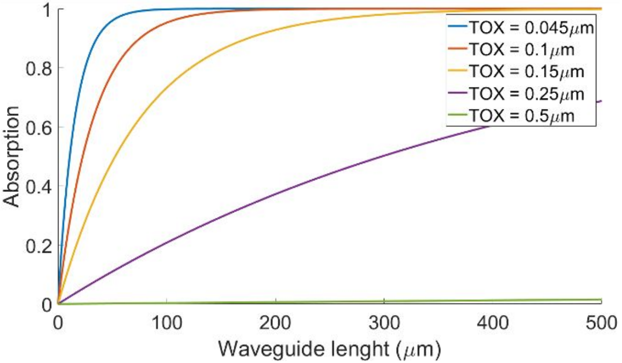


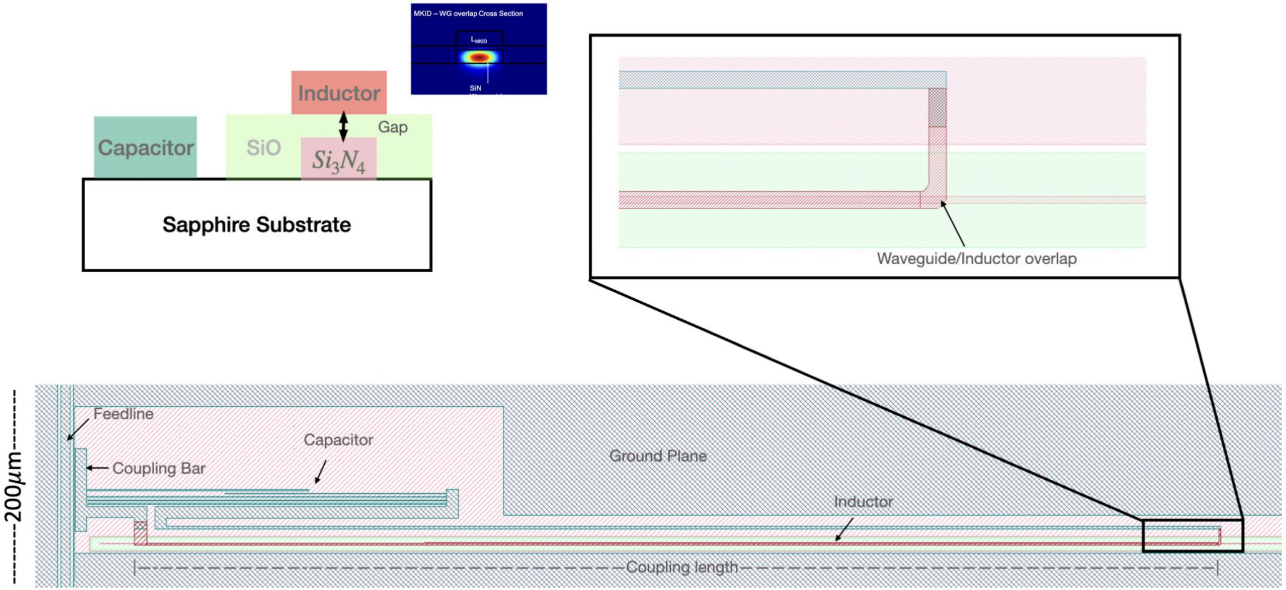
Figure 1. Top: Optical layout of the spectrographs. Bottom: mechanical implementation. The spectrograph is 1.8 m wide × 1.4 m deep × 0.6 m high. https://hal.science/hal-02003974

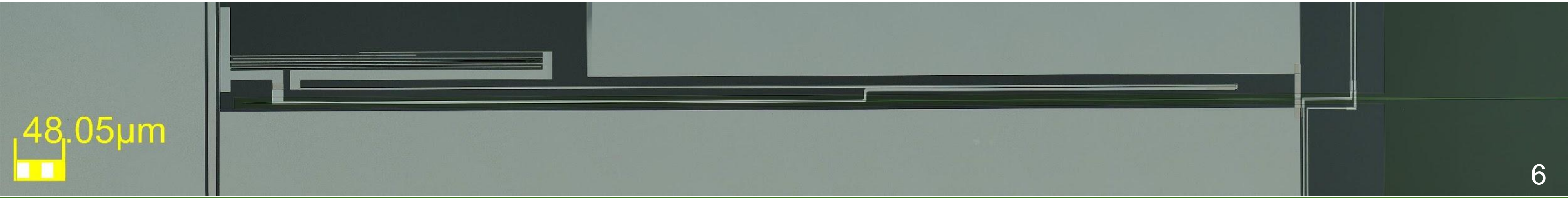
Photon Detection Through Evanescent Coupling

- Photonic waveguides run over MKID inductor

Coupling Efficiency

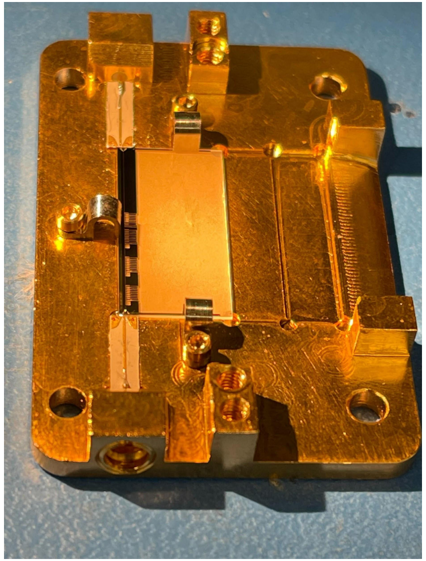


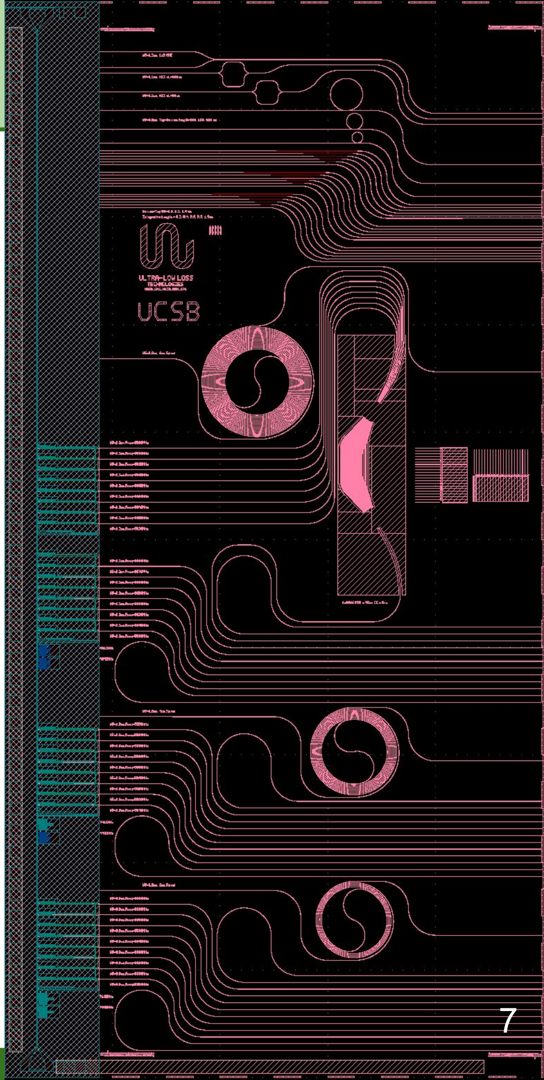




Test Chips

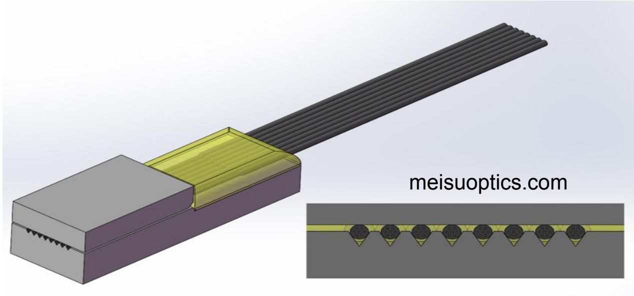
- 32 α- and/or β- tantalum MKIDs
- Arrayed Waveguide Gratings (AWGs) connected to MKIDs
- Spirals, Ring resonators, Mach-Zehnder Interferometers (MZIs)
- Sapphire substrate / ‘Platform’
- Single mode fiber couple-able

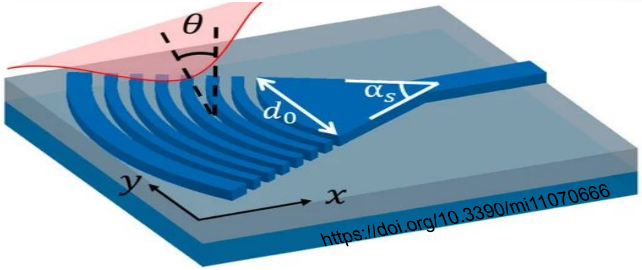


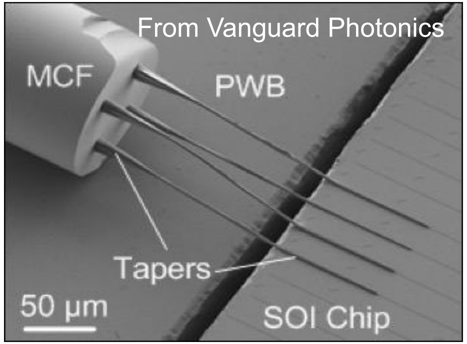


Fiber to Chip Coupling

Pros	Cons
Fiber Array	
Standard Available	< 65% coupling > $2.5K to make + > $1.5K to attach Rigid connection of dissimilar materials
Grating / Free Space Coupler	
Can possibly give >95% coupling	Narrow band, $\Delta\lambda/\lambda$ < 5% Double sided
Photonic Wire Bond / 3D Lithography	
>80% coupling and highly optimizable Probably good at lot temp, Scalable	Expensive new unavailable ~$50k NRE + ~$1k/job
Edge Fire / Butt Coupling	
Fast, Free and Nondestructive	Expensive, Large positioning stage in the cryostat





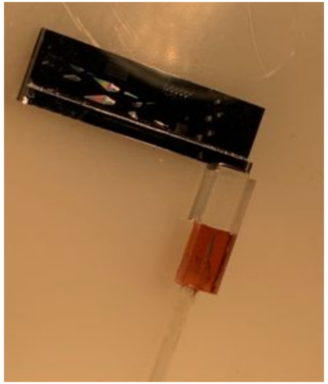


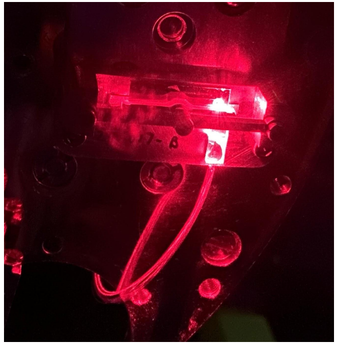
Key Challenges

- Monolithic WG-MKID integration
  - WGs need glassy dielectric processed at high temperature
  - Degrades MKIDs performance
  - Fab solutions accessible

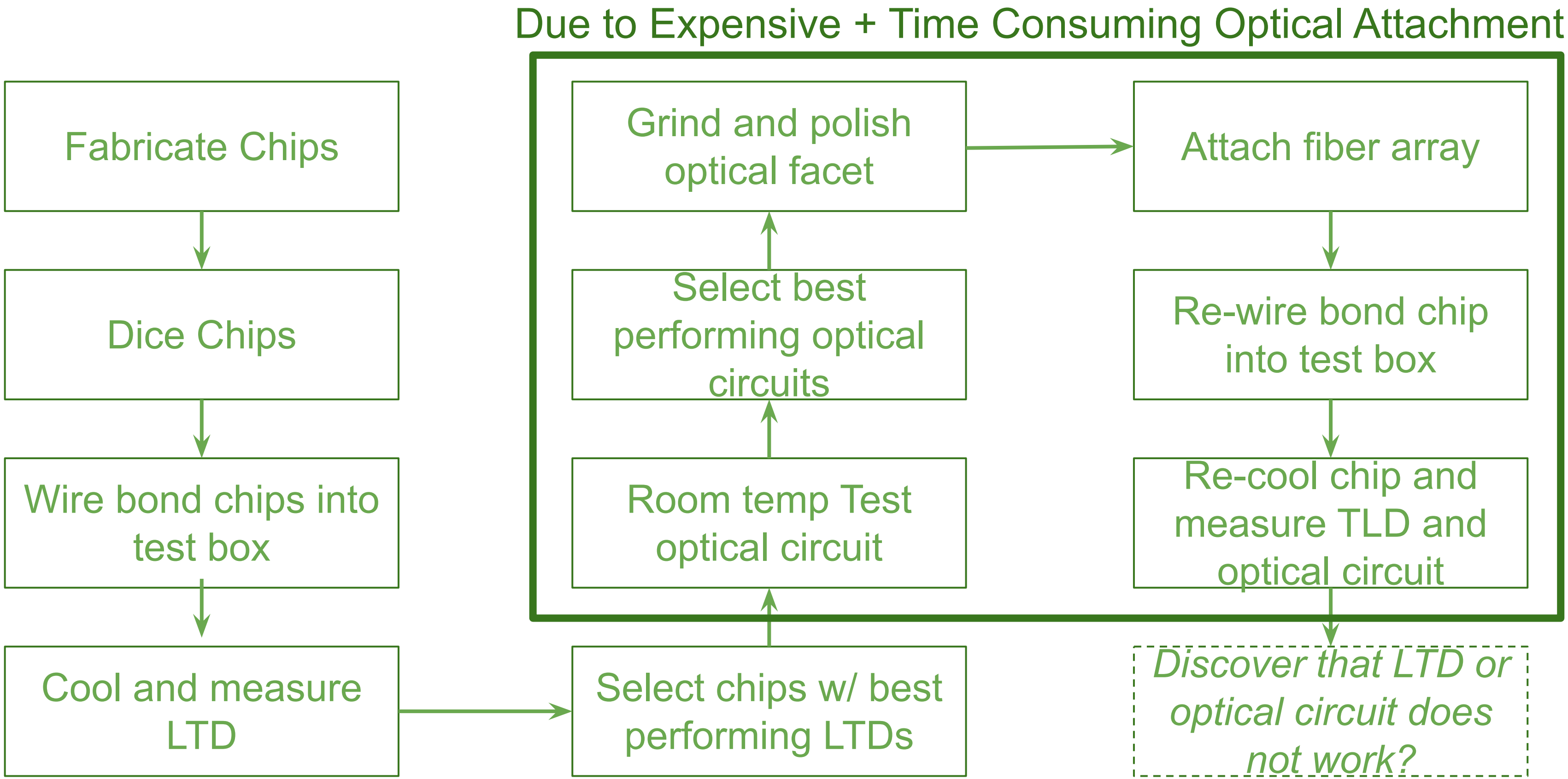
Our devices on sapphire platform @ 686 nm			
MKID Qi	MKID Yield	WG Loss	Coupling Loss
3,000 - 200,000	25% - 80%	1.2 to 24 dB/cm	> 4dB/facet (60% photon loss)

- Light Coupling
  - Fiber array thermal mismatch → progressive decline
  - Insertion loss
  - Stray light
  - Fridge heating (e.g. 0.5mW input @ 686 nm → 10mK to 125mK)





Lengthened, Costly Test & Iterate Cycle



Is efficient light coupling a common problem?

- Problem shared by folks moving light around on chip ⇒ single mode operation.
    - Relatively new capability, but increasingly needed ⇒ problem will be increasingly encountered by the community
- Astrophotonics
    - Single mode fiber systems (unlike DESI) allowing for on chip light processing
- Quantum information
    - Photonic quantum computing, communication, metrology, cryptography
    - Systems favor compact size, scalability and low tolerance for loss of light
- Other Applications: Strain measurement…, ?

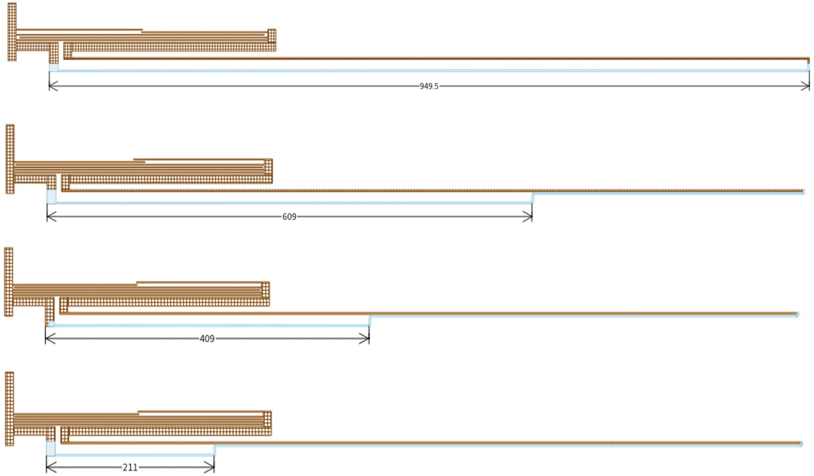
Suggestion: RDC Work Package ⊃ system integration challenges ∋ light coupling

Testing cycle

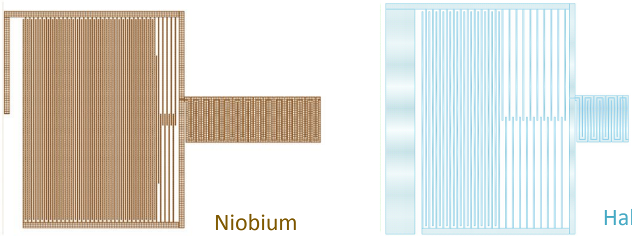
- END -

Resonator Design

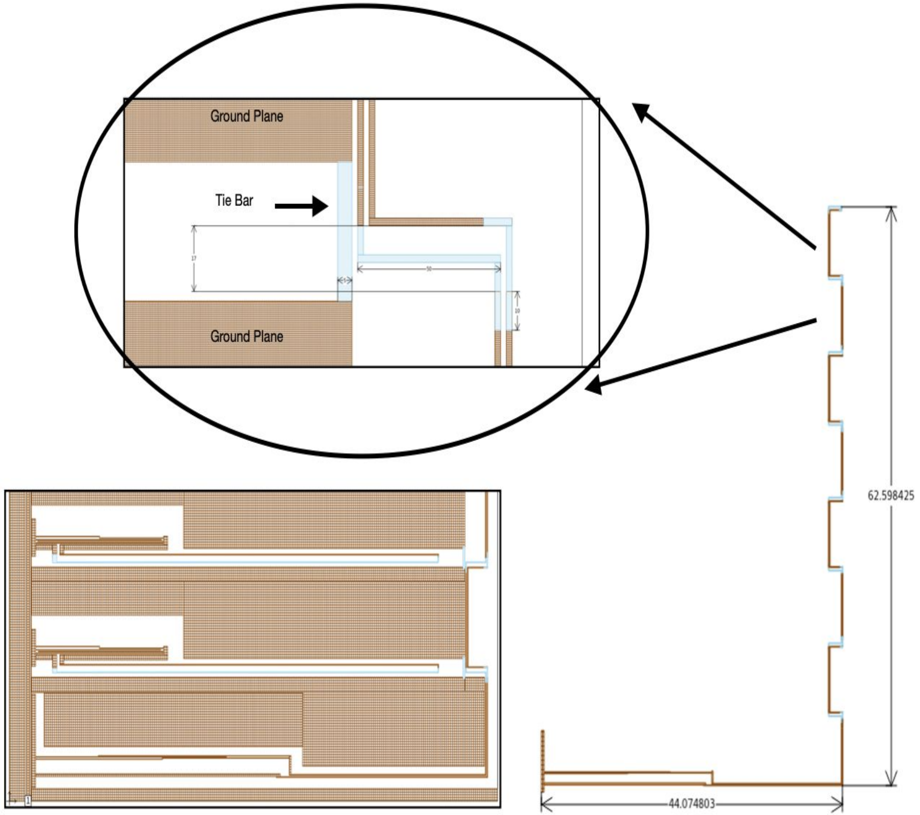
Hybrid Resonator



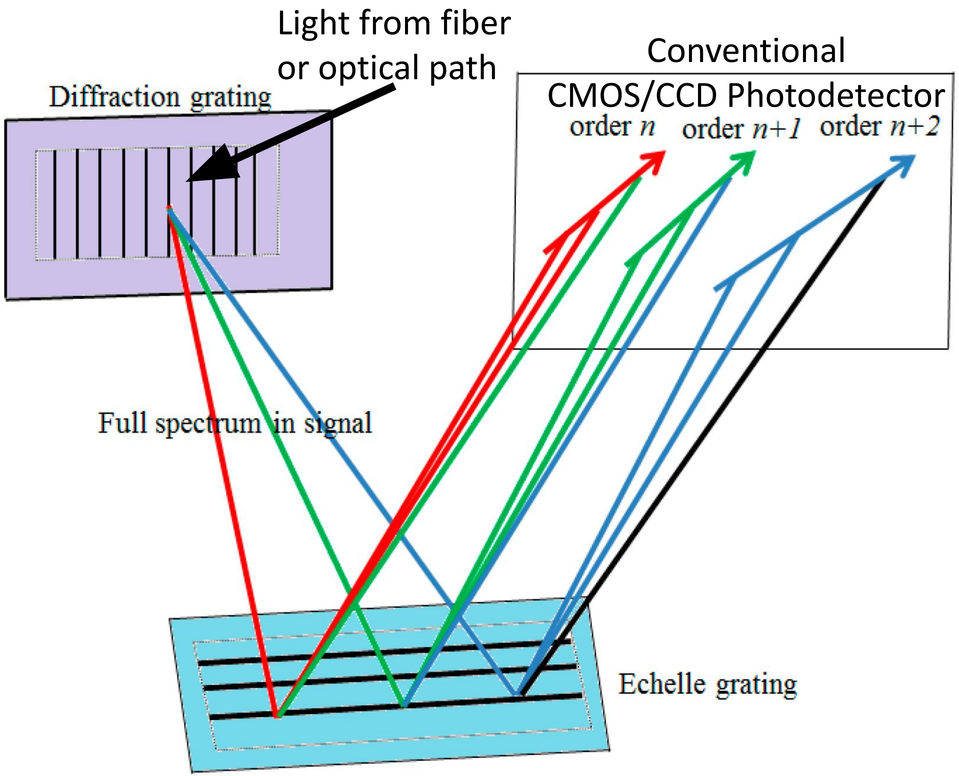
Reference Resonator

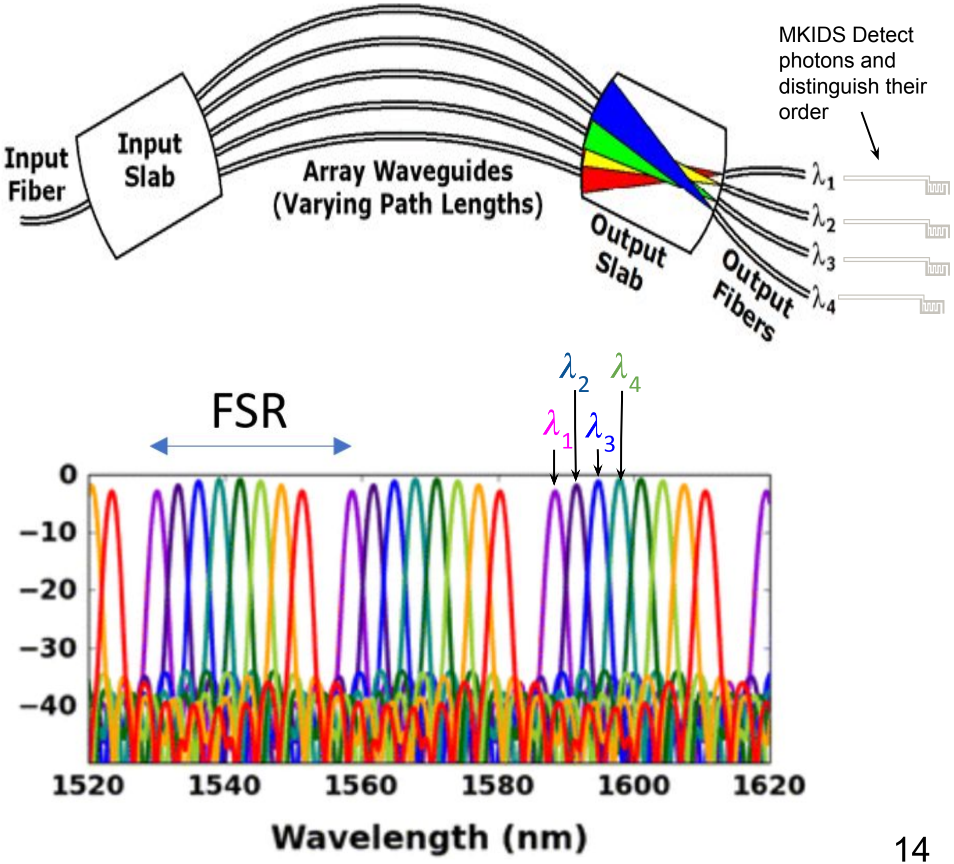


Sense Resonator

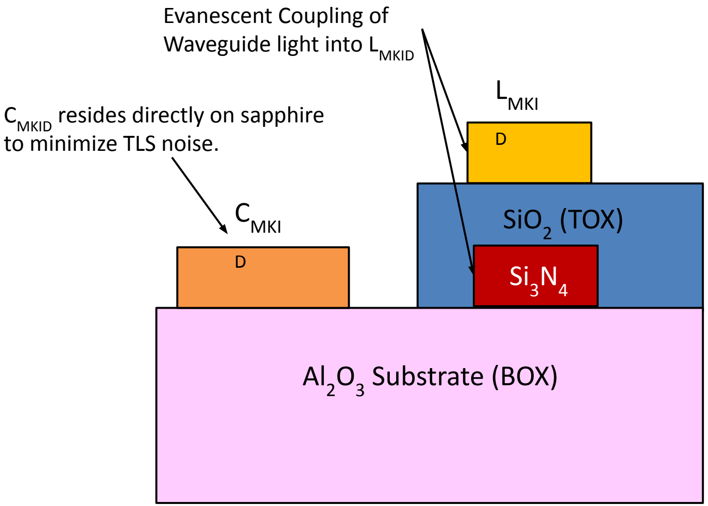


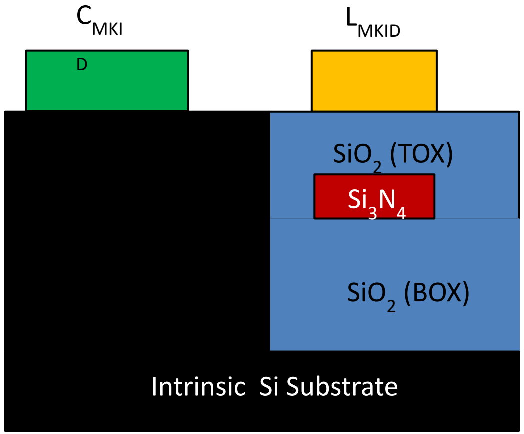
Order Sorting





Platforms


Evanescent Coupling of
Waveguide light into L_{MKID}
C_{MKID} resides directly on sapphire
to minimize TLS noise.
L_{MKI}
D
C_{MKI}
D
SiO_2 (TOX)
Si_3N_4
Al_2O_3 Substrate (BOX)


C_{MKI}
D
L_{MKID}
SiO_2 (TOX)
Si_3N_4
SiO_2 (BOX)
Intrinsic Si Substrate

Abstract

Integration of quantum and superconducting sensors with photonic circuits enables applications and solutions that are out of reach when the two technologies are instrumented separately. For example, it is not difficult to imagine that the size, weight and cost of an integrated photonic and sensing instrument would be less than a non-integrated instrument. Among the applications benefiting from such integration are high resolution spectrometers, photon number counters, quantum computers. The challenges of integration include ensuring the efficient coupling of light into the instrument. The sensors require low temperature operation so the integrated photonic circuit must be placed at the cold stage of a cryostat, where loss of light could create a background for the sensor, warm the cryostat and/or result in loss of quantum information. The technique used for light coupling must be stable against vibrations, thermal expansion, and compatible with sensor and waveguide fabrication so as not to degrade the performance of either. Multiple techniques are needed to accommodate the diversity of applications of these integrated instruments, for example applications permitting cryostat windows and applications with fibers fed into the cryostat. This talk describes work we would like to do in the context of a CPAD RnD Collaboration to find fabrication techniques and manufacturers of use to achieving efficient light coupling into instruments with integrated photonic and sensing circuits.

– END BACKUP SLIDES –

Project: SiN-MKID

Prepared by: Gopi

Institution: ULLT

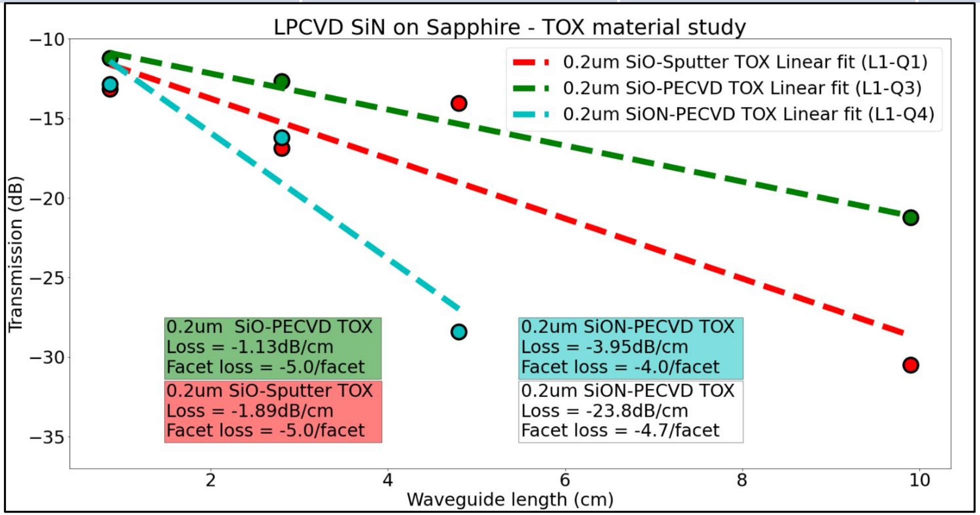
Date: 2023-11-08

SiN on Sapphire measurements
for Miguel's presentation

Loss measurement plots for LPCVD Nitride

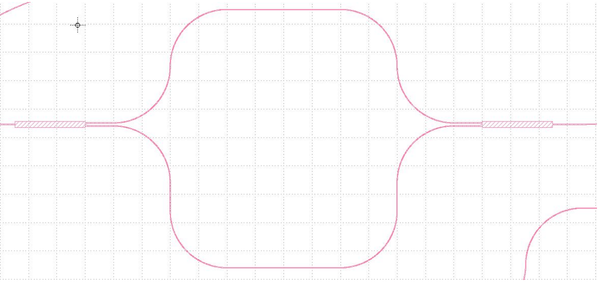
Loss measurements for 200nm LPCVD SiN on Sapphire: Wavelength = 686nm

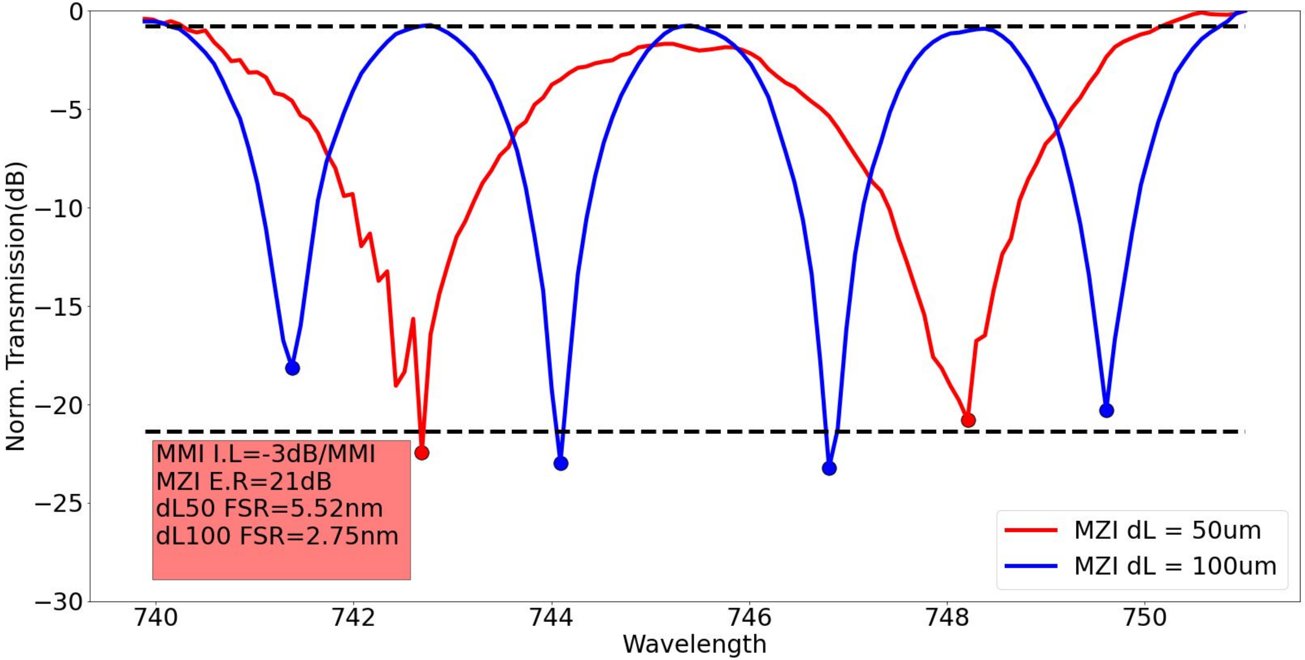
Wafer	BOX	Core	TOX	Loss	Coupling loss	Comments
L1-Q1	Sapphire	SiN LPCVD 200nm Thick, 1.8um wide	SiO Sputter 200nm Thick	-1.89dB/cm	-4.99dB/Facet	
L1-Q2	Sapphire	SiN LPCVD 200nm Thick, 1.8um wide	SiON Sputter 200nm Thick	-23.8dB/cm	Could not measure	
L1-Q3	Sapphire	SiN LPCVD 200nm Thick, 1.8um wide	SiO PECVD 200nm Thick	-1.13dB/cm	-5.26dB/Facet	
L1-Q4	Sapphire	SiN LPCVD 200nm Thick, 1.8um wide	SiON PECVD 200nm Thick	~3.95dB/cm	-4.00dB/Facet	
L1-Q4	Sapphire	SiN LPCVD 200nm Thick, 1.8um wide	SiON PECVD 1000nm Thick	~1.61dB/cm	-4.50dB/Facet	



LPCVD SiN on sapphire
Photonic components

MZI Measurements

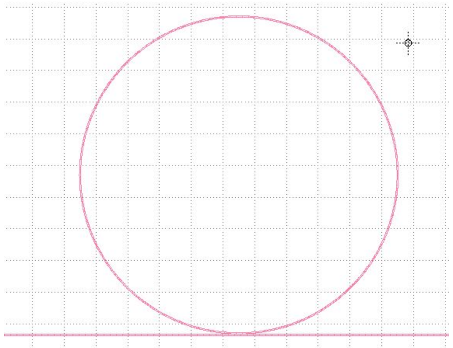


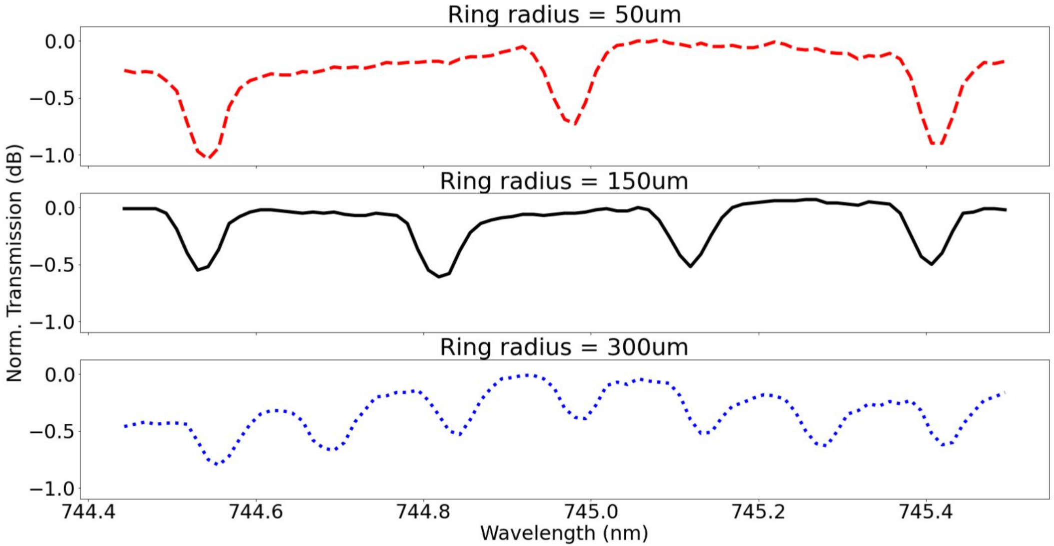


MZI Insertion loss = -3dB
MZI Extinction ratio = 21dB

MZI dL (um)	Measured FSR (nm)	Expected FSR (nm)
50um	5.52nm	6.21nm
100um	2.75nm	3.12nm

Ring Measurements





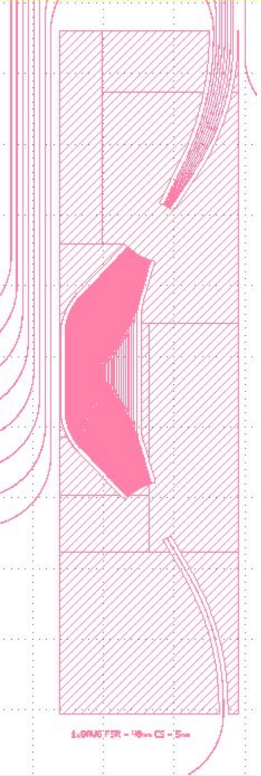
Ring radius (um)	Measured FSR (nm)	Expected FSR (nm)
50um	0.44nm	0.98nm
150um	0.28nm	0.33nm
300um	0.14nm	0.16nm

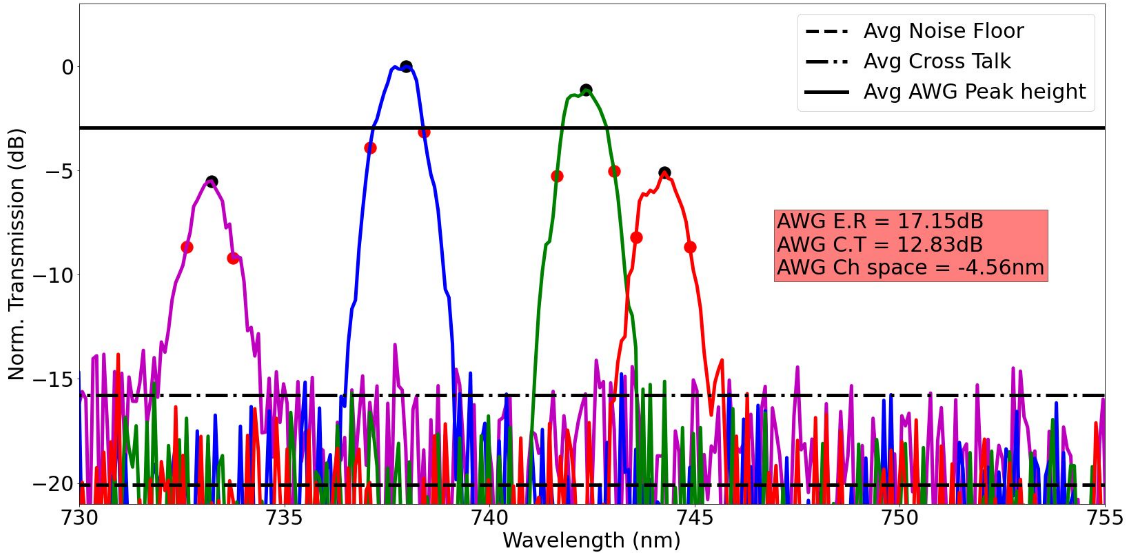
Could not do proper curve fitting

Ring radius (um)	Kappa(nm)	Loss (dB/cm)
50um	??	??
150um	??	??
300um	??	??

AWG measurement

1x8 AWG (1.2um WVG)
FSR=40nm, CS=5nm





- Could get transmission only from Ch6, Ch7, Ch8, Ch1(second order)
- Light from broad band source not guiding in Ch2, Ch3, Ch4
- The AWG center wavelength seemed to have shifted

Average AWG Extinction ratio = 17.15 dB
Average AWG Cross Talk ratio = 12.83 dB
Measured AWG Channel space = 4.56 nm

Photonic Wire Bonding

Cost of Photonic wire bonds

- Not sure how much is the cost. But it is very easily scalable to large arrays in a single chip because it is done using two phonon lithography
- It would be a completely new research project on its own

Fiber array - PM$4000 to make (16channel), $1,750 to install; non-pm $2600, attach $1700 + polish
Freedom Photonics - not standard - $10K based on what chips are bonded, mode vmatching involved, mostly set up

ULTRA-LOW LOSS

TECHNOLOGIES