A silicon photonic channelized spectrum monitor for UCSD's multi-wavelength ring network

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Introduction

Increasing need for fast real-time diagnostics of optical signals, ranging from communications to sensing and metrology.

Sub-microsecond measurements can be useful e.g., transients in communication networks, and monitoring flows at the level of a few packets.

There are plenty of ~100 millisecond-scale multichannel power monitors.
Lack of comparable solutions at microsecond / nanosecond time-scales.

AXSUN Omx-DCR
MEMS tunable filter
micro-optics
30 dB input power dynamic range
Spectral Resolution < 3.5 GHz
Power Accuracy 1 dB
Readout time 0.5 s
Power 5W

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Proximion WISTOM
Fiber Bragg grating based
30 dB input power dynamic range
Channel spacing 25 GHz
Power Accuracy 1 dB
Scan time 40 us
Response time 50 ms
Power 15 W

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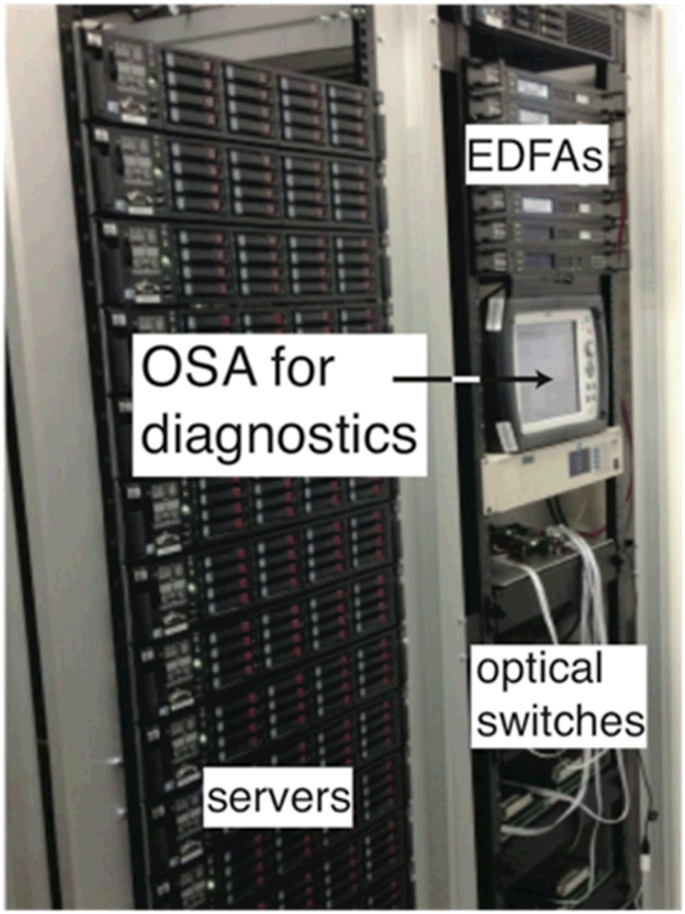
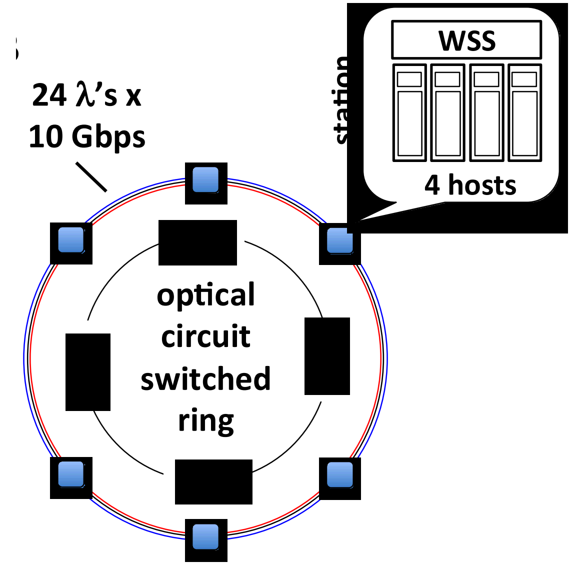
Q: Is there a simple way to obtain fast, real-time, multi-channel **spectral-domain** measurements using silicon photonics?

If yes, then such a component can be integrated together with other silicon photonic components in the future, for intelligent network components.

MORDIA
Optical circuit-switched WDM network hosted at UC San Diego





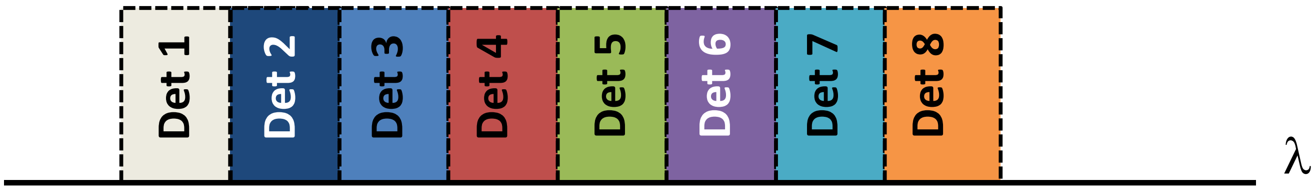
- Ring topology
- Six nodes, four hosts per node
- 20-24 channels, 10 Gbps each
- 100-GHz ITU grid, C-band

Functionality of OSA:

- OSA mainly used for power monitoring (e.g. power drifts)
- Readout is slower than desirable; off-the-shelf OSA is not an ideal solution

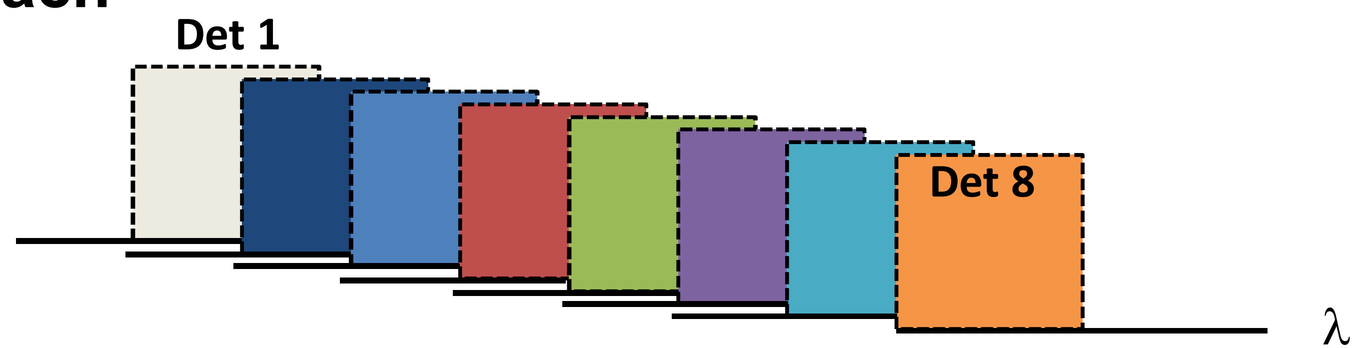
N. Farrington et al., IEEE Photon. Technol. Lett. **25**, 1589 (2013)

Conventional approach



Slice spectrum up and send to individual detectors (or sequentially scan)
- Requires very sharp filter edges
- High resolution requires narrow bandwidth, lots of detectors (or slow)

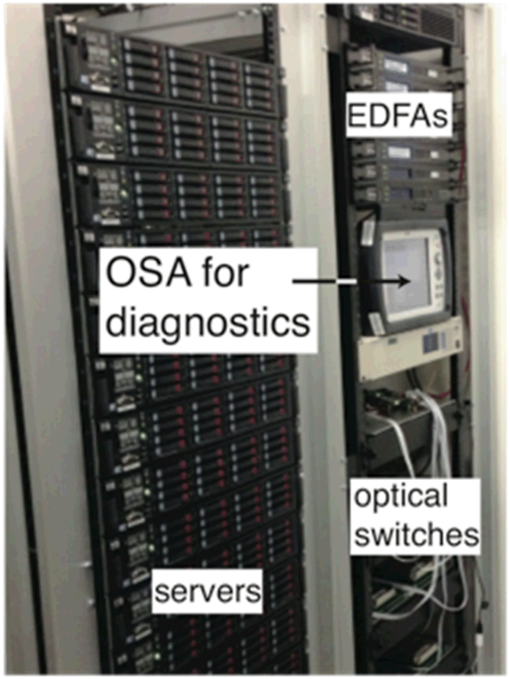
Our approach

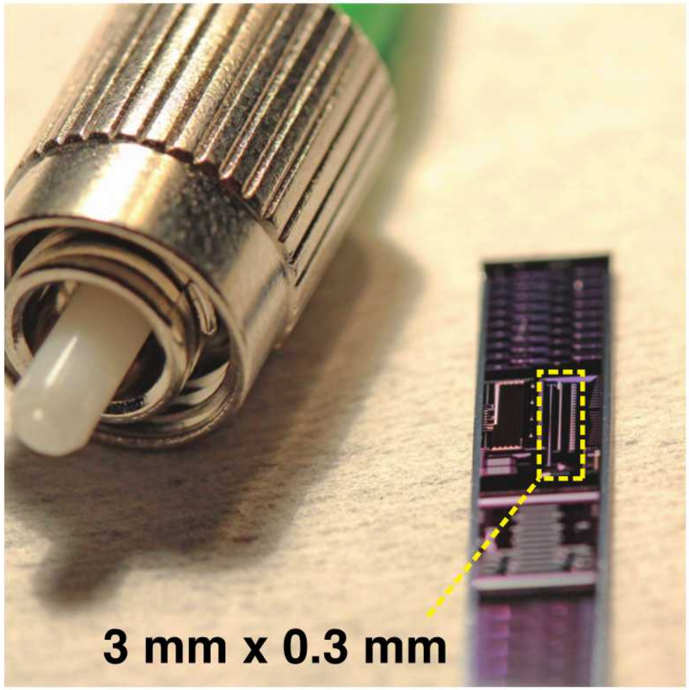


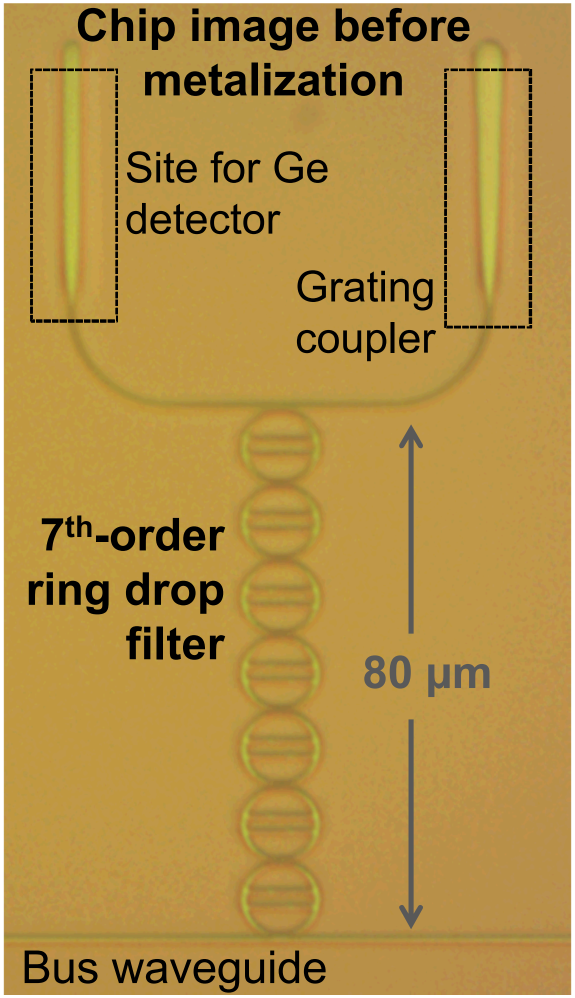
Individual detectors see overlapping spectra; linear algebra dis-entangles
- Relaxes fabrication constraints on device
- Can handle flexible-grid signals more naturally (no change in speed)
- Needs more signal processing (electronic hardware or software)

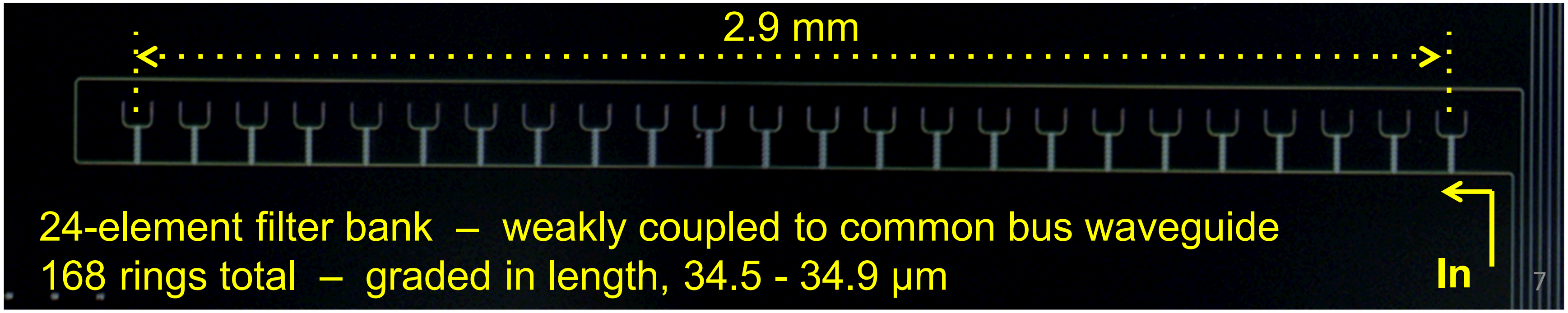
Channelized spectrum monitor

Tracks power levels of up to 24 WDM channels with arbitrary channel bandwidths



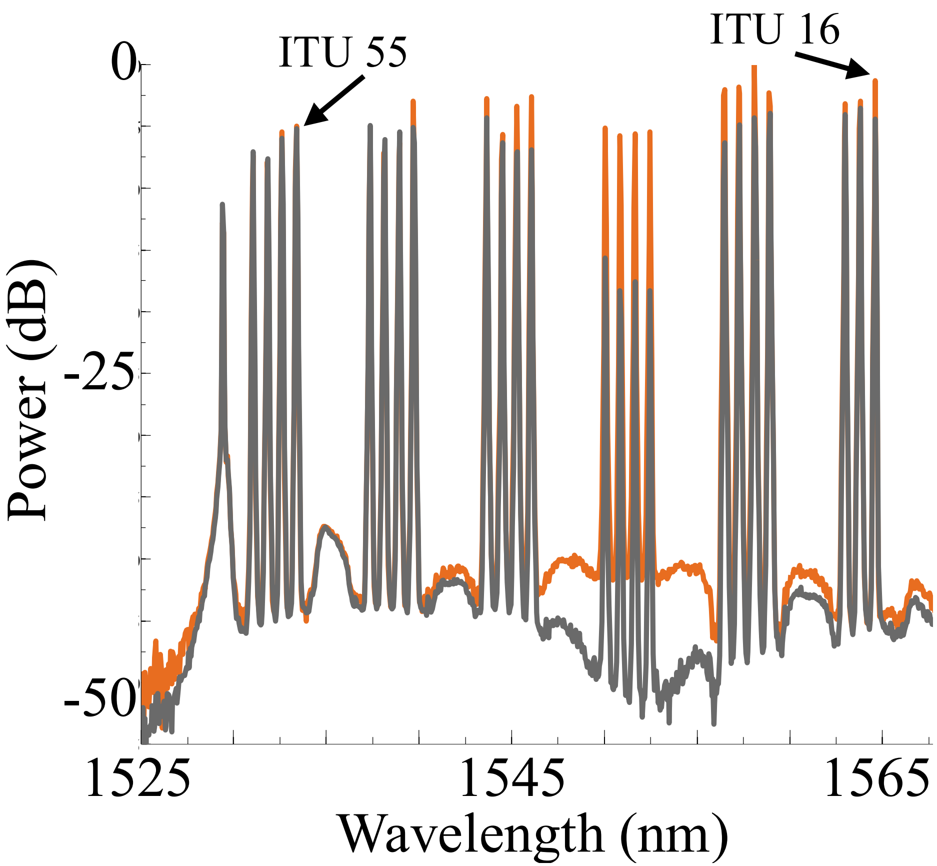




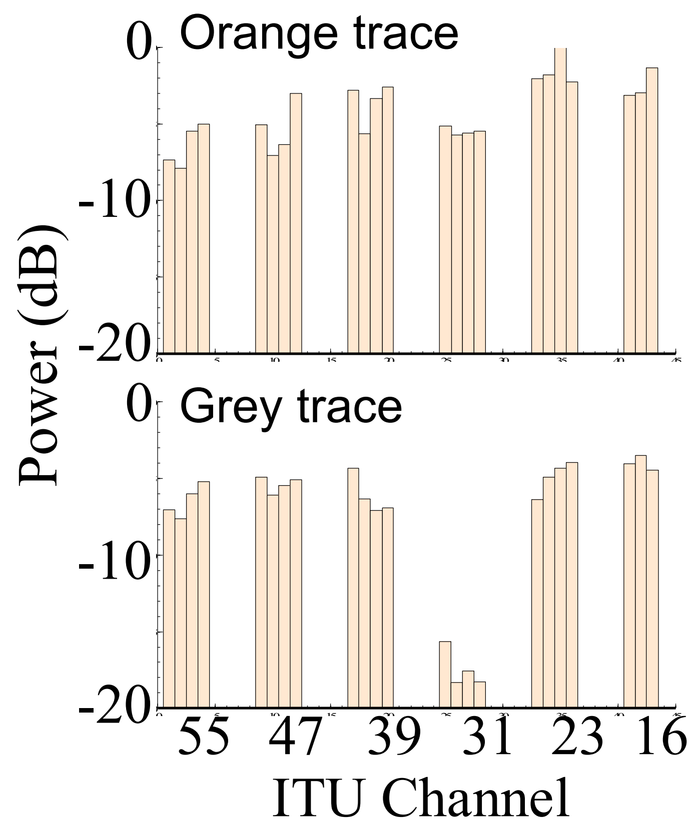


- In this presentation, we track the power levels of 24 DWDM channels.
- Light source: SFP+ transceivers, each @ 10 Gbps NRZ data
- Transceiver lineshape is known; power levels need to be tracked

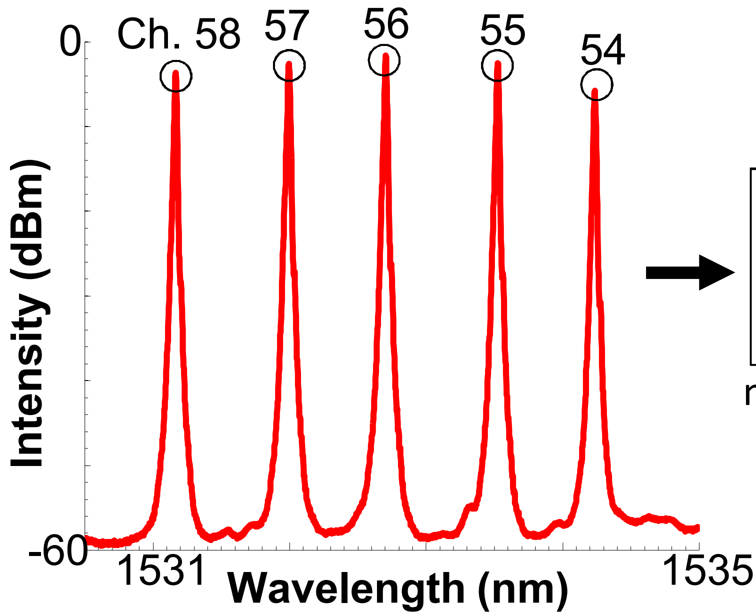
Actual spectrum

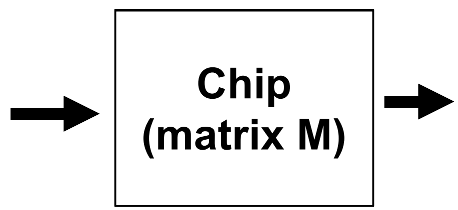


Desired information



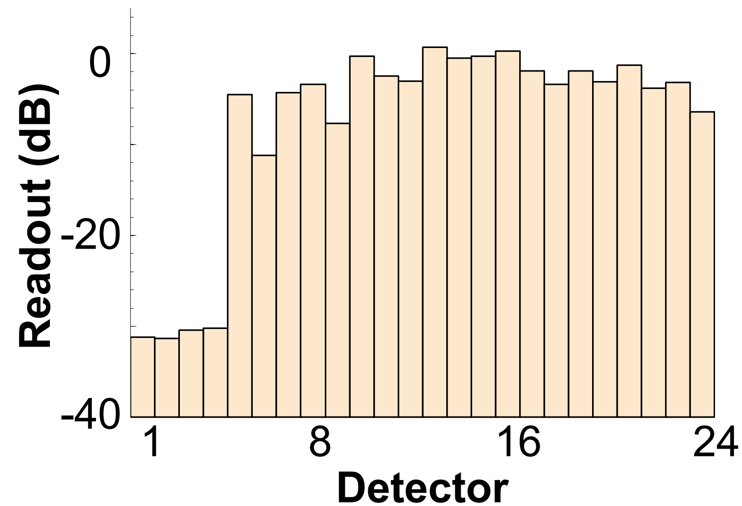
Example input spectrum
(vector of powers: P)





measured during calibration

Chip maps input spectrum into detector readouts (vector: D)

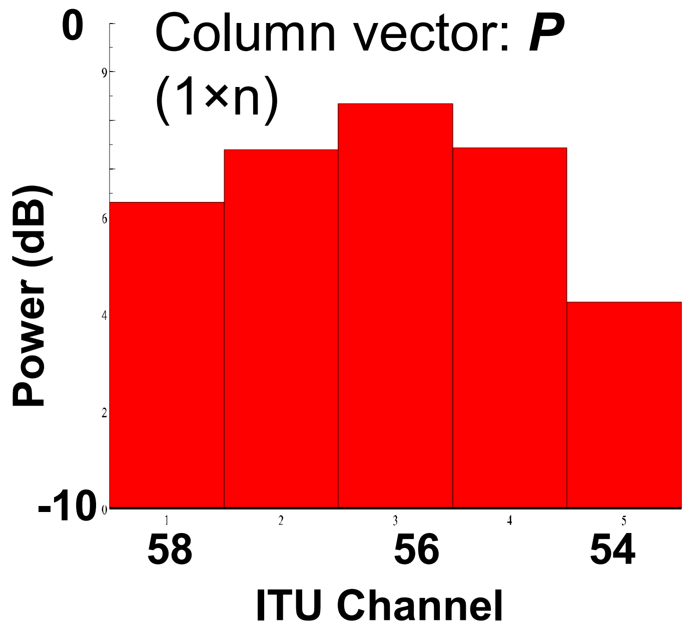


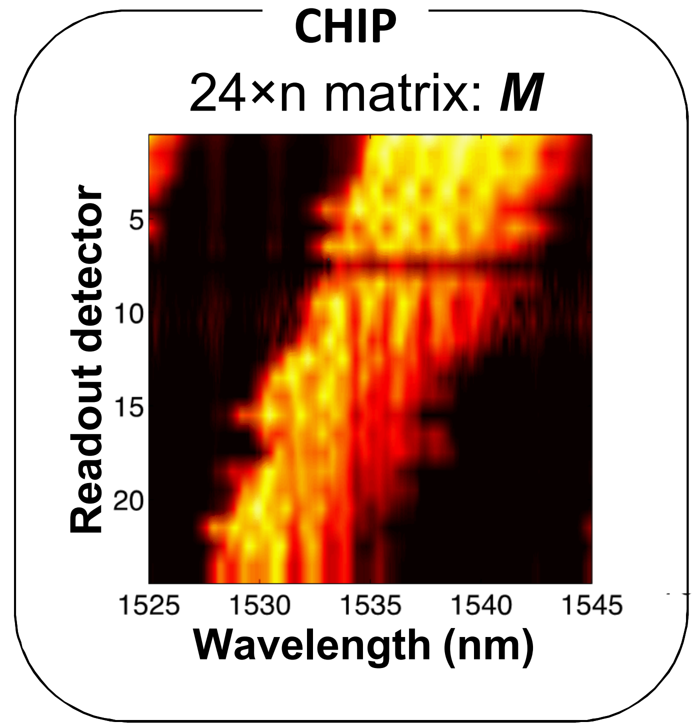
Inversion problem:

Given the detector readouts …

… "invert" the matrix that represents the chip's mapping function

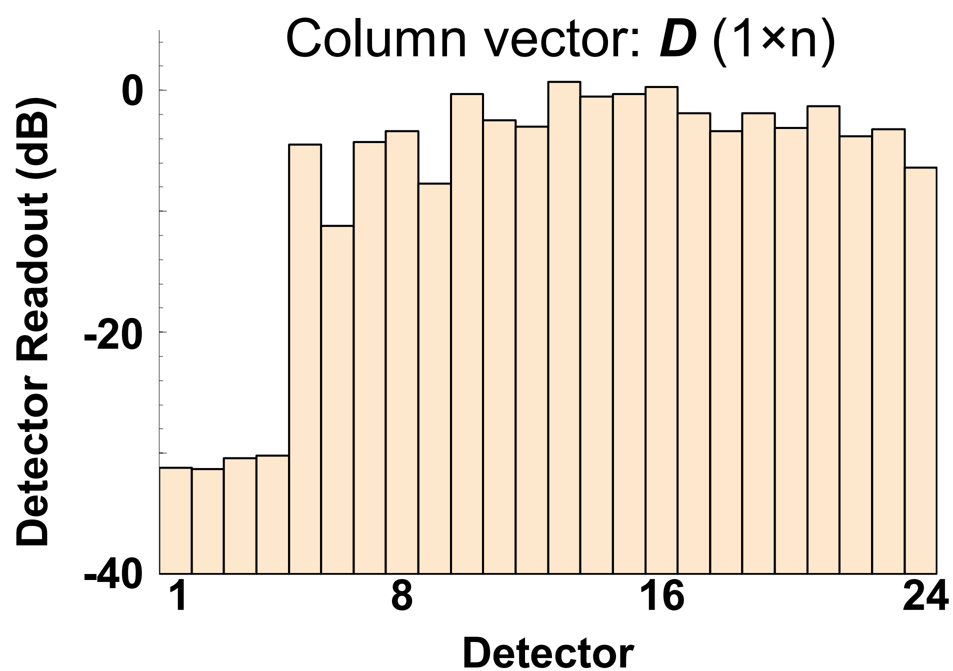
… and calculate the power levels





D = M x P
Therefore,
P = M^{-1}×D

- **Moore-Penrose pseudo- inverse**
- **SVD or QR factorization**



<u>minimum</u> linear least-squares error solution

matrix describing chip:
optical-in to detector-out

Assume M has SVD $U\Sigma V^T$ where $S = \begin{pmatrix} S & 0 \\ 0 & 0 \end{pmatrix}$.

detector-out

Let $c = U^T D = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$ in general.

Need to solve

$$\min_P ||MP - D||_2$$

optical input powers

Can show that

$||MP - D||_2 = ||Sz_1 + c_1||_2^2 + ||c_2||_2^2$

where $z = V^T P$.

Moore-Penrose Inverse

To minimize error, set $z_1 = S^{-1}c_1$, i.e., $P_{\text{opt}} = VZ = M^\dagger D + V_2 z_2$.

arbitrary

Min. residual error $= ||c_2||_2^2 = ||U_2{}^T D||_2$

Lemma: If M is full rank, then there is no "V_2" in the SVD.

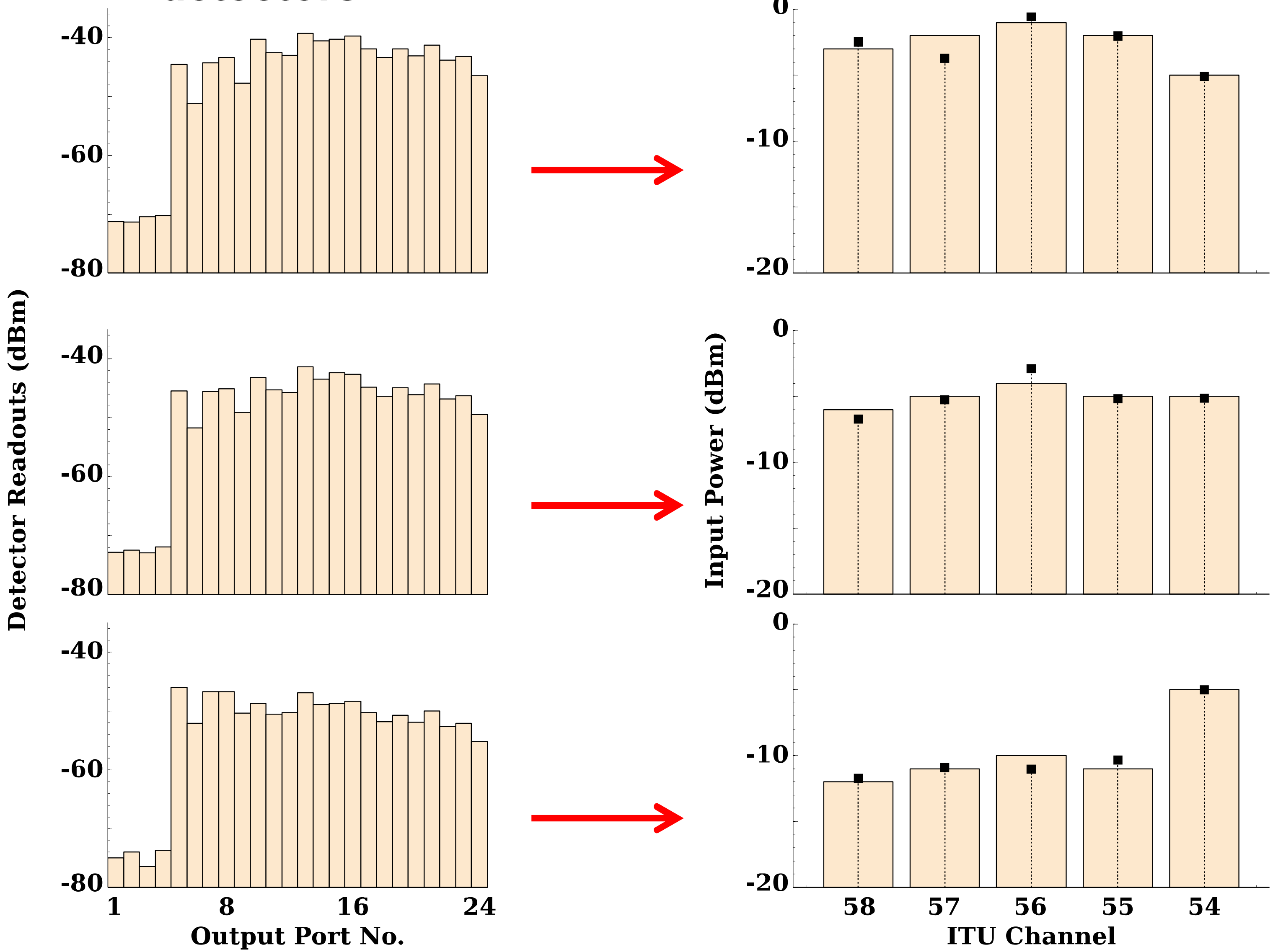
Examples

Bars: unknown input

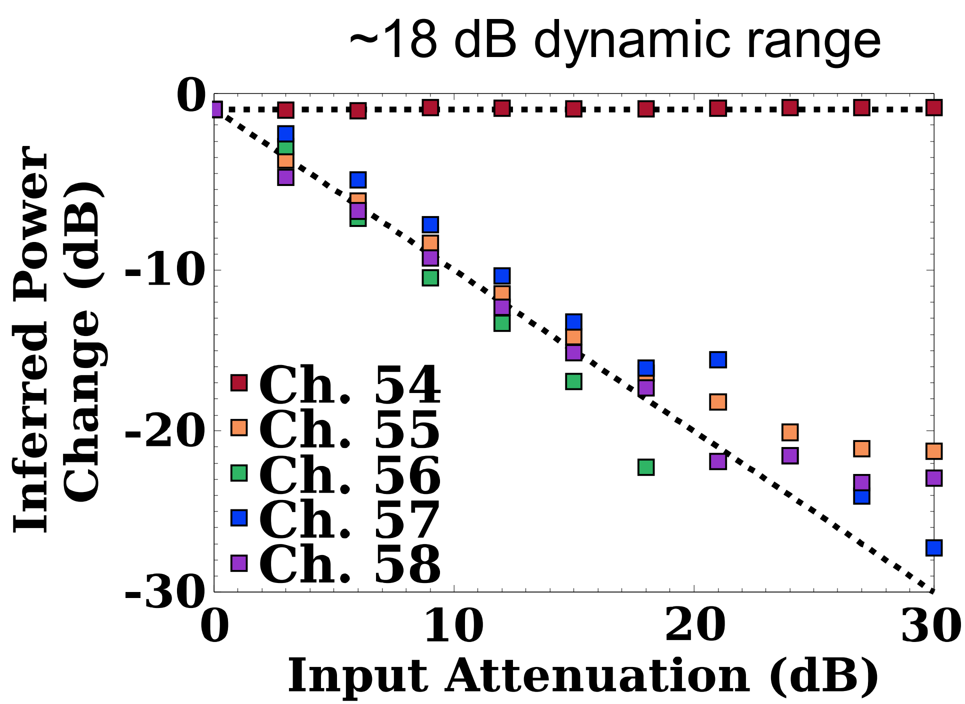
Stems: reconstructed input

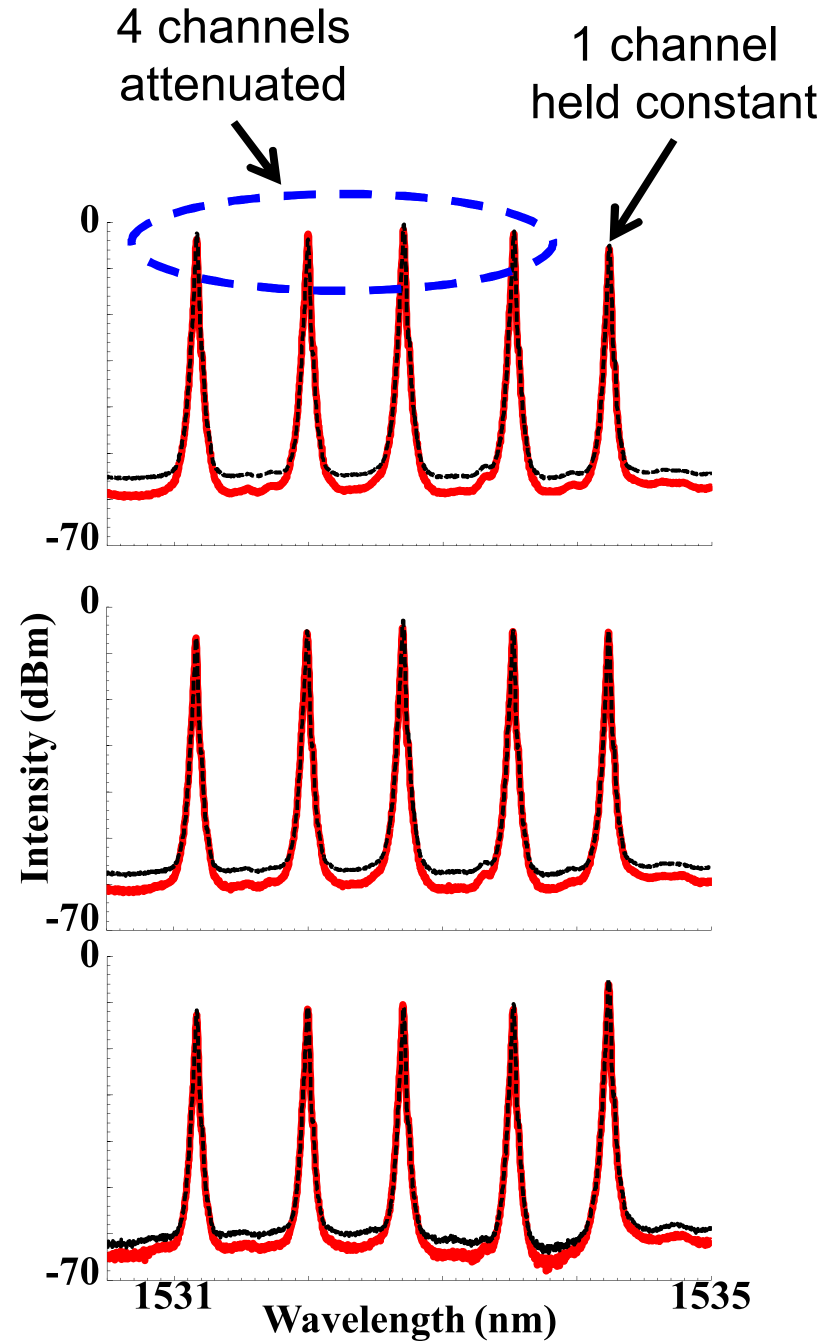
(offline at present)

Measured from output detectors



Track the power variations of multiple channels





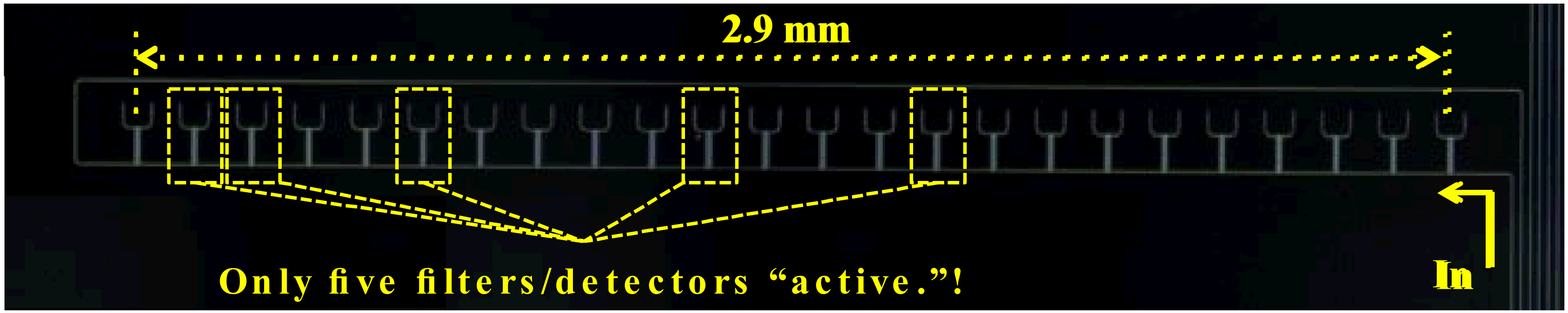
Limitations at present:

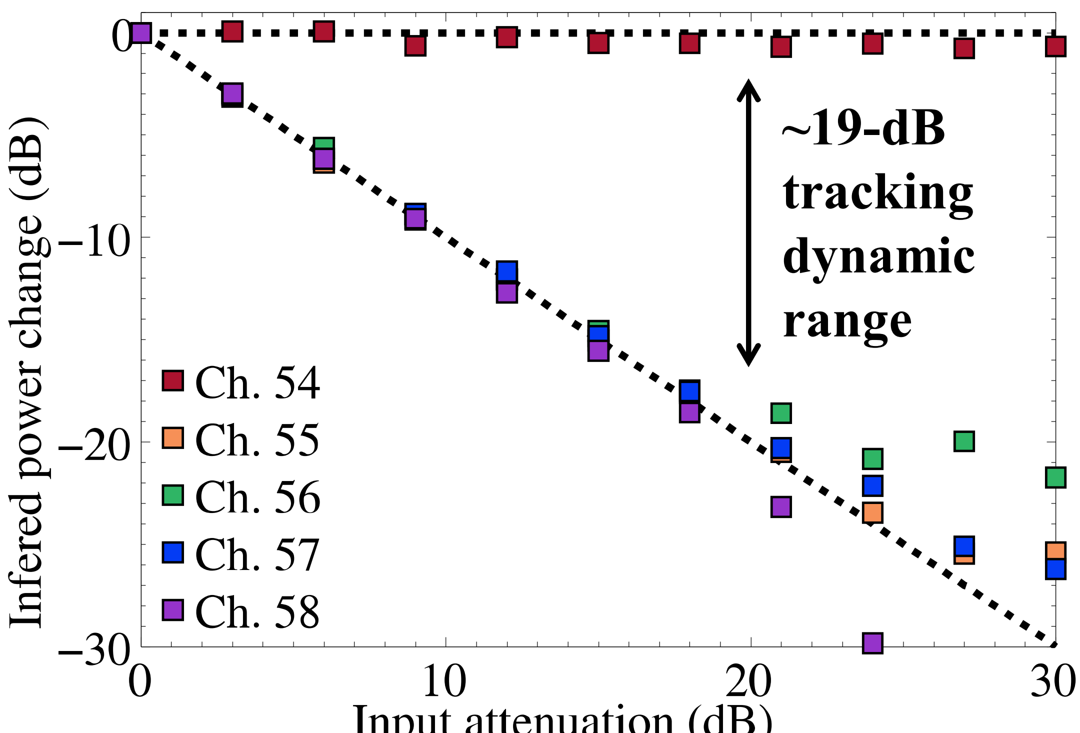
- polarization instability of setup
- slow, sequential readout of detectors (will be improved with on-chip detectors)

To minimize error, set $z_1 = S^{-1}c_1$, i.e., $P_{\text{opt}} = VZ = M^{\dagger}D + V_2 z_2$.

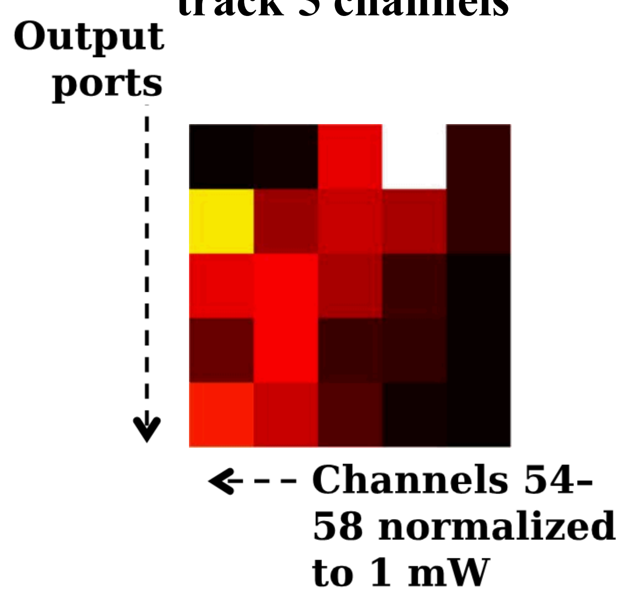
Min. residual error $= ||c_2||_2^2 = ||{U_2}^T D||_2$

Lemma: If M is full rank, then there is no "V_2" in the SVD.





Using 5 detectors to track 5 channels



Conclusions

UCSD
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1. An on-chip silicon photonic reconfigurable channelized spectrum monitor can be useful for designing "intelligent" network hardware
2. Our proposed architecture & method allows for:
   - arbitrary channel positioning
   - reconfigurable channel center wavelength (and width)

   Architecture needs:
   - known spectrum (lineshape function of transceivers)
3. Full functionality of photonic chip requires integration with electronics for processing detector readouts (linear algebra – either hardware or software)

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