Ring Resonator Development for LSST Dark Energy Science

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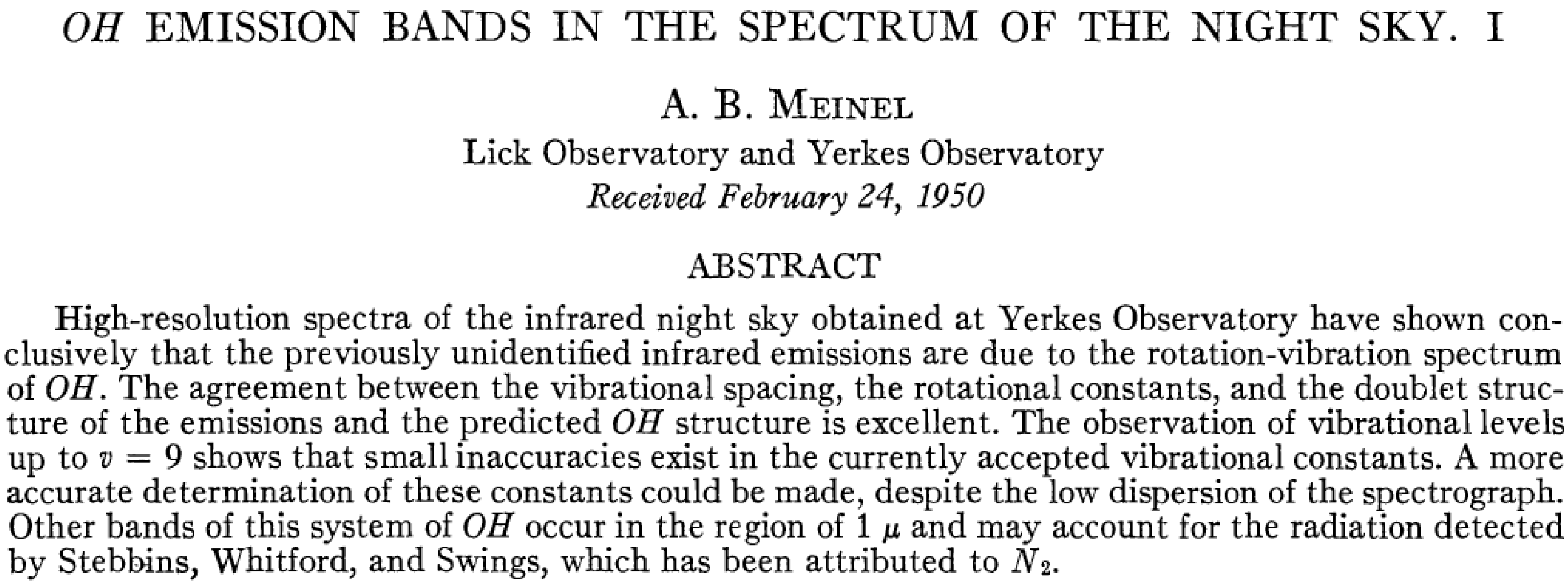
Simon Ellis, Kyler Kuehn (AAO)

Quick Summary:

Solve longstanding problem with sky background in near-infrared

Take LSST Supernova Dark Energy to next Level, plus many other uses

Ring Resonators are scalable and cost-effective technology

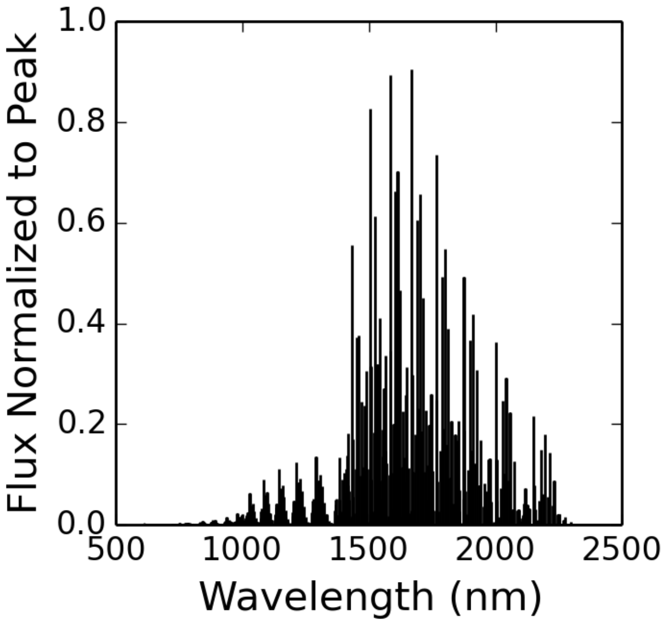


OH EMISSION BANDS IN THE SPECTRUM OF THE NIGHT SKY. I

A. B. Meinel
Lick Observatory and Yerkes Observatory
Received February 24, 1950

ABSTRACT

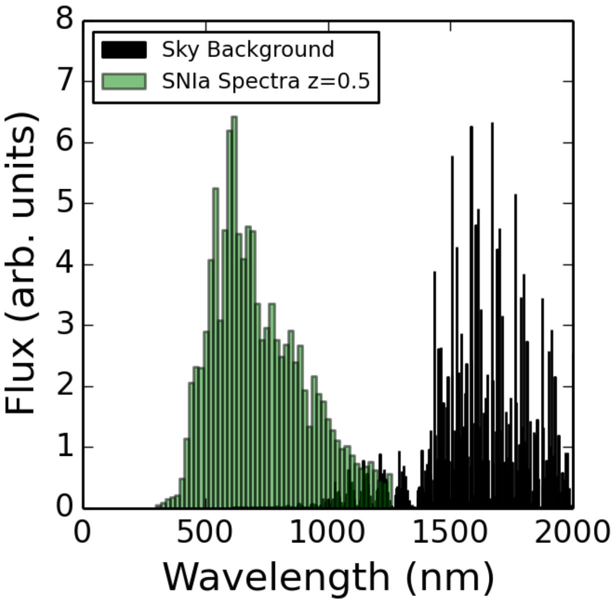
High-resolution spectra of the infrared night sky obtained at Yerkes Observatory have shown conclusively that the previously unidentified infrared emissions are due to the rotation-vibration spectrum of *OH*. The agreement between the vibrational spacing, the rotational constants, and the doublet structure of the emissions and the predicted *OH* structure is excellent. The observation of vibrational levels up to $v = 9$ shows that small inaccuracies exist in the currently accepted vibrational constants. A more accurate determination of these constants could be made, despite the low dispersion of the spectrograph. Other bands of this system of *OH* occur in the region of 1 μ and may account for the radiation detected by Stebbins, Whitford, and Swings, which has been attributed to N_2.

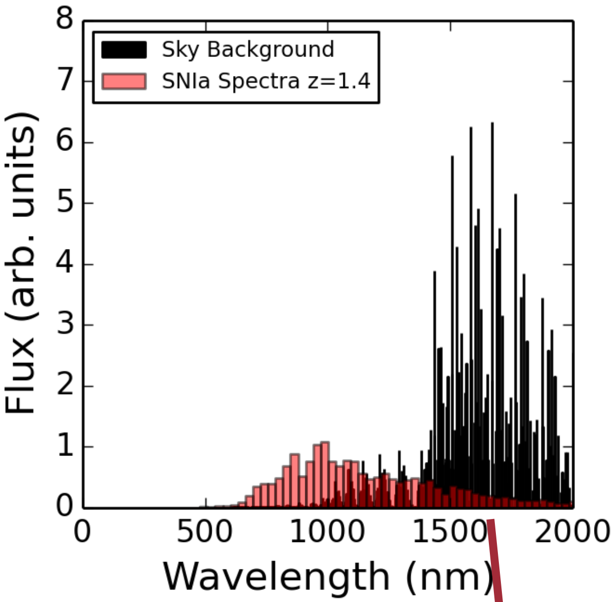


Source of Sky Background in Near-Infrared is Atmospheric OH molecules

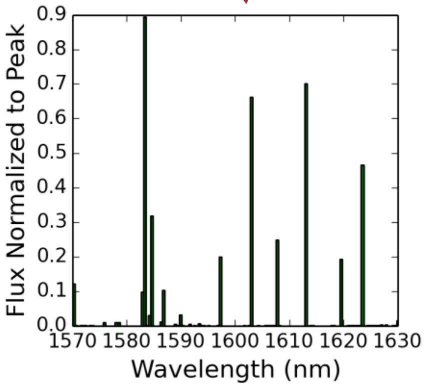
Sky Background from OH molecule emission

Need x1800 Longer Exposures in H band (NIR) than Optical (8.2 mags worse) for Same Signal-to-Noise (SNR)





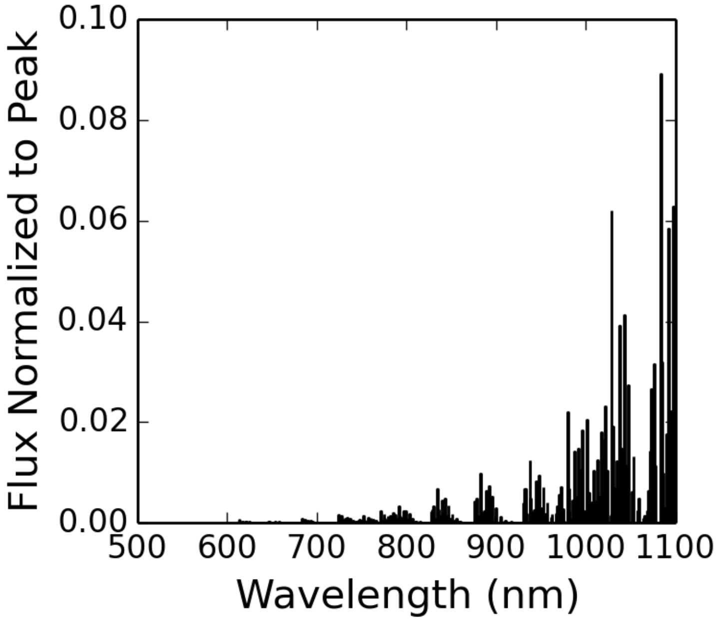
ZOOM 1600nm



Background are spikes ~0.1nm wide separated by ~5nm

Sky Background from OH molecule emission

Has significant impact in optical region too:



DES Supernovae in DEEP Fields take 1 hr of exposures per visit in z band (850-1000nm) compared to 10 min in g band (400-550nm), to reach reasonable Signal-to-Noise level.
Significant impact on survey operations.

DESI wavelength range up to 980nm, resolution 0.2nm

Motivations for Dark Energy Science with LSST Supernovae

Efficient and Fast follow-up NIR program for DEEP-Drilling LSST Supernovae with suppression of OH lines

NIR measurements known to be insensitive to dust effects, which are likely to be dominant systematic in LSST era (given improved photometric calibration specs)

Rest-frame NIR measures shown to be best Standard Candle with no corrections

Statistics from 50K LSST SNe crucial to understanding host galaxy correlations (~3K SNe from DES and WFIRST)

LSST Supernovae

- 50K Deep-Field Type Ia compared to 3K DES (z<1.2)
- 6 LSST filters vs 4 for DES
- x2 better photometric calibration requirements for LSST

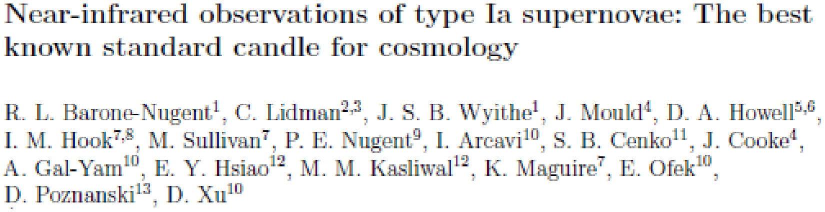
- Traditionally calibration dominates SN systematics but it's likely LSST will be limited by host galaxy dust effects and confusion with intrinsic color variations

- Near-infrared measurements are desired since they are insensitive to dust, and recently shown to be true standard candles

(optical light curves require large empirical corrections to be standardizable)

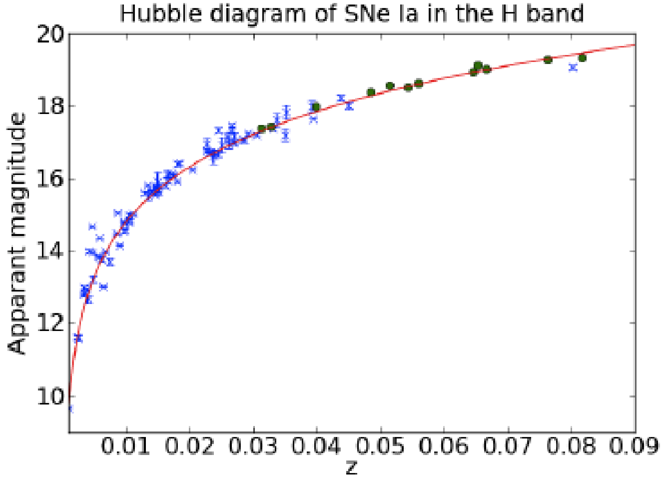
- Note that LSST detects ~7000 more Type Ia SN just from 1.2<z<1.4 but I'm ignoring those as "unusable". Near-infrared information could make many of these usable.

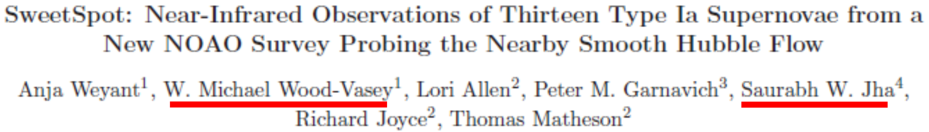
Near-infrared SN measurements are the best standard candle



Near-infrared observations of type Ia supernovae: The best known standard candle for cosmology

R. L. Barone-Nugent[1], C. Lidman[2,3], J. S. B. Wyithe[1], J. Mould[4], D. A. Howell[5,6], I. M. Hook[7,8], M. Sullivan[7], P. E. Nugent[9], I. Arcavi[10], S. B. Cenko[11], J. Cooke[4], A. Gal-Yam[10], E. Y. Hsiao[12], M. M. Kasliwal[12], K. Maguire[7], E. Ofek[10], D. Poznanski[13], D. Xu[10]





SweetSpot: Near-Infrared Observations of Thirteen Type Ia Supernovae from a New NOAO Survey Probing the Nearby Smooth Hubble Flow

Anja Weyant[1], W. Michael Wood-Vasey[1], Lori Allen[2], Peter M. Garnavich[3], Saurabh W. Jha[4], Richard Joyce[2], Thomas Matheson[2]

(LSST Supernova Group Leaders)

LSST Supernovae

- 50K Type Ia SN compared to 3K DES
- 6 LSST filters vs 4 for DES
- x2 better photometric calibration
- But will be limited by dust absorption, which is second MAJOR benefit of NIR measures, insensitive to dust

"NIR observations are expensive to take from the ground as a result of the significant emission and absorption from the atmosphere…"

"The optical light curve will give us the phase and we will measure the brightness in the near infrared."

"… significant potential in supplementing future large ground-based surveys such as LSST…"

Many Potential Customers World-Wide

- 27 optical/NIR telescopes with >4m mirror, operating costs >$3K/hour
- Oversubscribed: x2-4 more proposal time than available
- Perfect OH suppression gives x1800 shorter exposures with same SNR
- “Complete failure” x2 shorter exposures still a game-changer
  - Pays for itself in a few weeks with operating costs

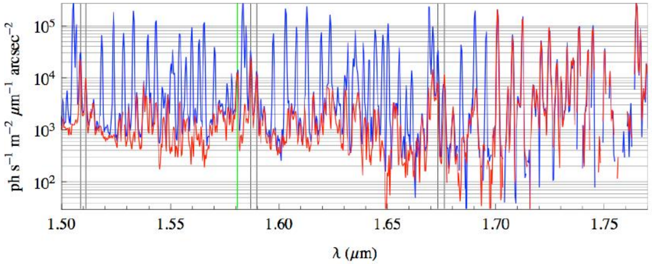
Wavelength Suppression Techniques

- **Major effort for Australian astronomy for almost a decade (Bland-Hawthorn and Ellis)**

- **Current techniques not scalable for LSST.**

- **Recommended ring resonators in 2012 publication before we started**

GNOSIS Instrument and first results using Fiber Bragg Gratings (S. Ellis et al. 2012)



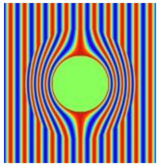
Potential applications of ring resonators for astronomical instrumentation

S.C. Ellis[a], A. Crouzier[b,a], J. Bland-Hawthorn[c], J.S. Lawrence[a] and J. Kepple[a]

2012 publication

Argonne's Entry into OH Suppression

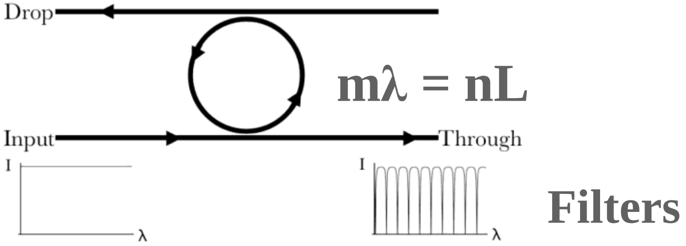
- Perlmutter's student Kyle Barbary came to ANL fall 2012
  - Kyle worked with Saul on OH suppression at LBNL
  - LBNL simulating metamaterials, if it works suitable for non-fiber applications but more speculative



- Investigated technologies with our Center for Nanoscale Materials (CNM)

- Our DES post-doc Kyler Kuehn took a position in Australian Astronomical Observatory R&D group, the world's leaders in OH technology.

- Successful CNM user proposals to fabricate ring resonators, used in telecommunications and biosensors

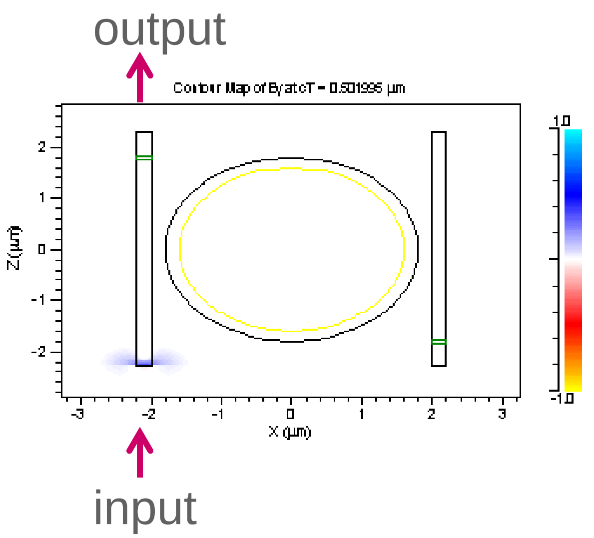


$m\lambda = nL$

Filters

Initial Ring Resonator Design for OH Suppression

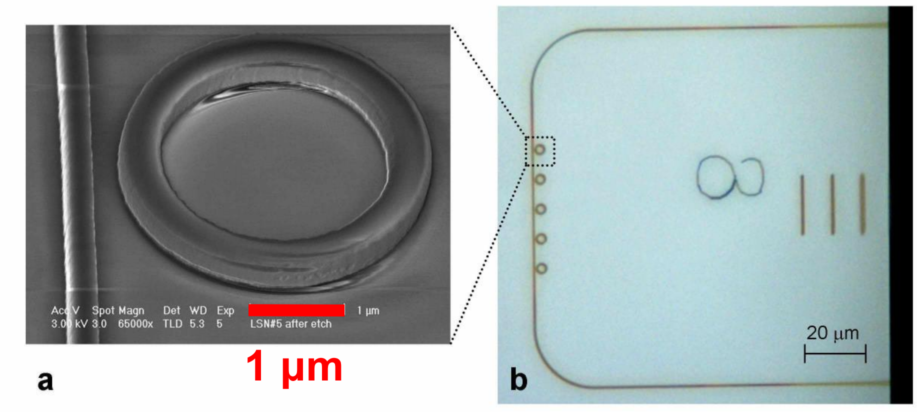
Single wavelength,
on-resonance animation (2ps total)

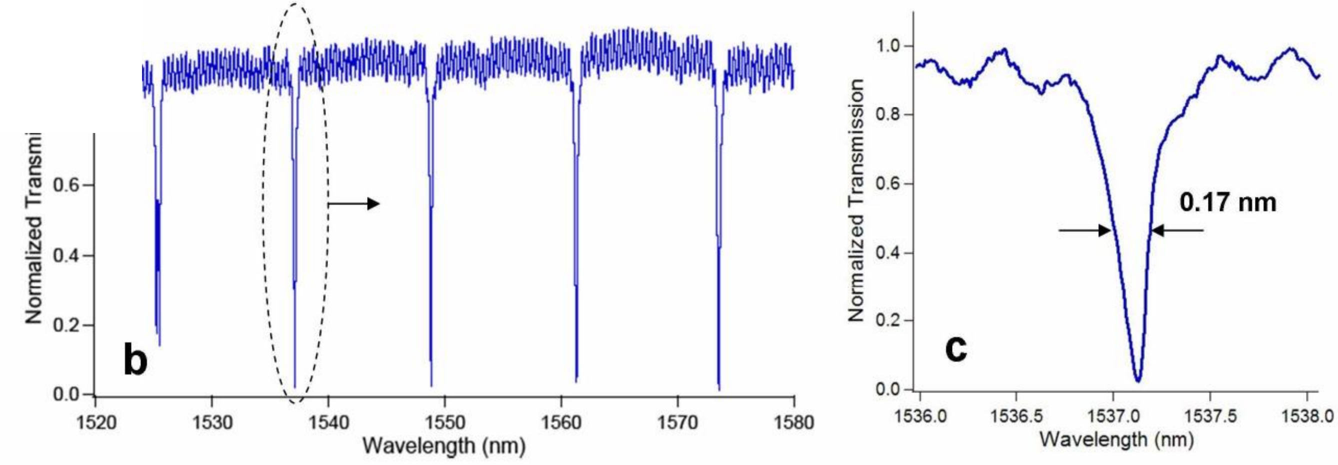


Silicon microring resonators with 1.5-µm radius

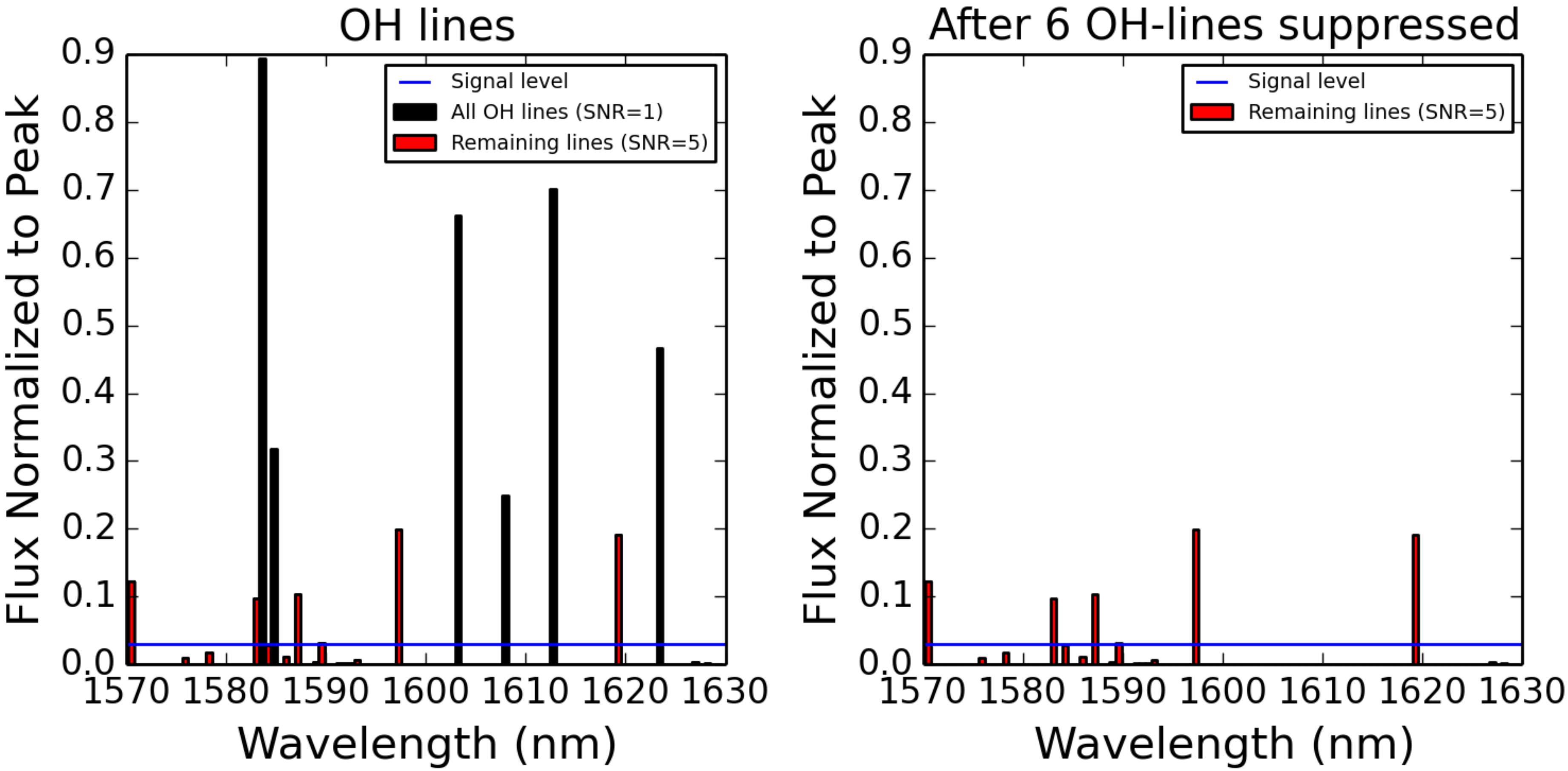
Qianfan Xu, David Fattal, and Raymond G. Beausoleil

Hewlett-Packard Labs, 1501 Page Mill Road, Palo Alto, CA 94304
qianfan.xu@hp.com



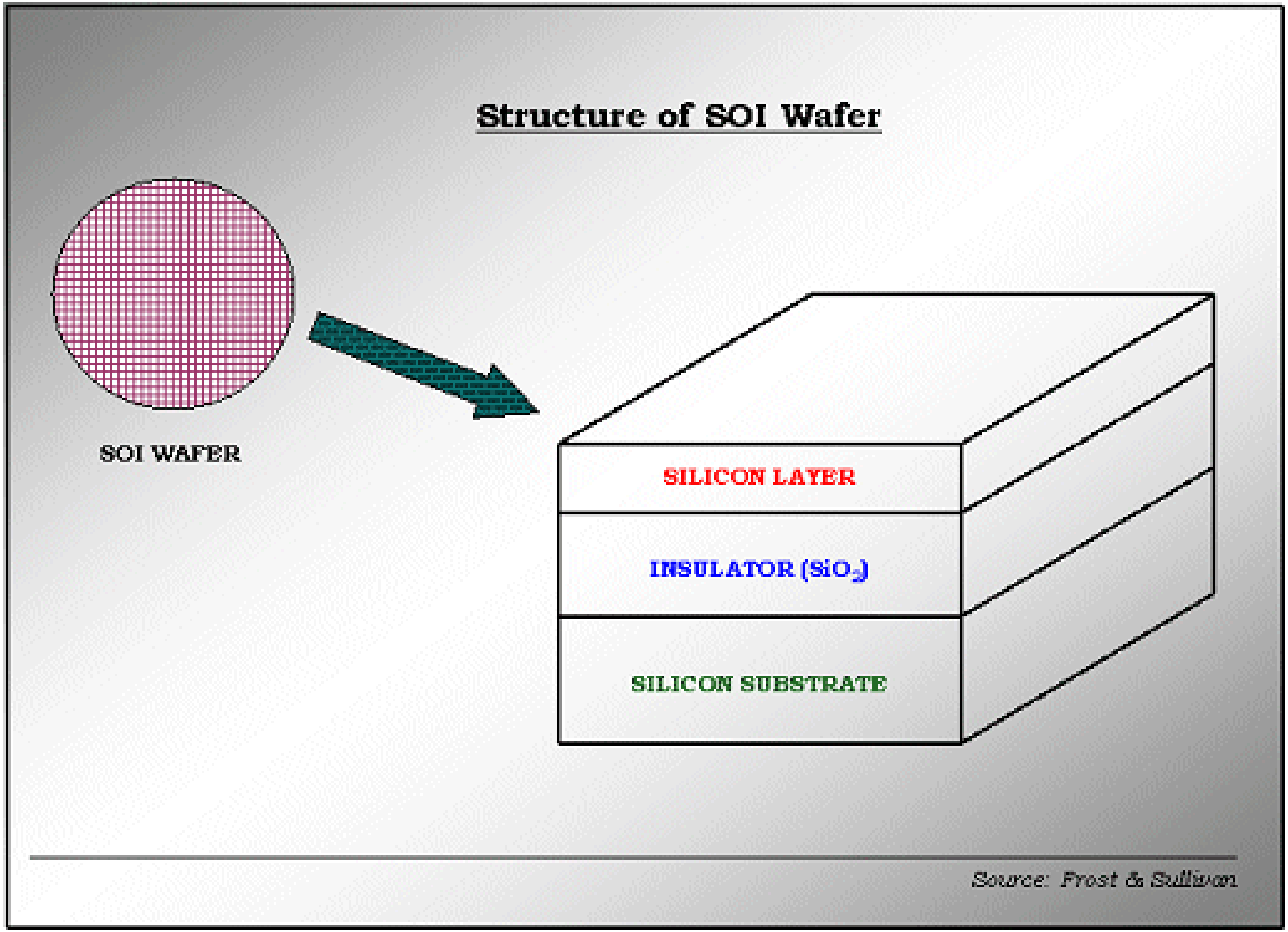


Small Number of Rings can have a Major Impact

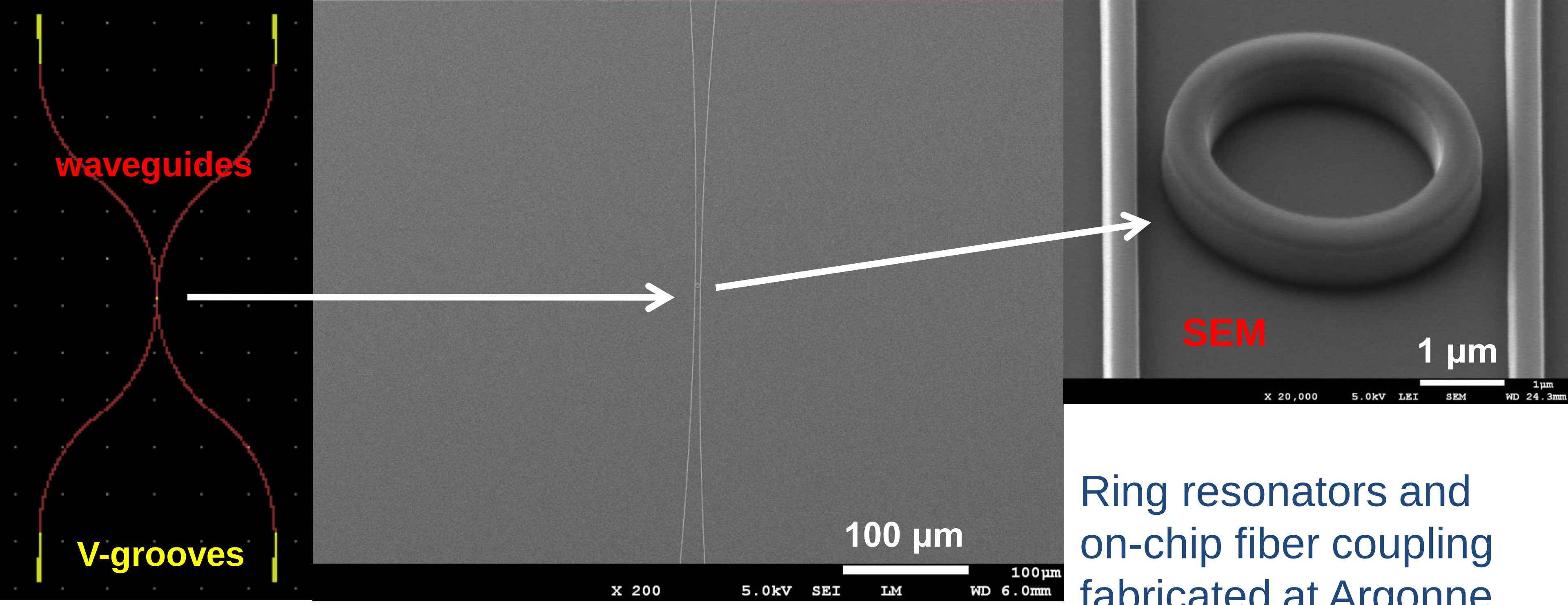


Middle of H-band Region

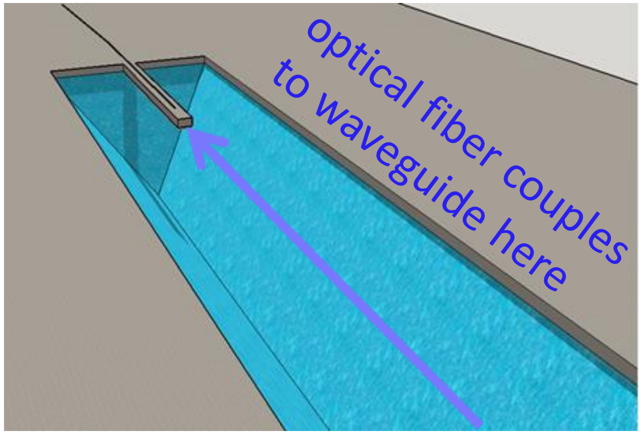
Silicon on Insulator (SOI) wafers

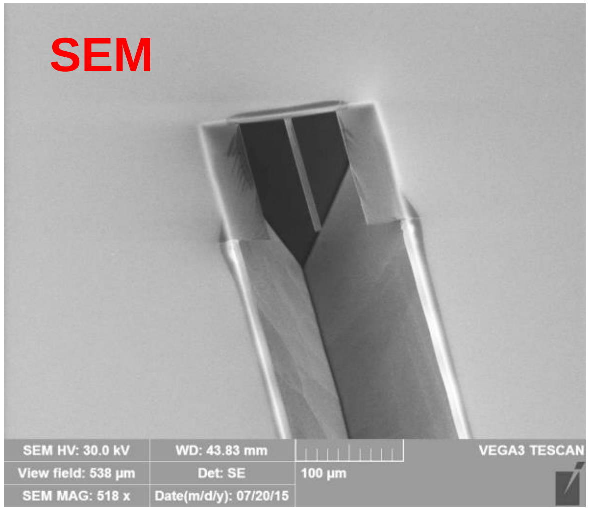


Source: Frost & Sullivan



Ring resonators and on-chip fiber coupling fabricated at Argonne.





No working device yet.

Issue still to be resolved:
Waveguide protection during the V-groove chemical etch. This complicates fabrication.

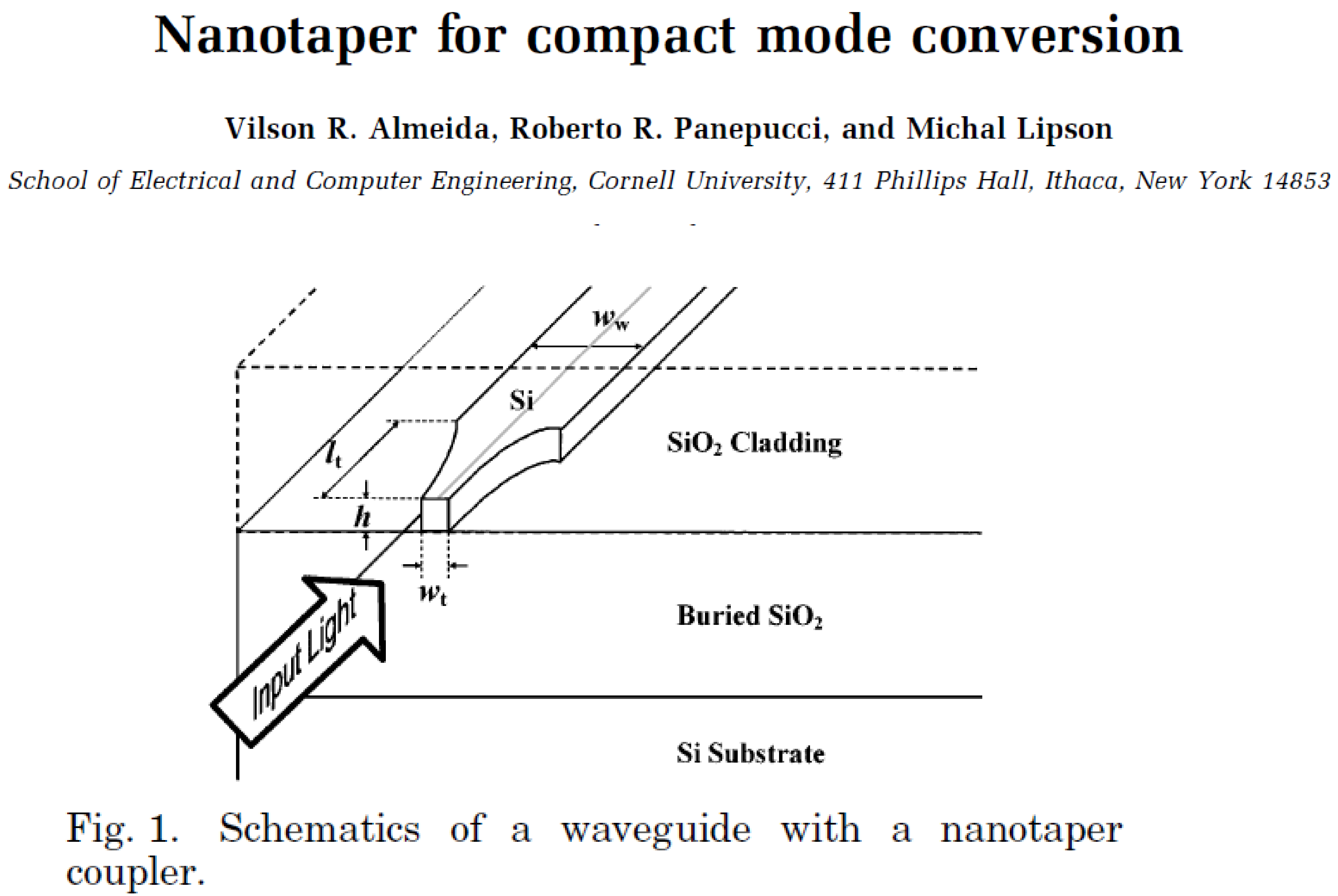
Two independent testing issues

Resonator performance can be tested with bright lamp/laser and inefficient non-final coupling

Fiber coupling performance can be tested without rings

Pursuing parallel path of simpler off-chip fiber coupling for resonator testing

Example of Edge Coupling of Optical Fiber



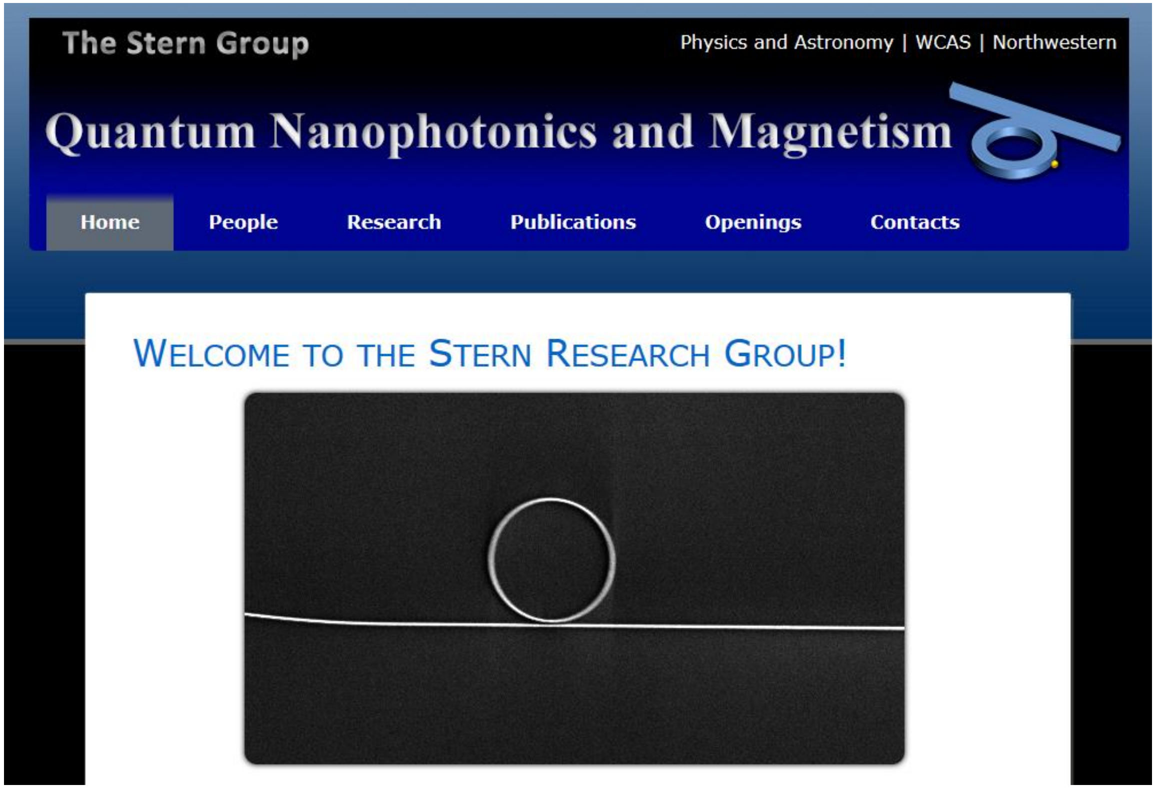
Nanotaper for compact mode conversion

Vilson R. Almeida, Roberto R. Panepucci, and Michal Lipson

School of Electrical and Computer Engineering, Cornell University, 411 Phillips Hall, Ithaca, New York 14853

Fig. 1. Schematics of a waveguide with a nanotaper coupler.

Northwestern Nanophotonics Group



The Stern Group

Physics and Astronomy | WCAS | Northwestern

Quantum Nanophotonics and Magnetism

WELCOME TO THE STERN RESEARCH GROUP!

Northwestern has fabricated working resonators at Argonne with both Edge Coupling and Vertical Coupling.
We are learning from them.

Much Simpler Fabrication with Edge Coupling

	On-Chip V-Groove	Edge Coupling
Electron beam lithography	3	1
Chemical Etching	2	0
Plasma Etching	5	1
Vapor Deposition	3	1
Spin-coat	5	1

~3 day fabrication versus ~3 week. Will finalize the first Edge Coupling wafer design this week.

Conclusions

Dramatically lower exposure times in the near-infrared (up to x1800) will be a game-changer for ground-based NIR astrophysics especially supernova dark energy science.

Potential fast follow-up of LSST deep-field supernova discoveries (up to 50,000 SNe) with near-infrared measurement(s) will have a major impact in reducing dust systematics and improve standardization and host galaxy correlation understanding.

Ring resonators are a cost-effective and scalable technology that can accomplish this.

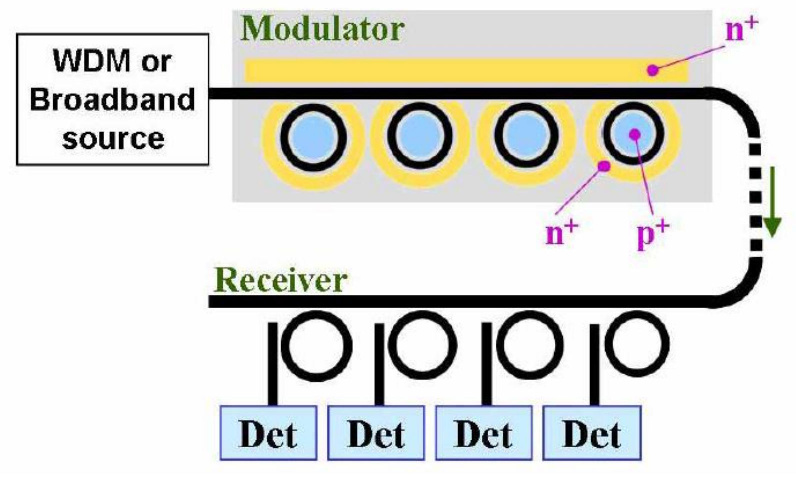
Additional slides…

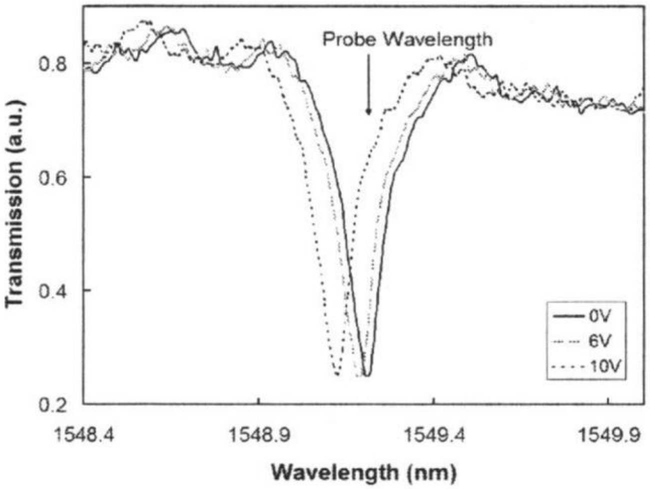
Wavelength Tuning

- First option: tune electron beam currents for each ring to get DIFFERENCES in ring radii close, then control temperature to move all wavelengths.

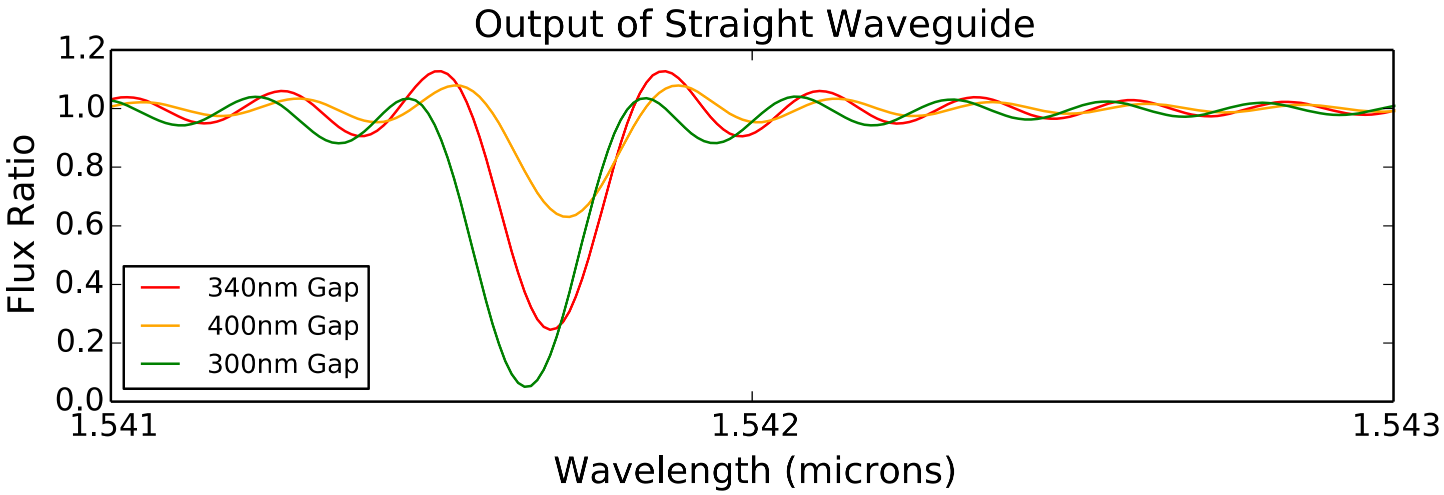
- Second option: If #1 not good enough, also vary gap width to make suppression wider in wavelength to cover all target lines.

- Third option: pn diodes in each ring with voltage control, demonstrated in many papers.



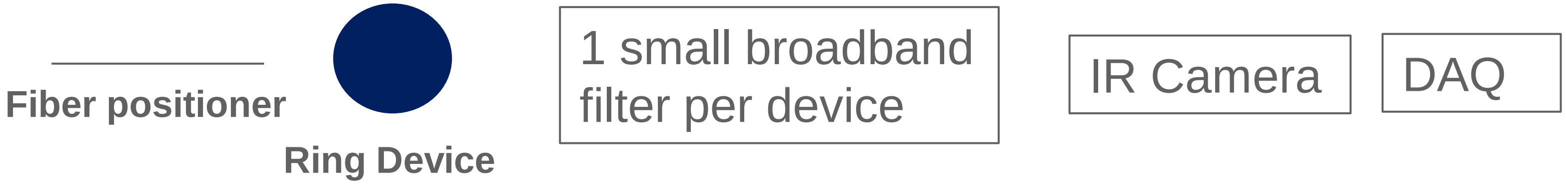


Result from Resonator simulation using MEEP



Project phases and cost estimates

- Phase 1: From working single-ring to reproducible multi-ring devices
  - Fabrication equip.: CNM is a user facility and all equipment use is free.
  - Manpower: Fabrication ~35 hrs per wafer split among three scientists and spread over 2 weeks. Minimum 0.15 FTE per scientist.
  - Materials: Wafers and fibers $35K ($1500/wafer)
- Phase 2: Reproducible multi-rings (10-15 rings) to controllable device
  - Add ~$50K of engineering for temperature control system
- Phase 3: On-sky non-Supernova test of 1 controllable multi-ring device
  - Reproduce AAO test, plug in replacement? Assume $<500K
- Phase 4: Supernova follow-up demonstration with 6 devices covering H-band
  - In collaboration with AAO, and others in SN community ($1-3M)
  - Use SN discoveries from DECam, PTF, or other source.



Fiber positioner

Ring Device

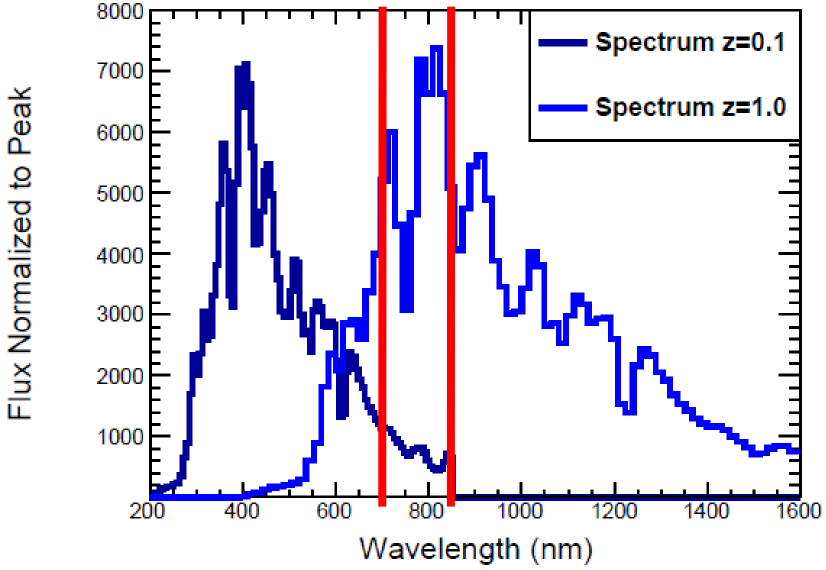
1 small broadband filter per device

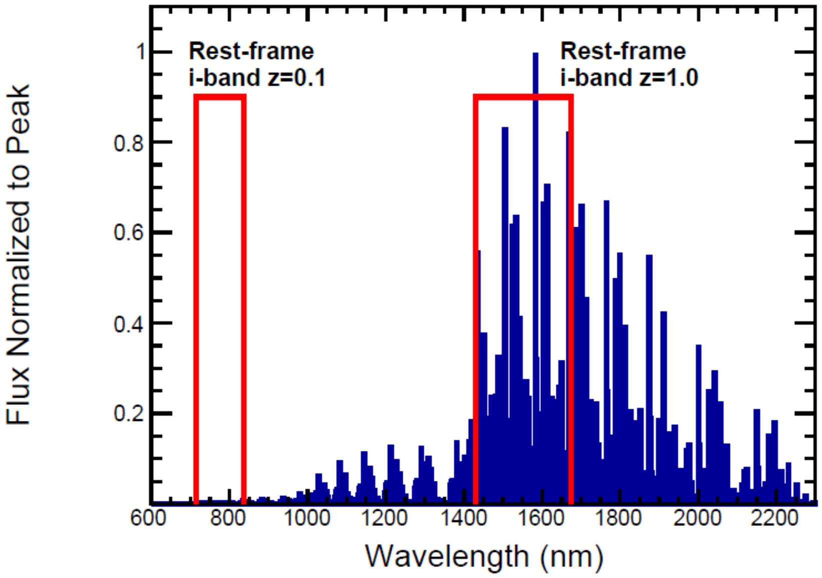
IR Camera

DAQ

- Phase 5: The demonstration device could measure the 50K LSST SN with 15 min/SN exposures. Not bad but assume expanded wavelength range and follow-up capabilities for LSST ($3-10M)

Sky Background Impact on Supernovae





Upcoming Space-based SN Surveys

- Euclid 1500 Type Ia (0.7<z<1.5)   4 filters (1 optical, 3 NIR), no spectrograph. They assume redshift comes from host galaxy spectra.

- WFIRST (not yet approved) 1200 (0.1<z<0.6) plus 1500 (0.6<z<1.7) 4 filters plus spectrum of each.

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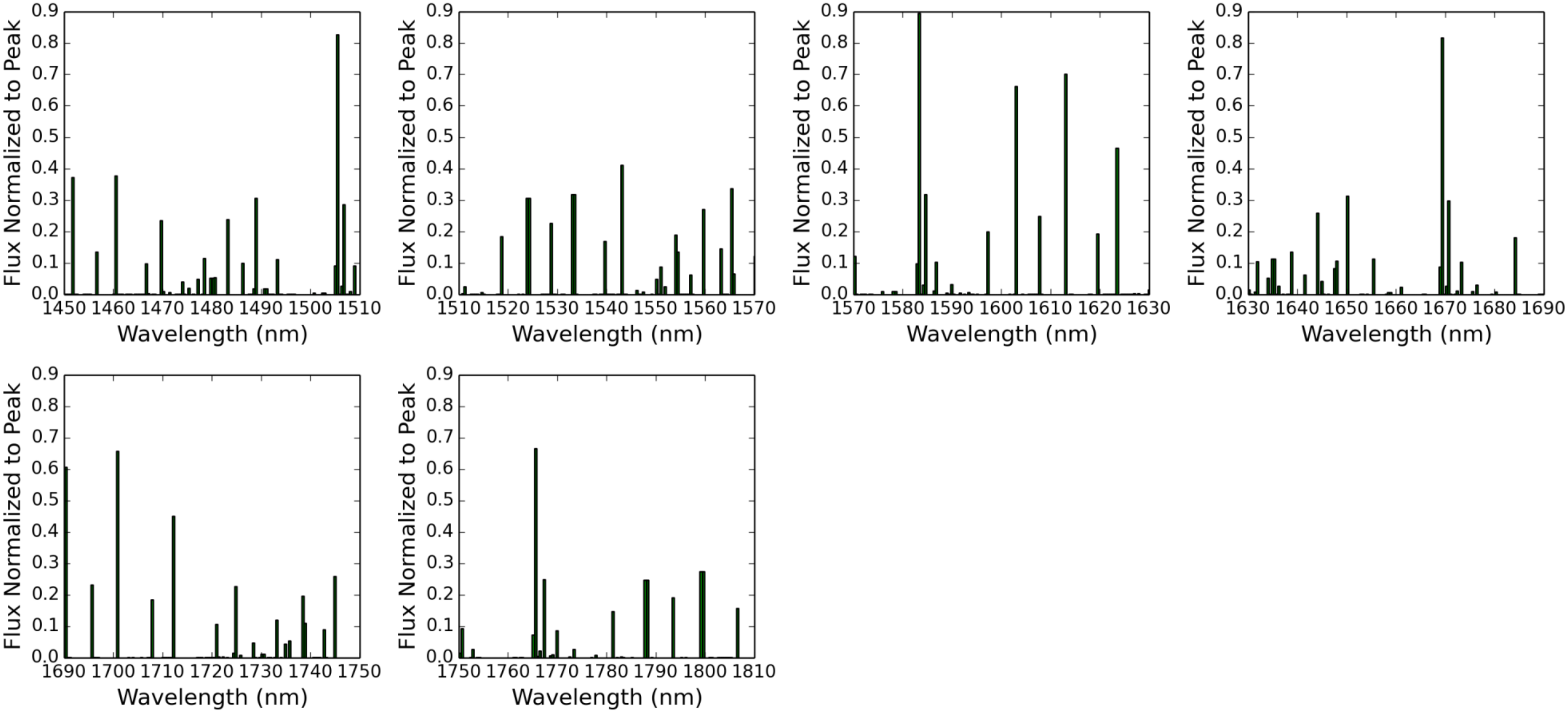
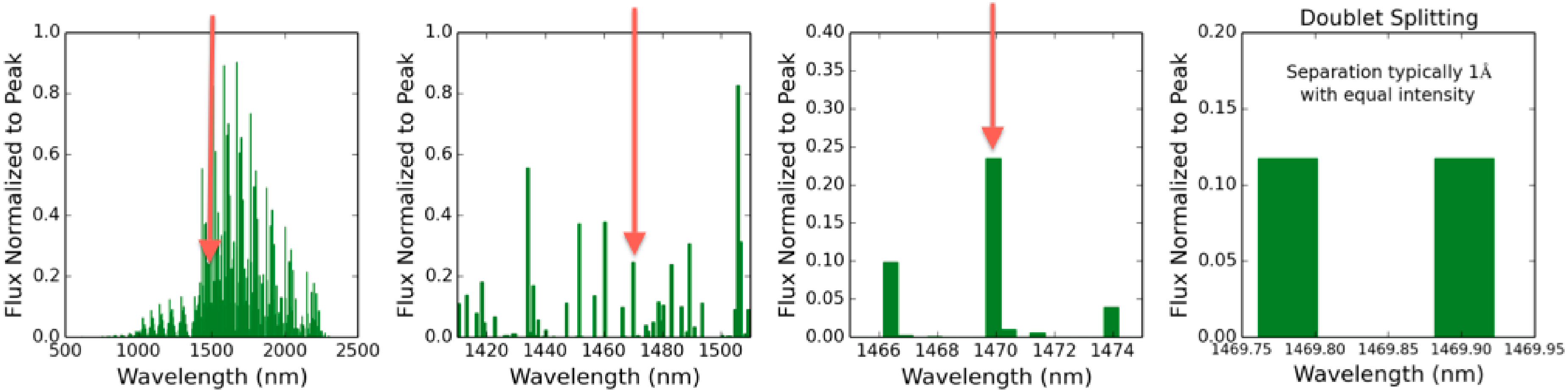
OH lines in 60nm slices of H band





- **OH emission lines comprised of thousands of doublet peaks**
- **Distribution of doublet separations from the OH lines**
- **Most separations are smaller than 0.2nm**