

Mid-Infrared Prism Coupler

Amy Qiao and Norm Anheier

Pacific Northwest National Laboratory



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Research Motivation

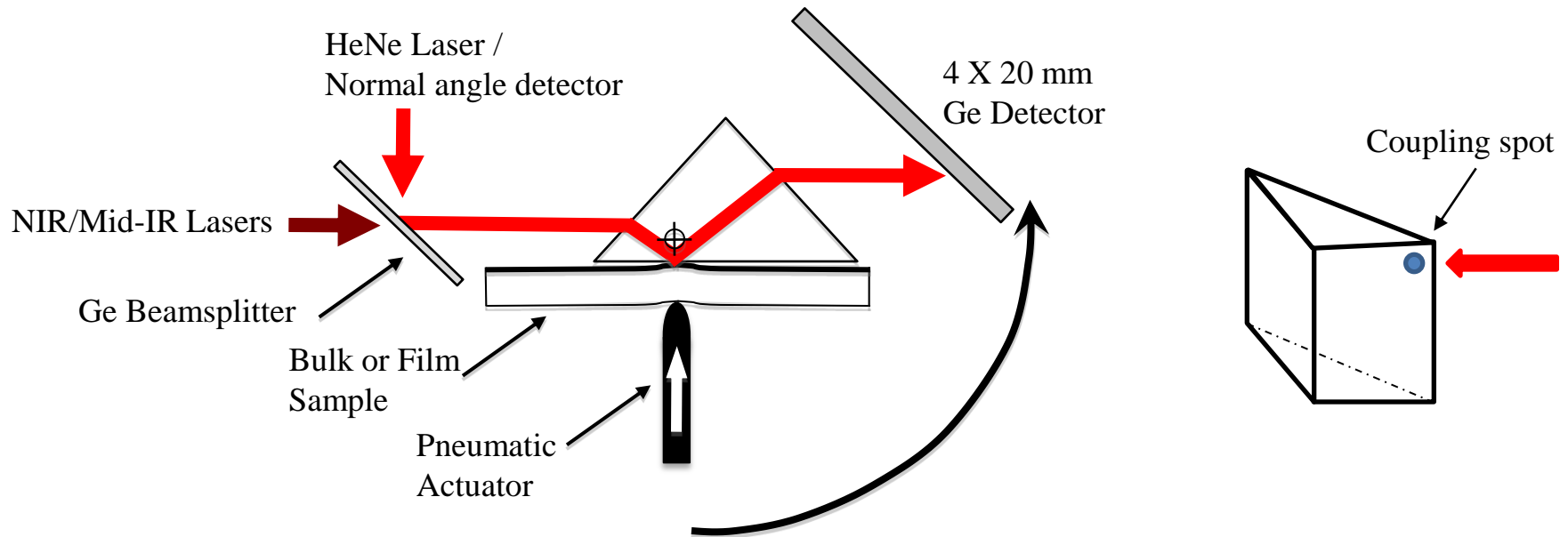
- ▶ Rapid progress made in quantum cascade laser technology has stimulated development of new mid-infrared optical materials that provide broader range of optical, thermal, and mechanical properties
- ▶ Motivation - comprehensive knowledge of the refractive index dependencies on wavelength and temperature for:
 - New materials development efforts requiring rapid, low cost characterization
 - Optical material processing research: molding, photomodification...
 - Variability of commercial materials: legacy specifications, emerging markets
- ▶ Goal – index and dn/dT accuracy...



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Index Measurement by Prism Coupler Method



- + Direct measurement of index and dn/dT
- + Measures bulk, single and dual films
- + Measures anisotropy/birefringence
- + Minimal sample preparation
- + Measurement and analysis is quick
- + Index accuracy can reach 0.0001

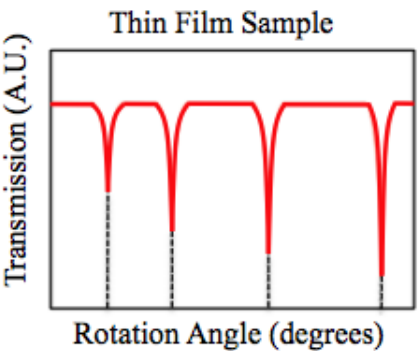
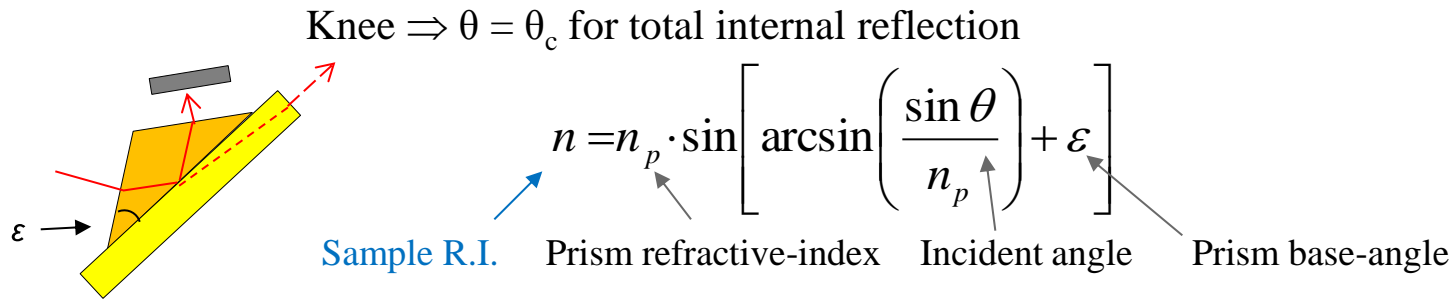
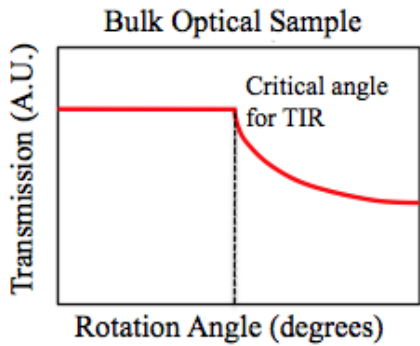
- Prism index needs to be higher than samples measured.
- Measurement limited to low spatial resolution
- Contact measurement, can damage fragile films
- Uses discrete laser wavelengths rather than a broadband source



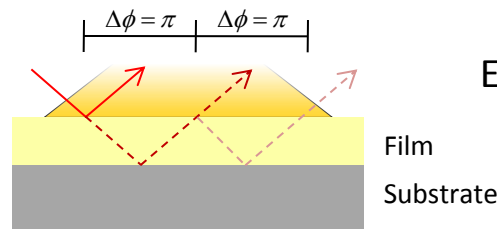
Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Index Measurement by Prism Coupler Method



Destructive interference of reflected light \Rightarrow coupled mode



Effective mode index¹

$$N_m = \sin \theta_m \cos \varepsilon + \left(n_p^2 - \sin^2 \theta_m \right)^{1/2} \sin \varepsilon$$

Incident angle Prism base-angle Prism Index

Coupling occurs when:

$$k_{xf} W + \phi_{fs} + \phi_{fa} = m\pi$$

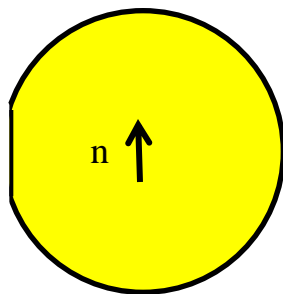
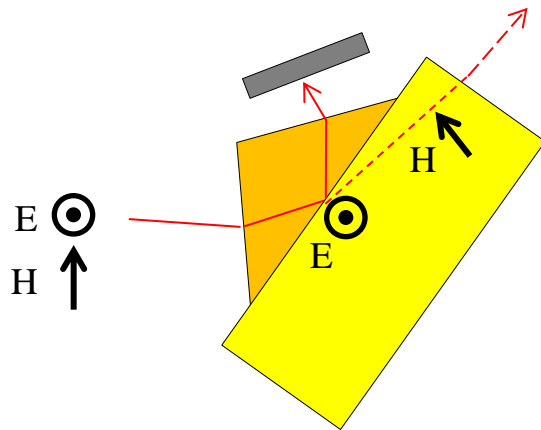
Magnitude of wave vector Film thickness Fresnel phase shifts Order number (integer)

$$\phi_{fi} = -\tan^{-1} \left(\frac{N_m^2 - n_i^2}{n_f^2 - N_m^2} \right)$$

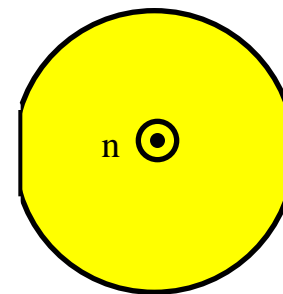
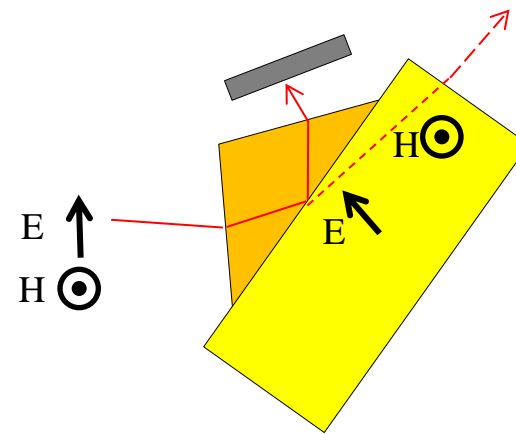
Algorithm required to solve set of transcendental equations at multiple wavelengths

Anisotropy/Birefringence Measurement

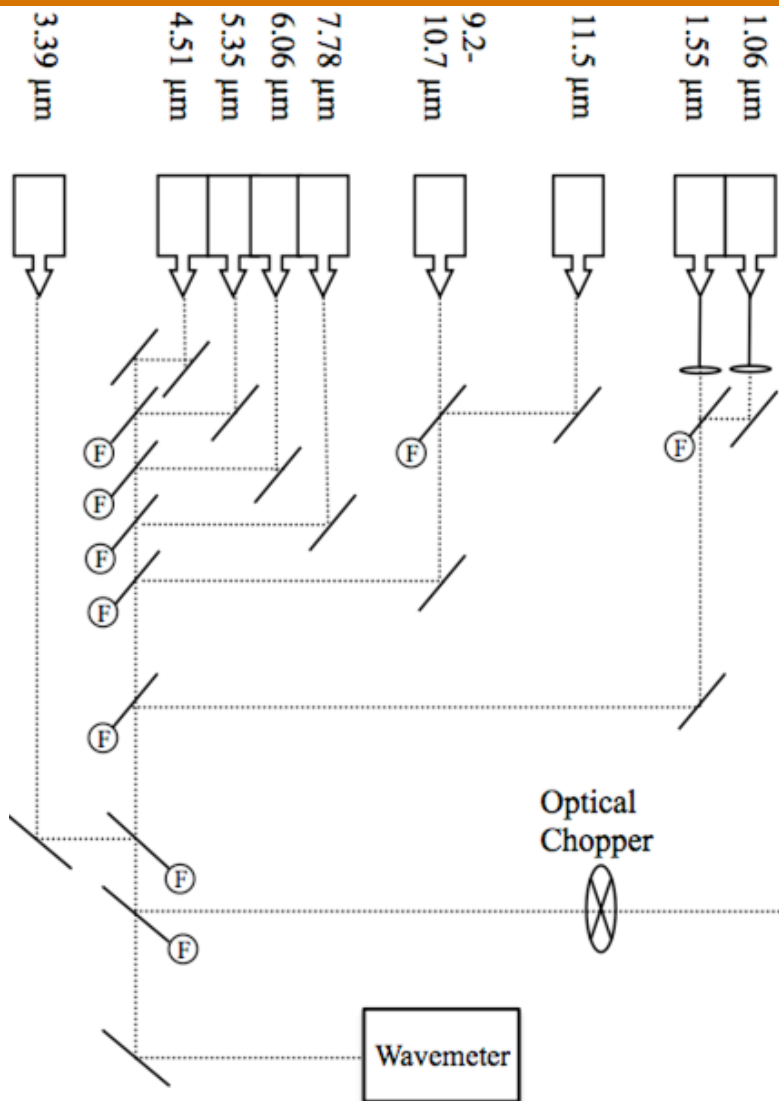
TE mode measures indices along any direction in sample surface



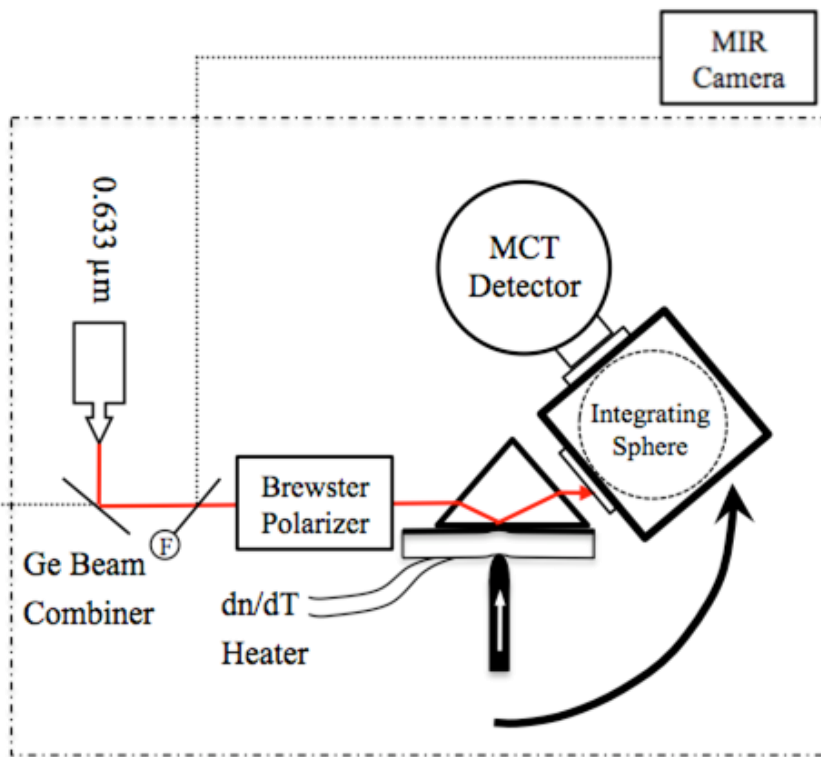
TM mode measures index perpendicular to sample surface



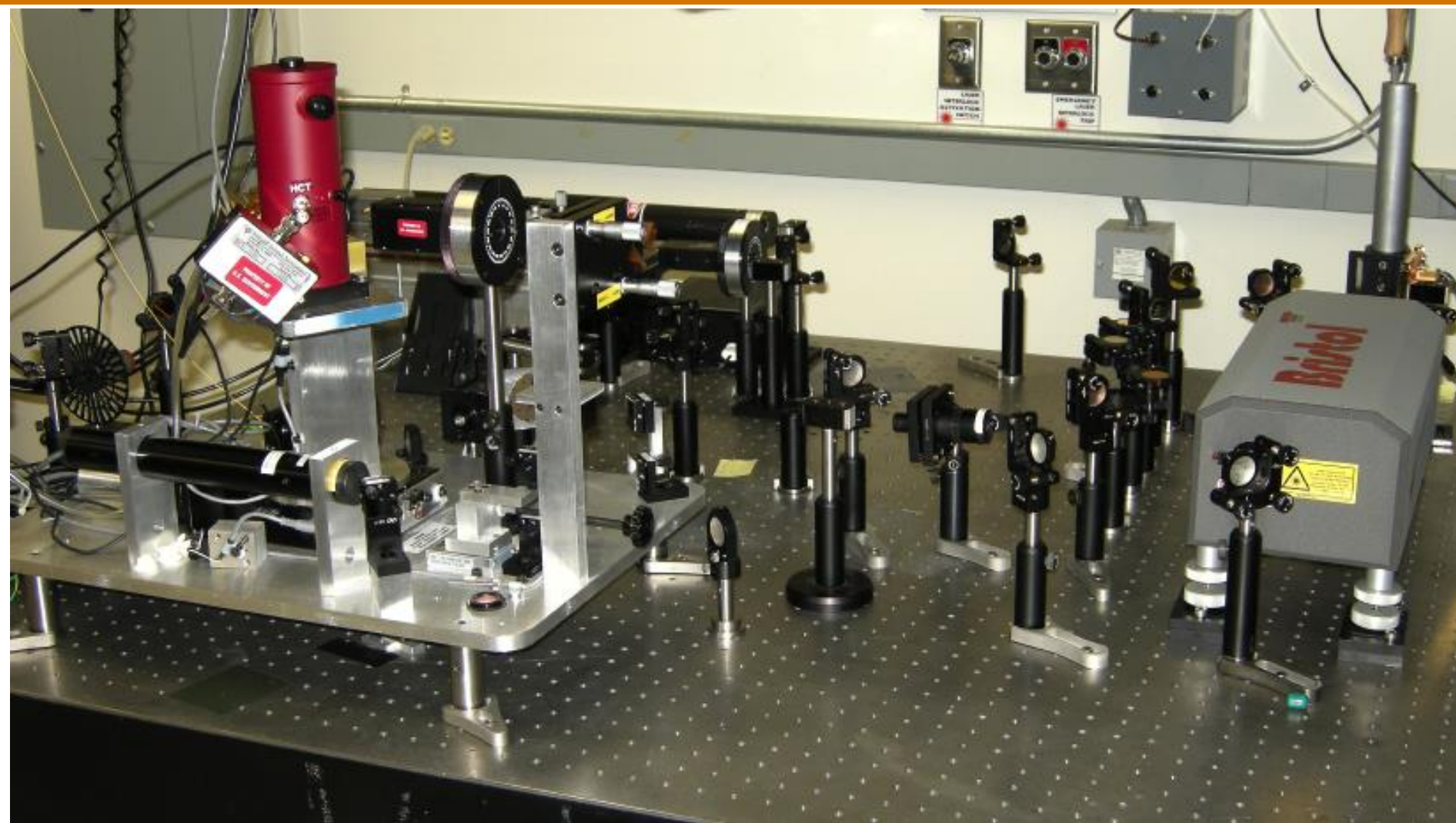
Mid-Infrared Prism Coupler System Layout



- New NIR and Mid-infrared laser sources
- Mid-infrared coupling prisms
- New mid-infrared detection module
- Mid-infrared optical components: mirrors, polarizer, camera, wavemeter
- Sample thermal control: dn/dT

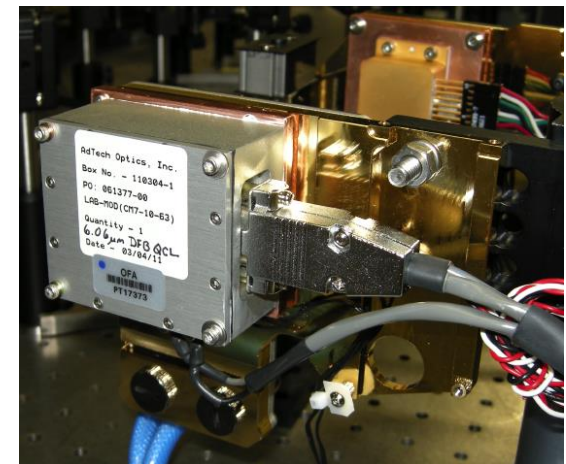
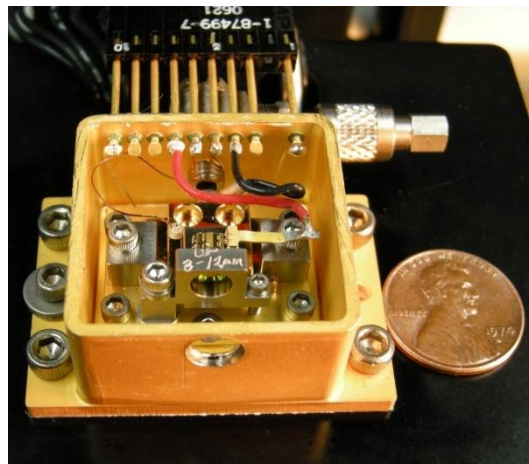


Mid-Infrared Prism Coupler System Layout



Mid-Infrared Prism Coupler Laser Sources

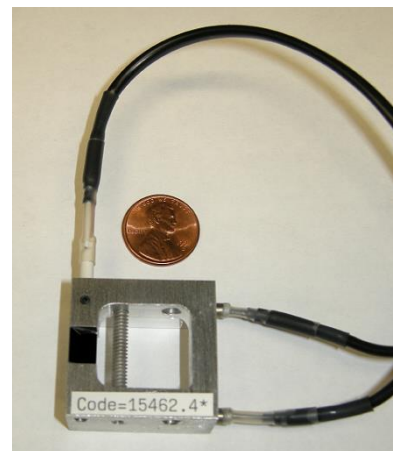
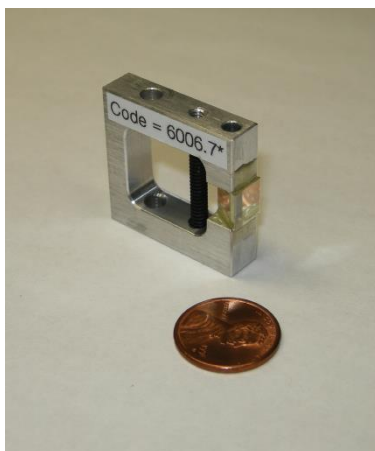
Laser Source	Laser Wavelength (μm)	Model #	Manufacturer
Fiber-coupled DFB	1.06	QFBGLD-1060-20PM	QPhotonics
Fiber-coupled DFB	1.55	81662A	Agilent
Infrared HeNe	3.39	LHIR-0100-339-21	PMS Electro-Optics
DFB QC Laser	4.51	CM7-10-68	AdTech Optics
DFB QC Laser	5.35	DQ5-M575D	Maxion
DFB QC Laser	6.06	CM7-10-63	AdTech Optics
DFB QC Laser	7.78	CM7-11-01	AdTech Optics
Waveguide CO ₂	9.3-10.6	LASY4G	Access Laser Company
Fabry-Pérot QC Laser	11.5	CS-09-10	AdTech Optics



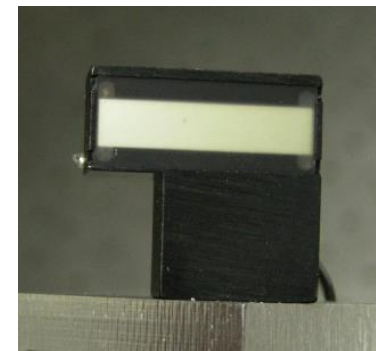
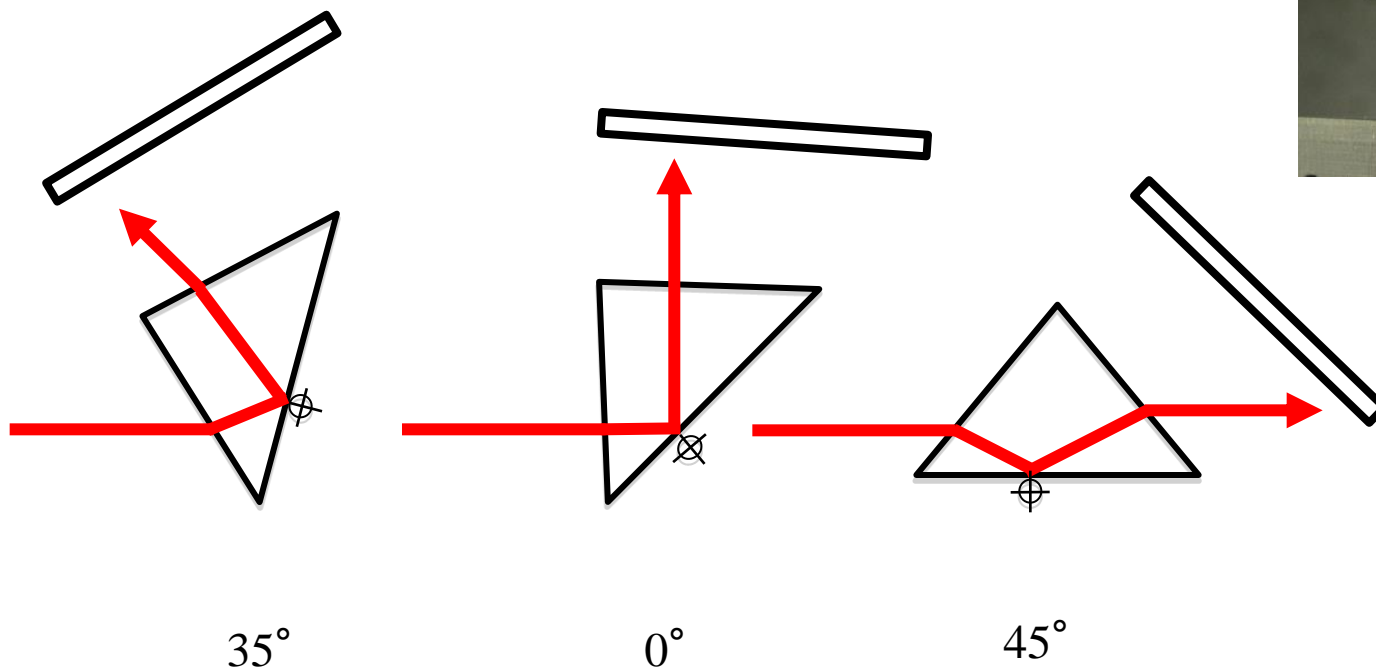
Proudly Operated by Battelle Since 1965

Mid-Infrared Prism Coupler Coupling Prisms

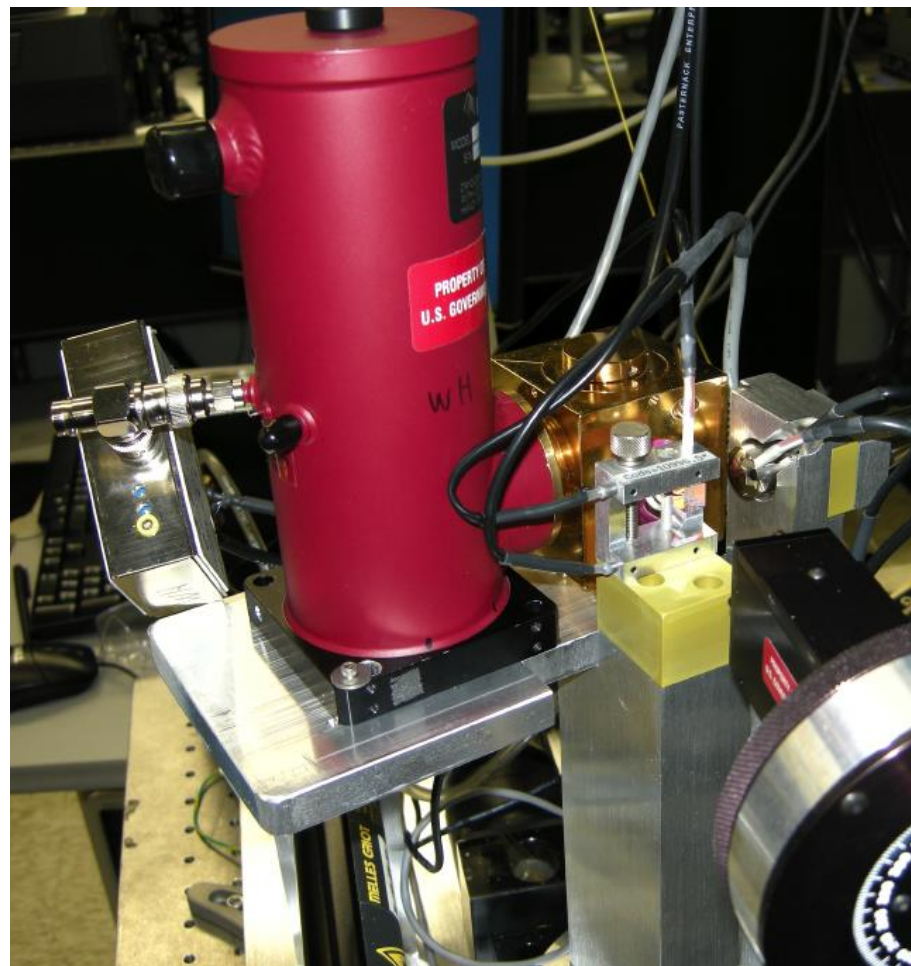
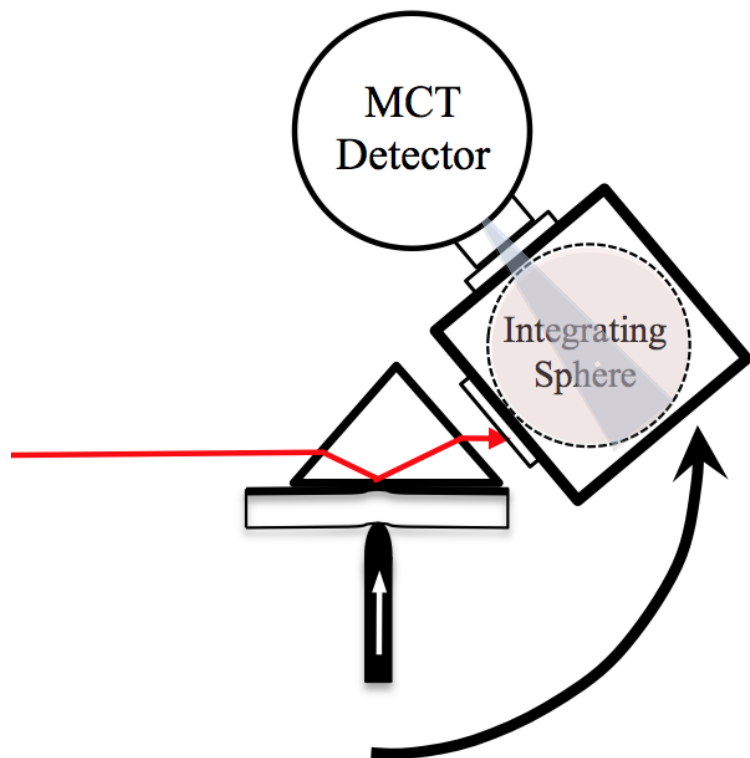
wavelength (μm)	Ge Prism		Si Prism		GaP Prism		Rutile Prism		GGG Prism	
	high	low	High	low	High	low	high	low	high	low
0.6328	n/a	n/a	n/a	n/a	2.90	2.01	2.69	1.95	1.84	1.00
1.547	n/a	n/a	3.14	2.32	2.70	1.81	2.54	1.80	1.81	1.00
3.391	3.14	2.12	3.10	2.28	2.68	1.78	2.54	1.79	1.79	1.00
5.348	3.14	2.11	3.09	2.28	2.67	1.77	2.54	1.79	1.75	1.00
10.591	3.13	2.11	n/a	n/a	2.63	1.73	n/a	n/a	n/a	n/a
11.5	3.13	2.11	n/a	n/a	2.61	1.71	n/a	n/a	n/a	n/a



Mid-Infrared Prism Coupler Signal Detection



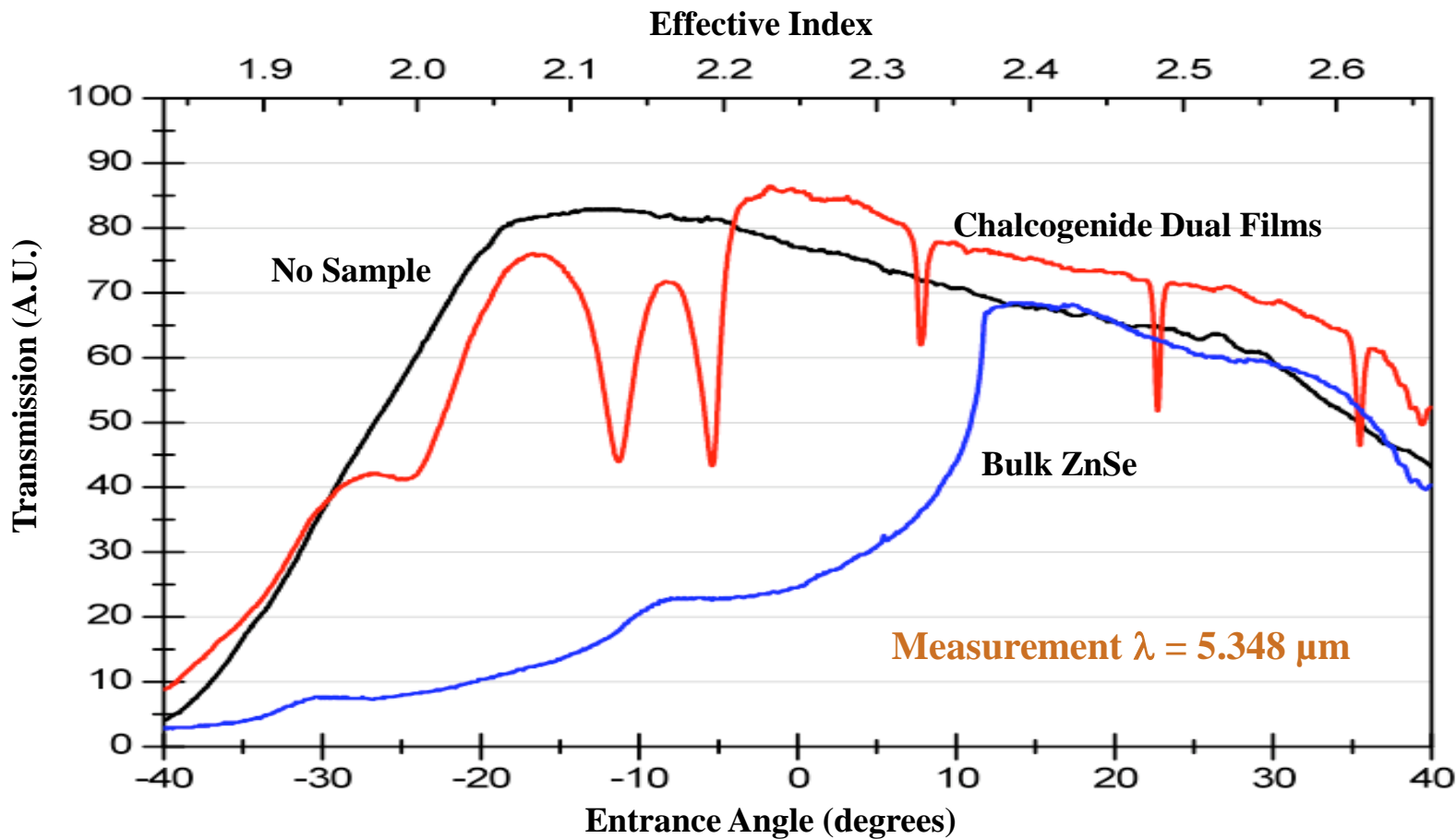
Mid-Infrared Prism Coupler Signal Detection



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Mid-Infrared Prism Coupler Signal Detection



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Mid-Infrared Prism Coupler Calibration

- The prism coupler measurement accuracy is dependent on accurate knowledge of the coupling prism index
- Index measurement accuracy approaches ± 0.0001 if coupler prism has well calibrated dispersion and dn/dT
- CVD ZnSe features:
 - ✓ Broad 0.5-14 μm transparency
 - ✓ High purity, non-birefringent
 - ✓ Mechanically rugged
 - ✓ Well behaved, low dn/dT
- CVD ZnSe calibration SRM by minimum deviation refractometry
 - Two temperature setpoints – 10° C and 70° C
 - Eight wavelengths – 0.633 to 13 μm

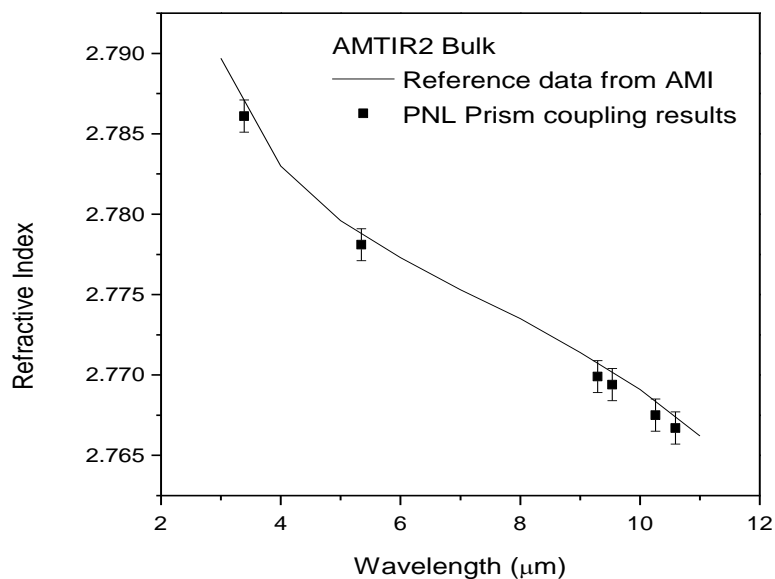


Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

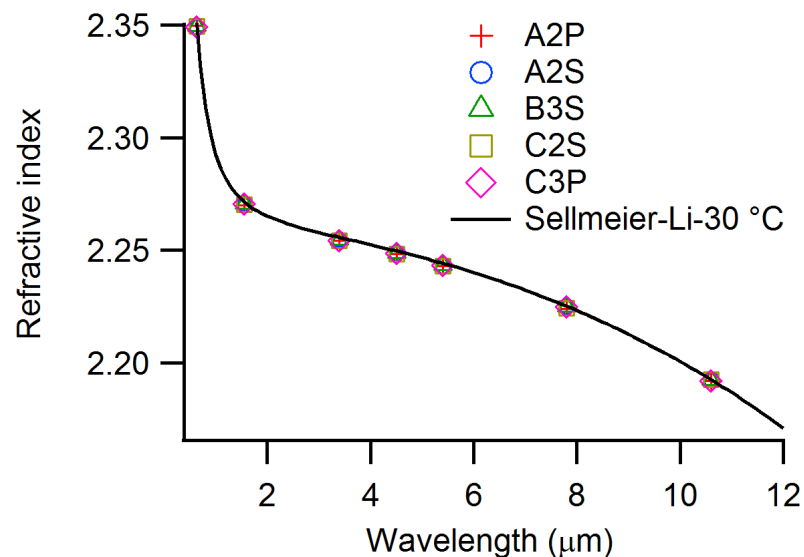
Studies Performed Using Mid-Infrared Prism Coupler

Comparison of AMTIR2 (As_2Se_3)



1) Carlie N, et al, Review of Scientific Instruments, V82 (5), Article #: 053103, 2011

Comparison of ZnS



2) Qiao HA, et al, Optics Letter, V37(9):1403-1405, 2012

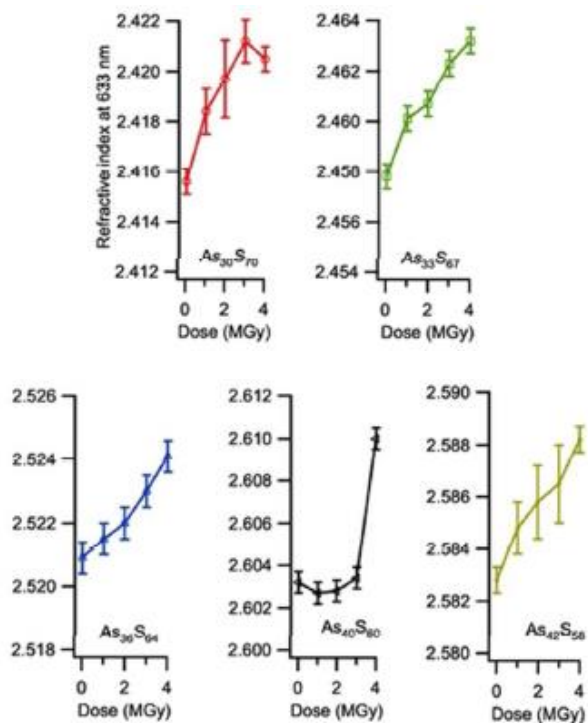


Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

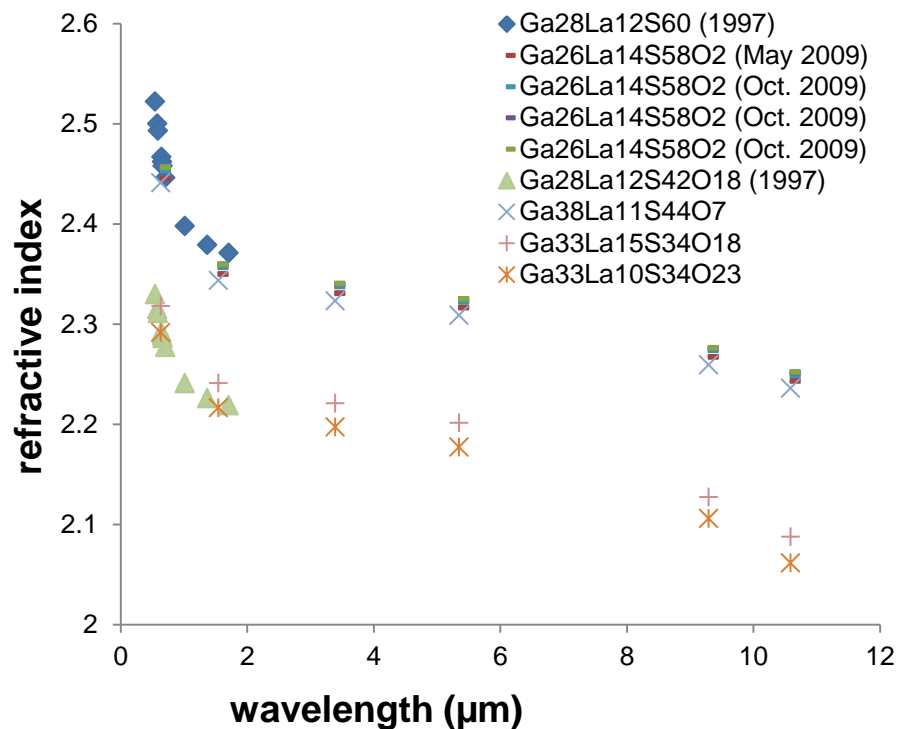
Studies Performed Using Mid-Infrared Prism Coupler

Gamma radiation effects on As-S



3) Sundaram SK, et al, Journal of the American Ceramic Society, V95 (3), 1048–1055, March 2012.

Composition effects on GLS



4) HA Qiao, et al, Proceeding of SPIE Defense, Security and Sensing, V8016-13, 2011.



Proudly Operated by Battelle Since 1965

Summary

- A prism coupler was developed to characterize index and dn/dT in bulk and thin film optical materials at mid-infrared wavelengths
- The commercial availability of single frequency QC lasers has greatly simplified adapting prism coupler to the mid-infrared
- A cyro-cooled MCT and an integrating sphere resolved challenging beam variation issues
- High-precision standards for coupling prism calibration are identified and procured
- Future work:
 - Characterize and align 11.5 μm laser
 - Calibrate thermal prism temperature



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Acknowledgments

- ▶ Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830.
- ▶ Research Funding: Supported in part by the U.S. Department of Energy, Office of Nonproliferation and Verification Research and Development (NA-22) and through a contract with Edmund Optics.



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965