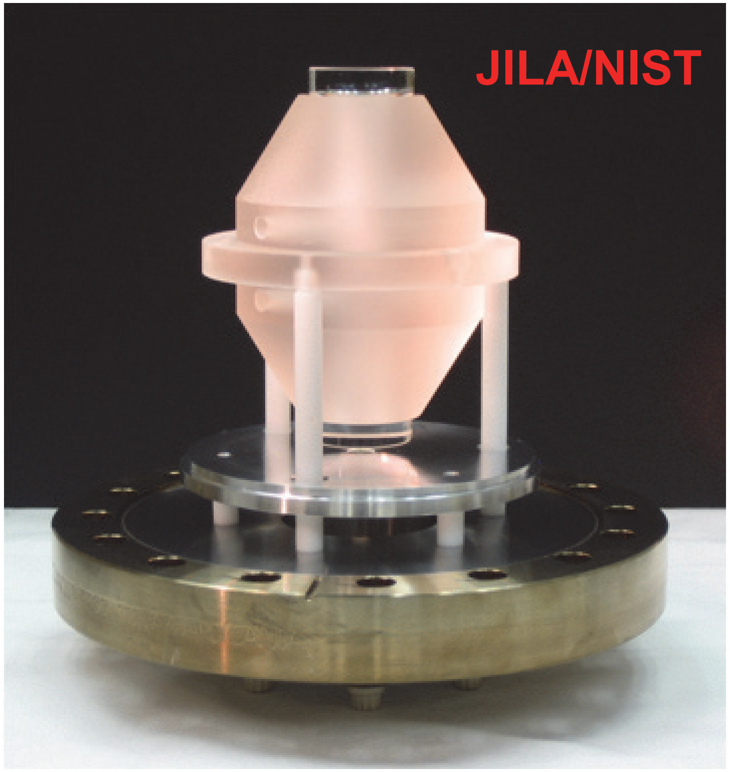
CRYSTALLINE MIRROR SOLUTIONS

Recent advancements in substrate-transferred crystalline coatings

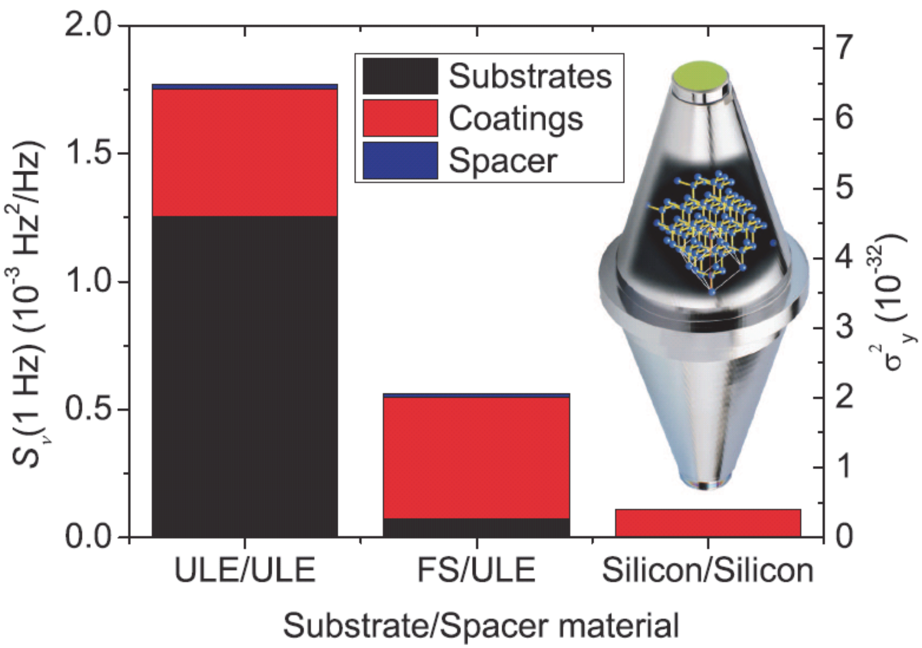
February 16, 2019

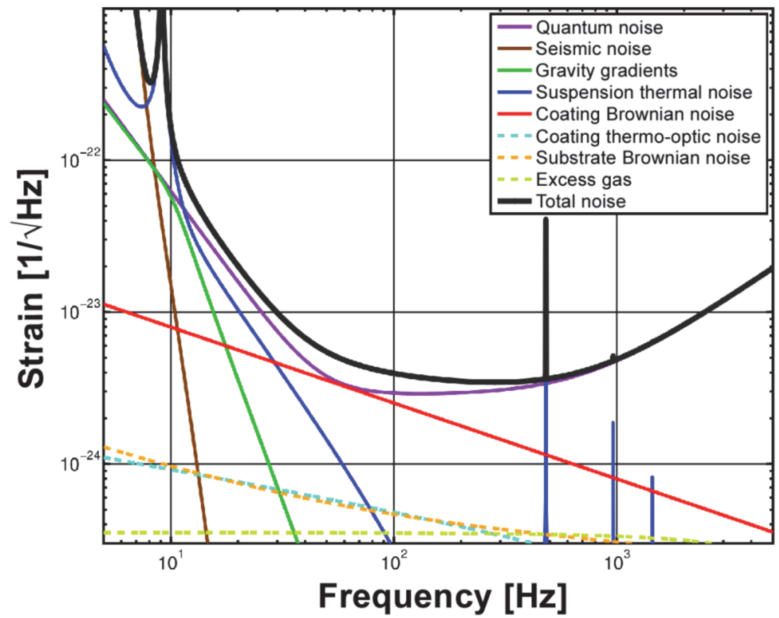
Thermal (Brownian) Noise



- Precision interferometers are now limited by Brownian noise
  - from cm-scale reference cavities to km-length GW detectors

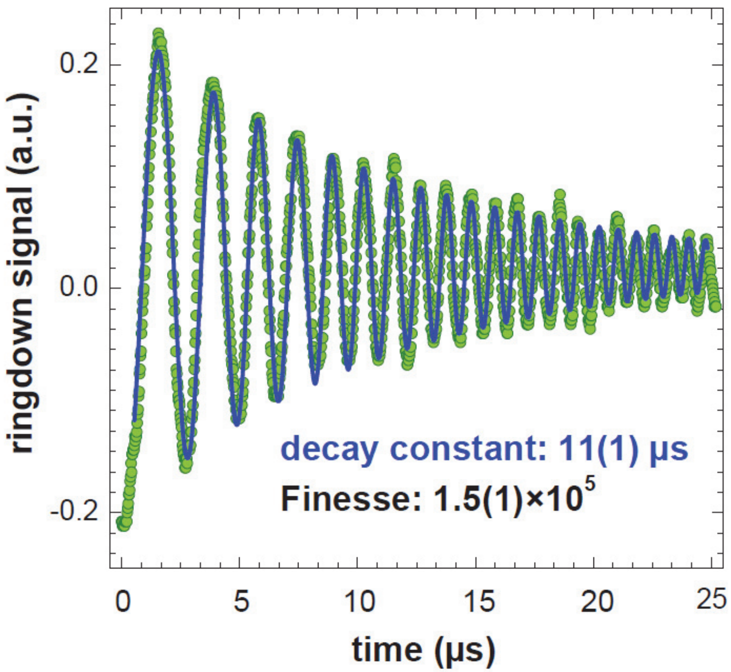
Consequences of Excess Elastic Loss

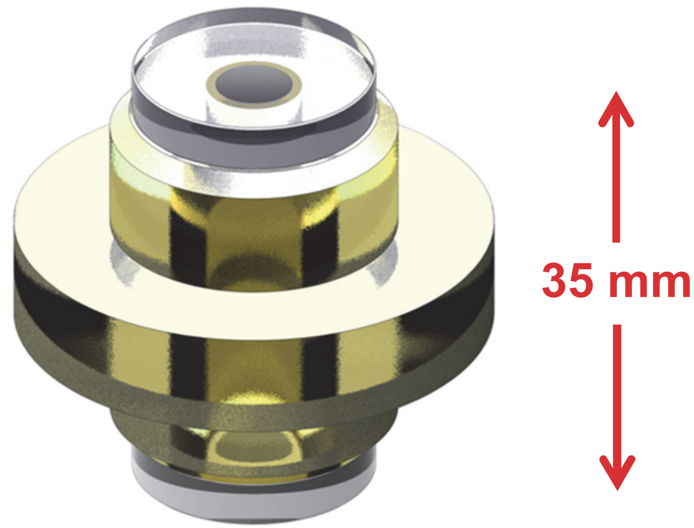




- Dielectric optical coatings (Ta_2O_5/SiO_2) are a major limitation
  - from LSC studies by Crooks, Harry, Penn, etc. Ta_2O_5 is the culprit
  - loss angle has been reduced by a factor of ~2 over the last decade
- Crystalline coatings represent an excellent alternative solution
  - simultaneous achievement of high optical and mechanical quality

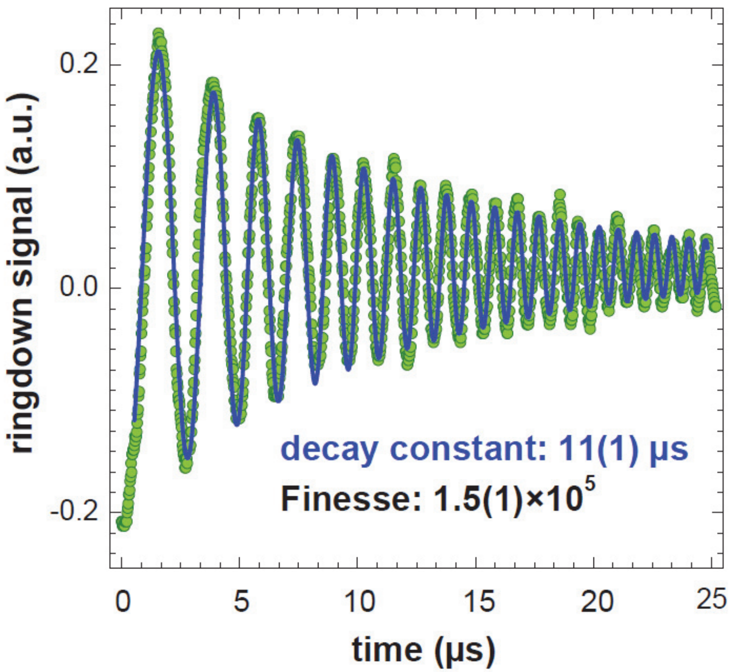
Kessler, et al. Nature Photonics 2012 | Harry, Bodiya, DeSalvo eds., Camb. Univ. Press 2012

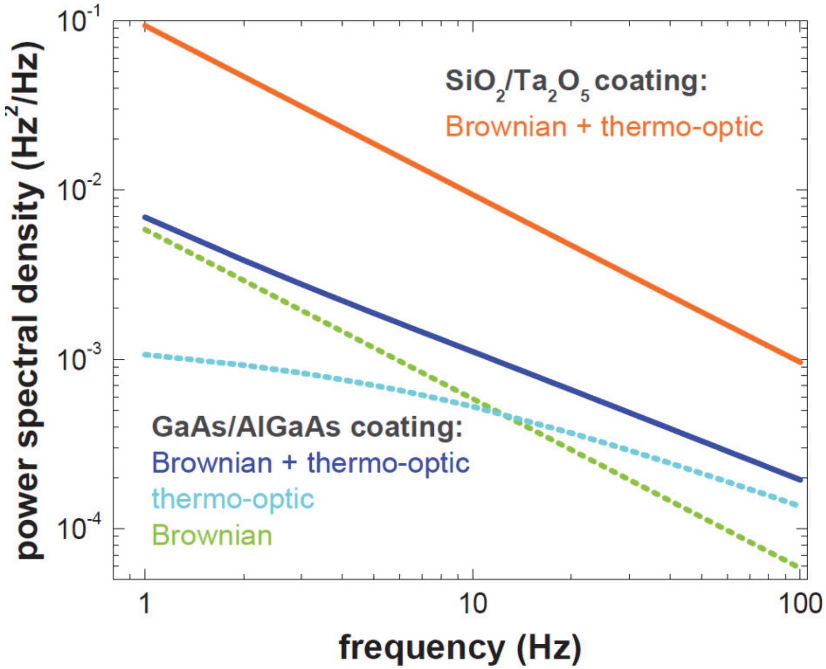




- Optical cavity ringdown yields a finesse of 150,000 @ 1064 nm
  - transmission of ~5 ppm, scatter + absorption loss of 15 ppm
- Extracted quality factor matches measurements on μ-resonators
  - coating loss angle below 4×10^{-5} (potential for $<5 \times 10^{-6}$ at cryo)

G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, Nature Photonics (2013)





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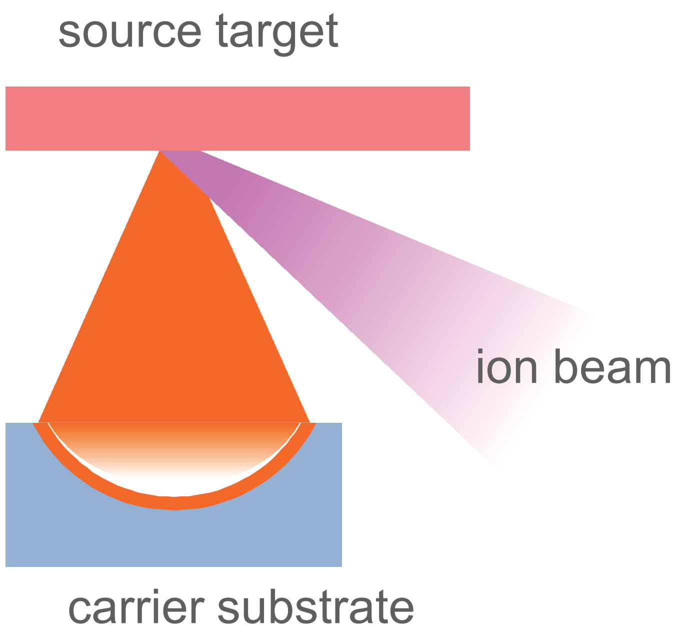
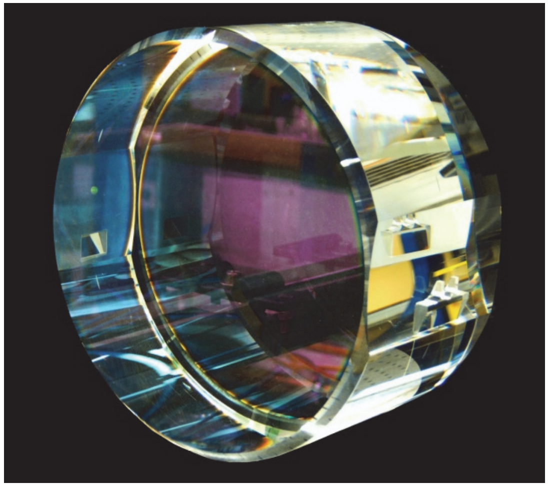
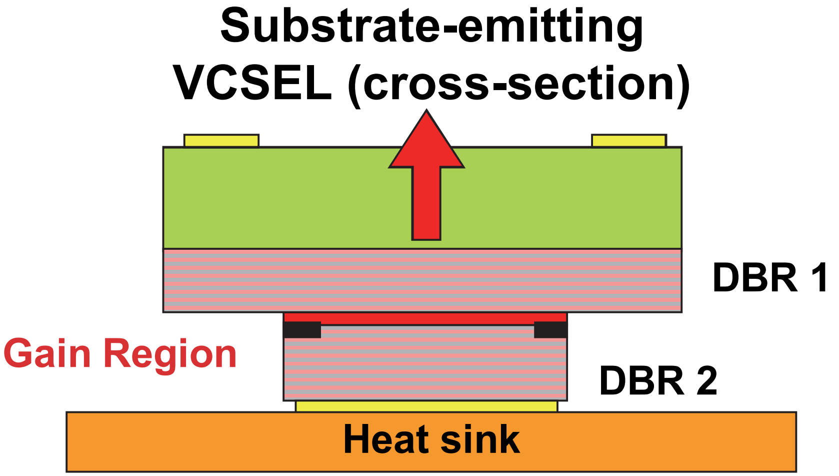


State-of-the-art multilayer mirrors:
sputtered Ta_2O_5/SiO_2



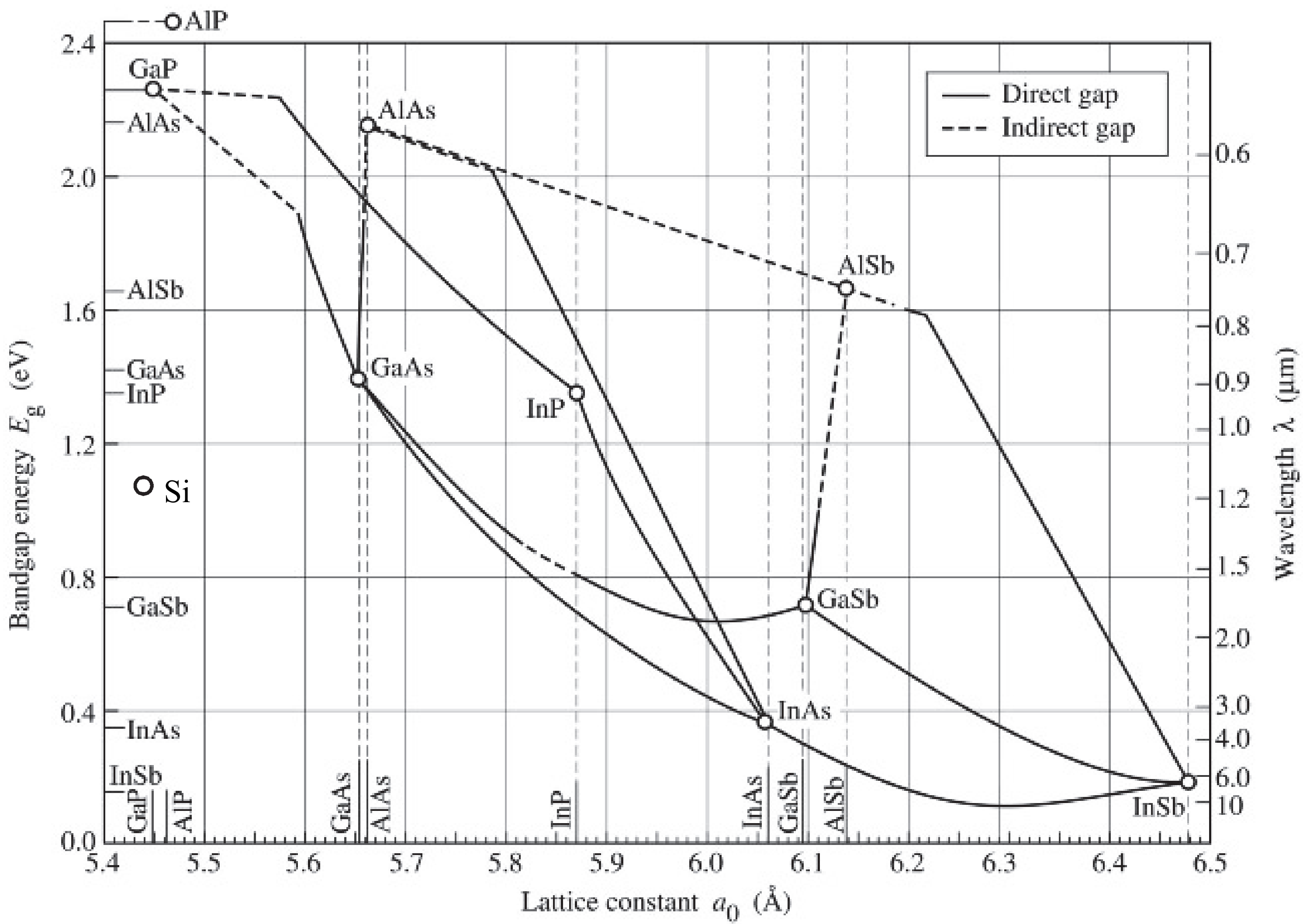
- Multilayer of amorphous thin films via ion beam sputtering (IBS)
- Phenomenal optical properties: high R, low absorption and scatter
- Flexible choice of substrates assuming excellent surface quality
  - super-polished SiO_2, Si, ULE, sapphire, etc.

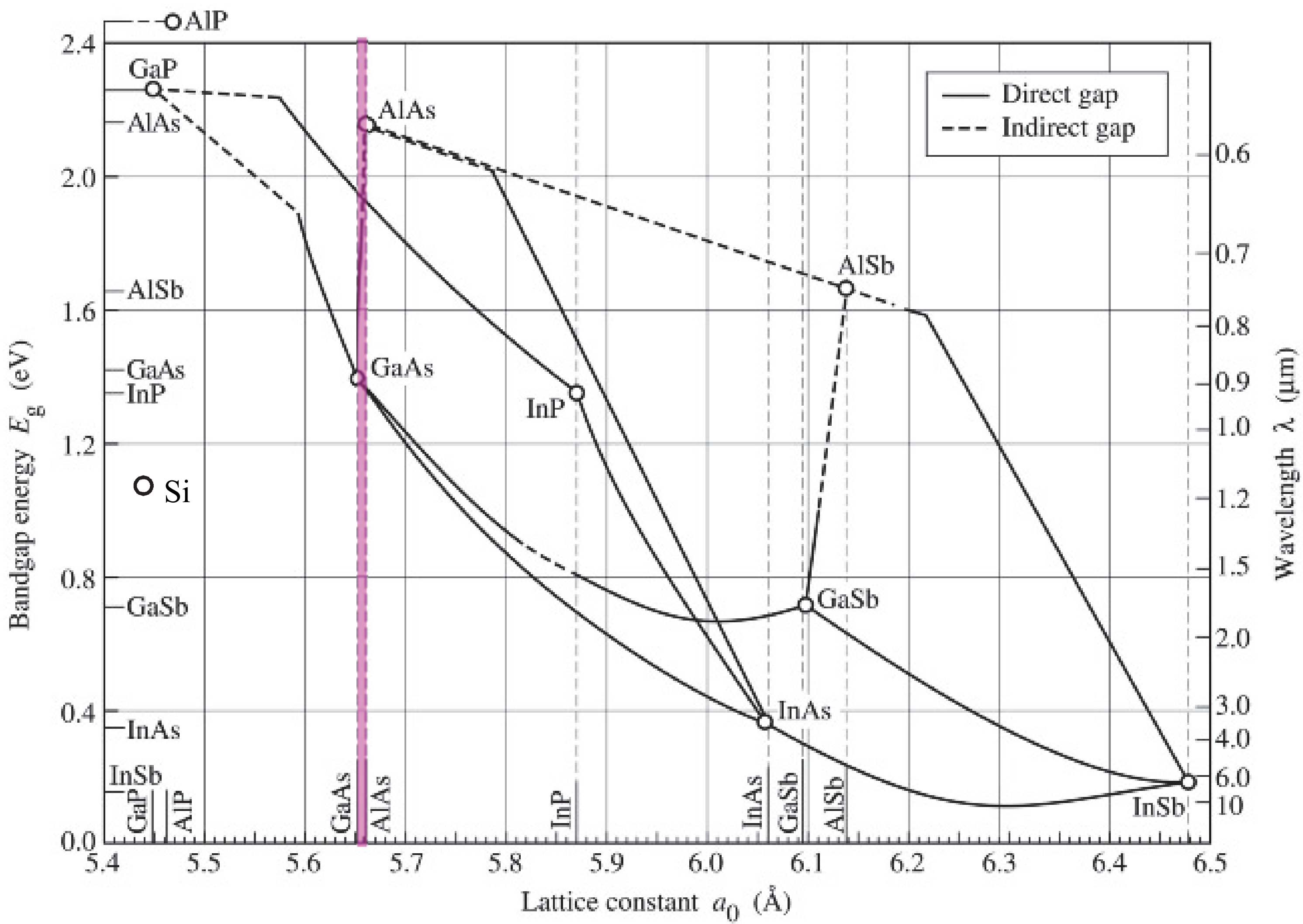
- First demonstrated in 1975
  - interference coatings by van der Ziel and Ilegems, Bell Labs
- Primary application: VCSELs
  - K. Iga's group (Tokyo) and Bell Labs (Jewell et al.)
  - VCSELs consist of high-reflectivity mirrors surrounding a semiconductor microcavity
  - cheap, high-volume diodes, 40 million units shipped in 2010
- Lattice matching constraints limit substrate selection
  - monocrystalline multilayers require a crystalline template



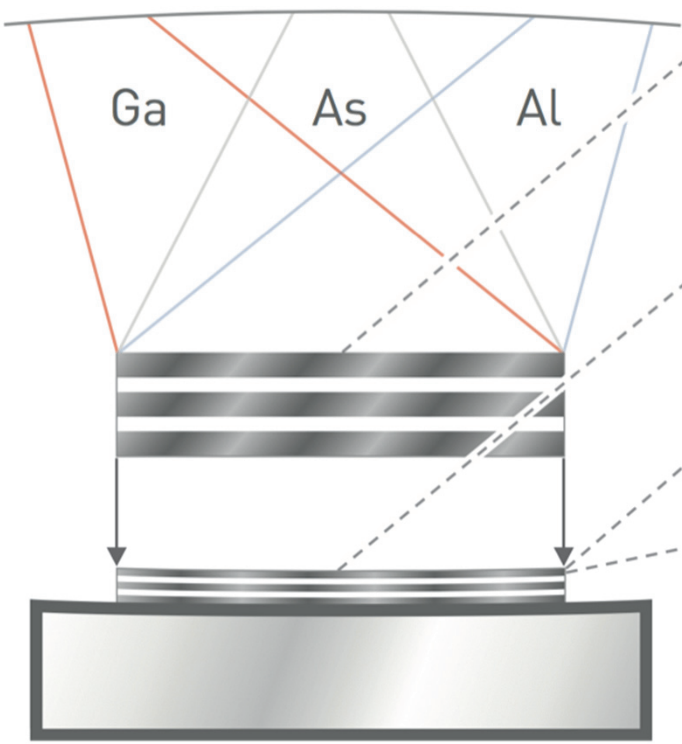
Large-aperture linear VCSEL array, Aerius Photonics, LLC (FLIR Electro-Optical Components)

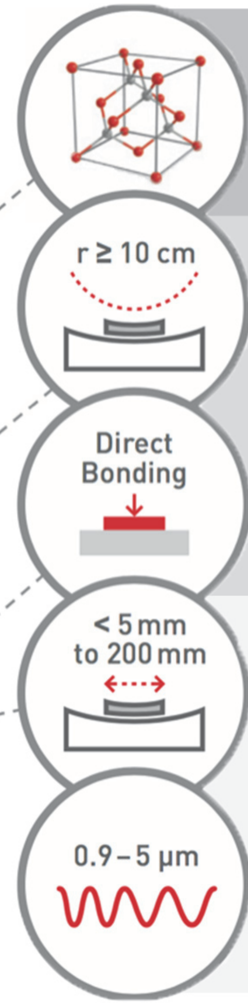
Lattice Matched Epitaxial Multilayers





AlP
GaP
AlAs
AlSb
GaAs
InP
Si
GaSb
InAs
InSb
Direct gap
Indirect gap
Bandgap energy E_g (eV)
Wavelength λ (μm)
Lattice constant a_0 (Å)
2.4
2.0
1.6
1.2
0.8
0.4
0.0
5.4
5.5
5.6
5.7
5.8
5.9
6.0
6.1
6.2
6.3
6.4
6.5
0.6
0.7
0.8
0.9
1.0
1.2
1.5
2.0
3.0
4.0
6.0
10





Monocrystalline GaAs/AlGaAs heterostructures grown on GaAs wafers by molecular beam epitaxy

Using semiconductor manufacturing techniques, the multilayer is extracted from the original GaAs wafer

Direct bonding is used to attach the single-crystal interference coating to the final optical substrate

Epitaxial multilayers on arbitrary substrates

Unique Capabilities and Advantages

- xtal stable™
- xtal mir™
- xtal therm™

- Various substrate materials and geometries possible
  - SiO_2, Si, SiC, Al_2O_3, YAG, YVO_4, diamond, etc.
  - ROC > 10 cm
  - 20 cm maximum diameter
- Ultralow Brownian noise
  - loss angle reduced 10-100 ×
- Low mid-IR optical losses
  - < 50 ppm loss to 5 µm
- High thermal conductivity
  - ~30 $Wm^{-1}K^{-1}$ GaAs/AlGaAs
- Respectable LIDT values
  - ~8 J/cm^2 for ns pulses
  - > 50 MW/cm^2 CW

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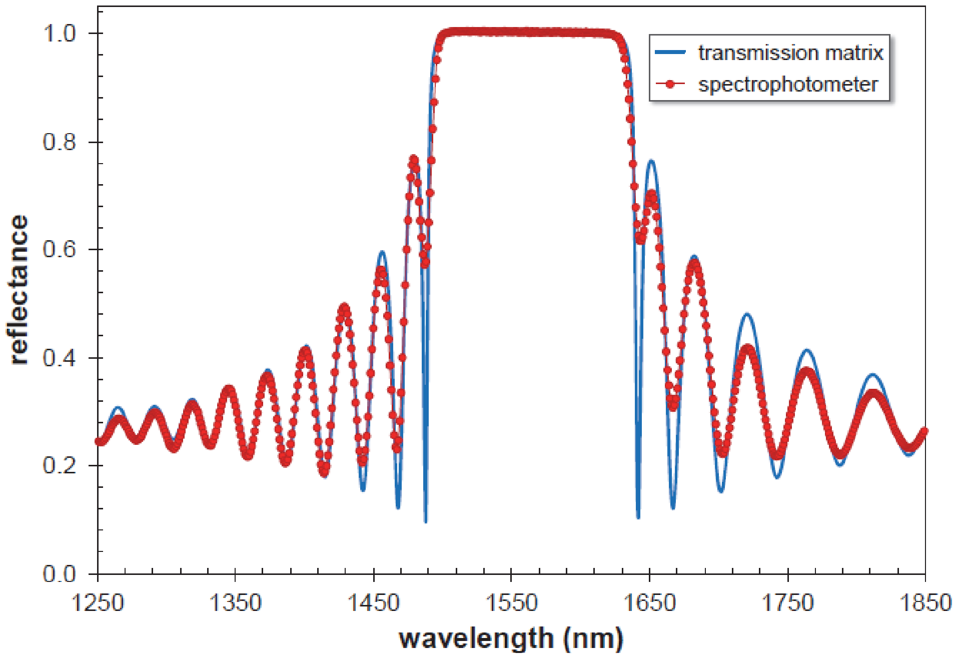
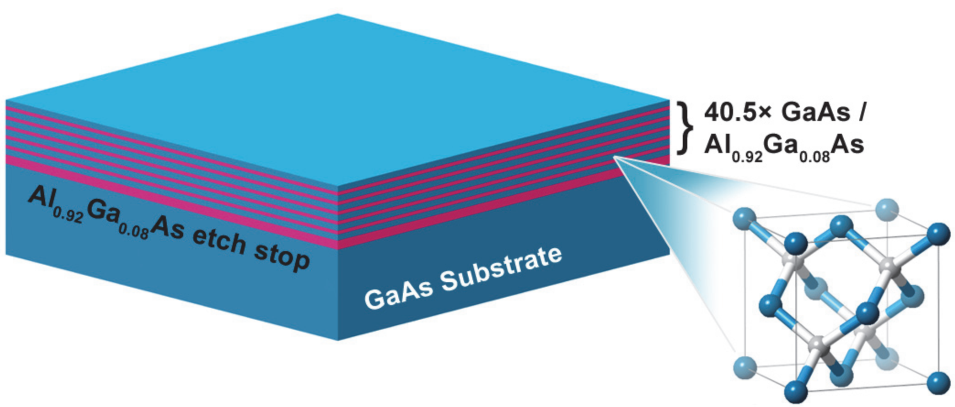
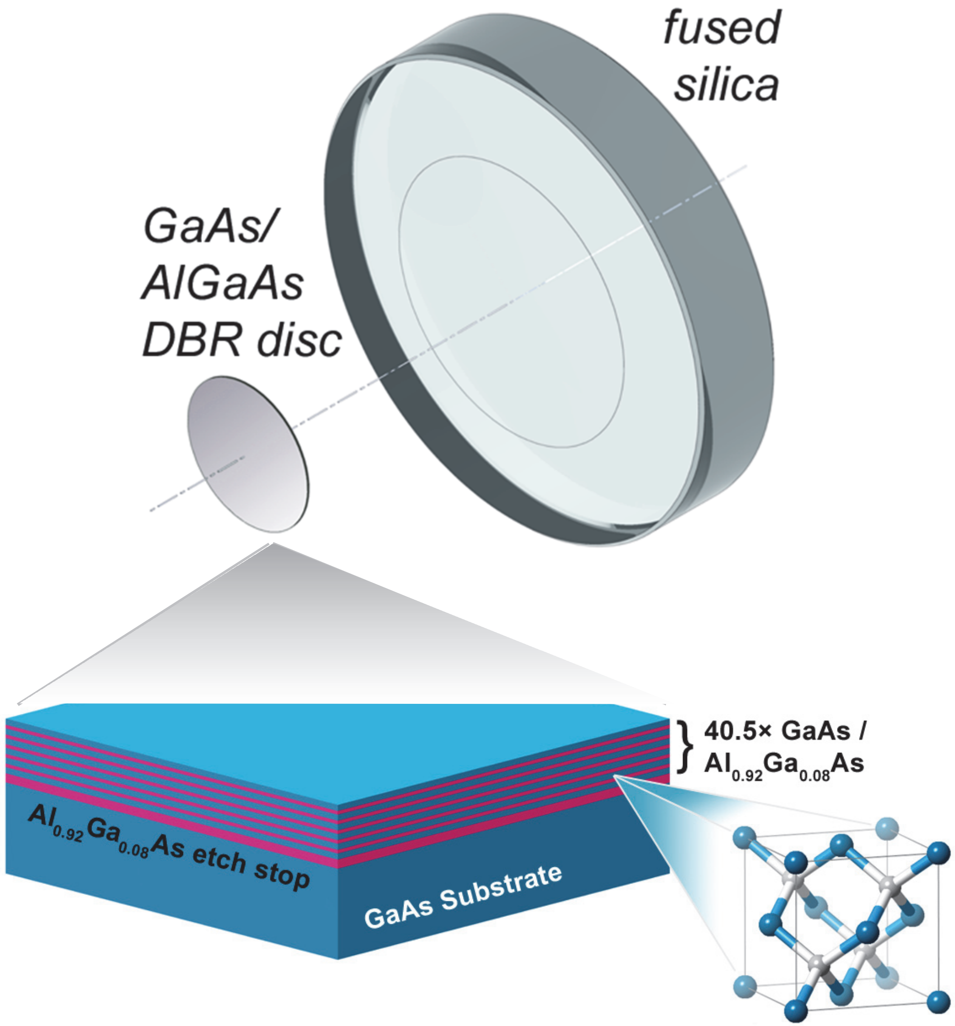




- AlGaAs multilayer with varying Al content for index contrast
  - high index layers consist of binary GaAs thin films
  - 8% Ga incorporated in low index AlGaAs layers to slow oxidation in ambient
- MBE required for minimizing optical losses (absorption)
  - free carrier limited
- Leverage direct bonding techniques from semicon. ind.
  - commonly employed process for manufacturing SOI (silicon-on-insulator) wafers up to 45 cm in diameter

G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, Nature Photonics (2013)



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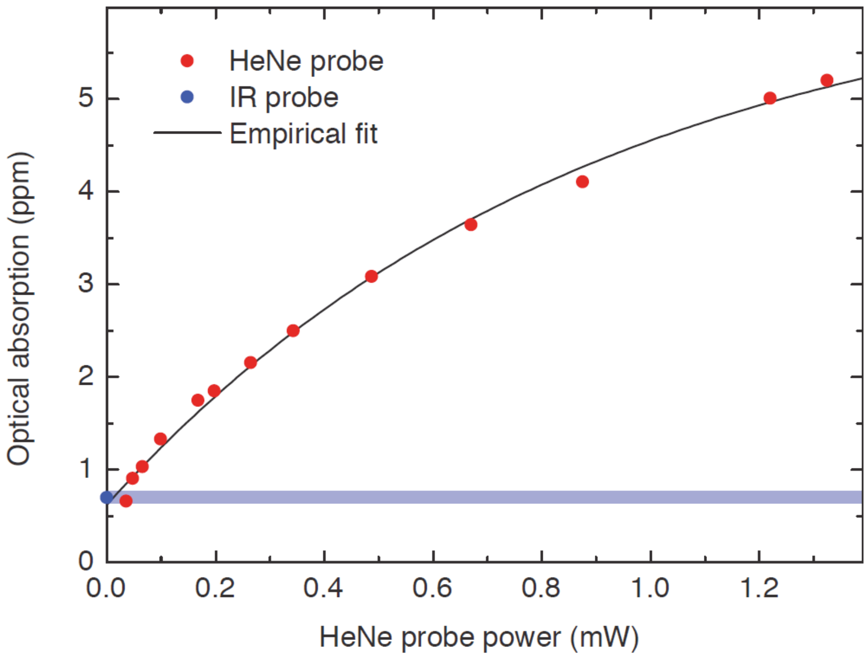
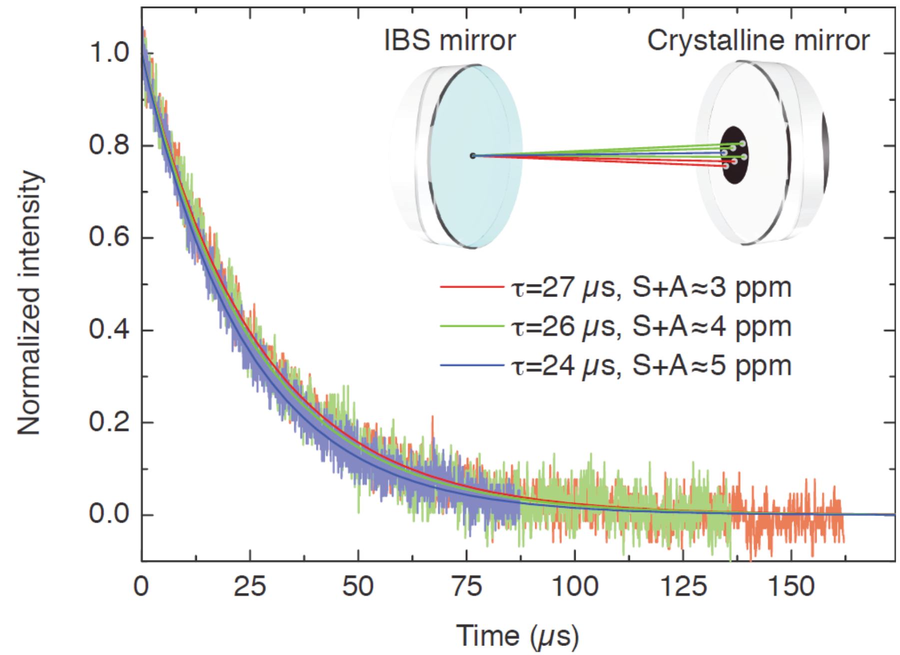
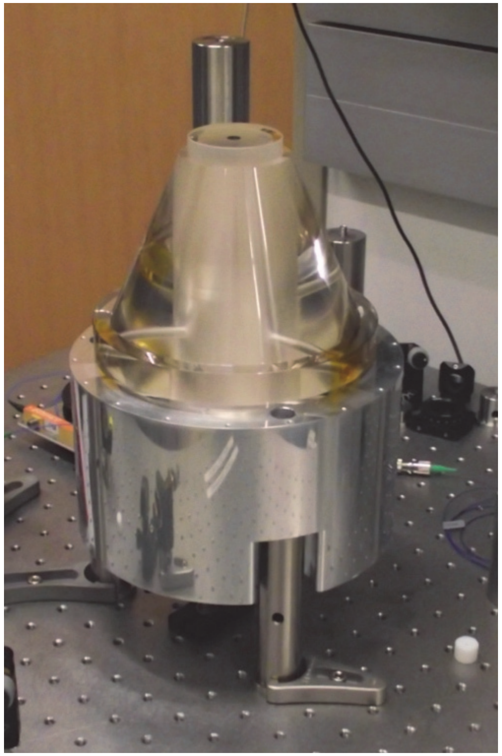


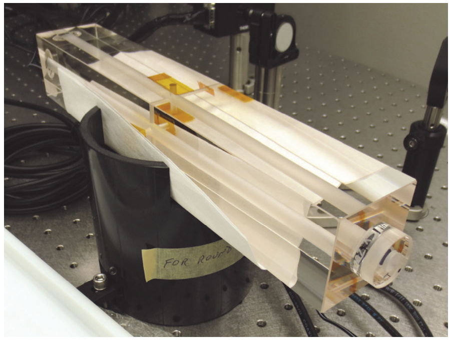


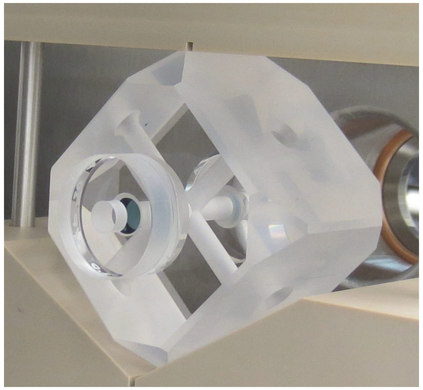
- Epitaxial growth process optimized for low background doping
  - direct measurements yield NIR absorption values <1 ppm
- Optimized coating process developed to reduce optical scatter loss
  - with improved epi and microfab we can reach loss levels of <3 ppm

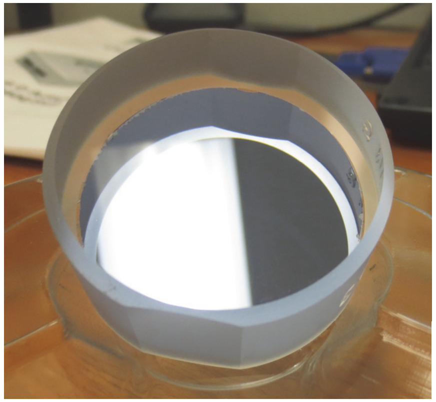
G. D. Cole, et al., Optica, vol. 3, no. 6, 647 (2016)

Custom Optical Reference Cavities and Low-Noise Optics





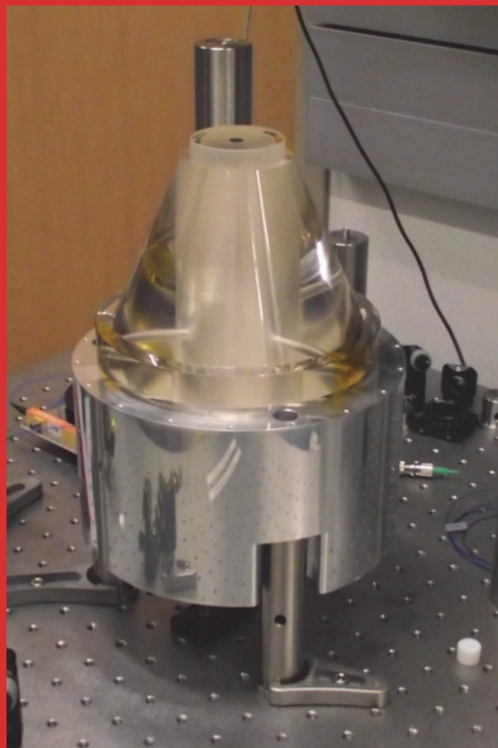


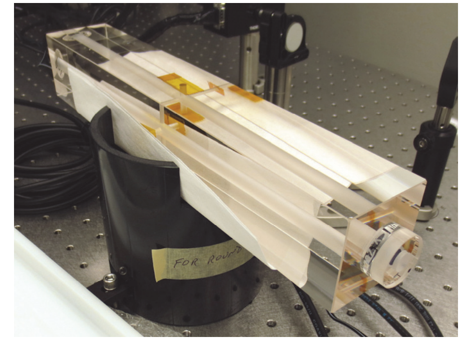


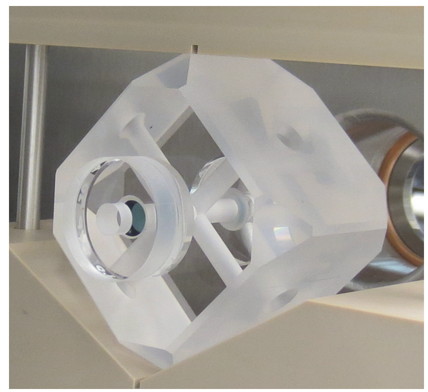
- Dozens of cavities & mirrors deployed on SiO_2, Si, and Al_2O_3 subs.
- Mirror diameters of 0.5″ to 2″ and spacer lengths up to 30 cm
- Wavelengths from ~1000 nm to 1600 nm, RT and cryo (4-124 K)
  - cavity finesse >600,000 (<3 ppm S+A) measured via ringdown

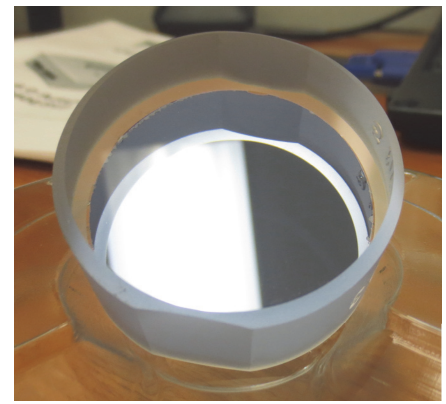
Custom Optical Reference Cavities and Low-Noise Optics

CMS









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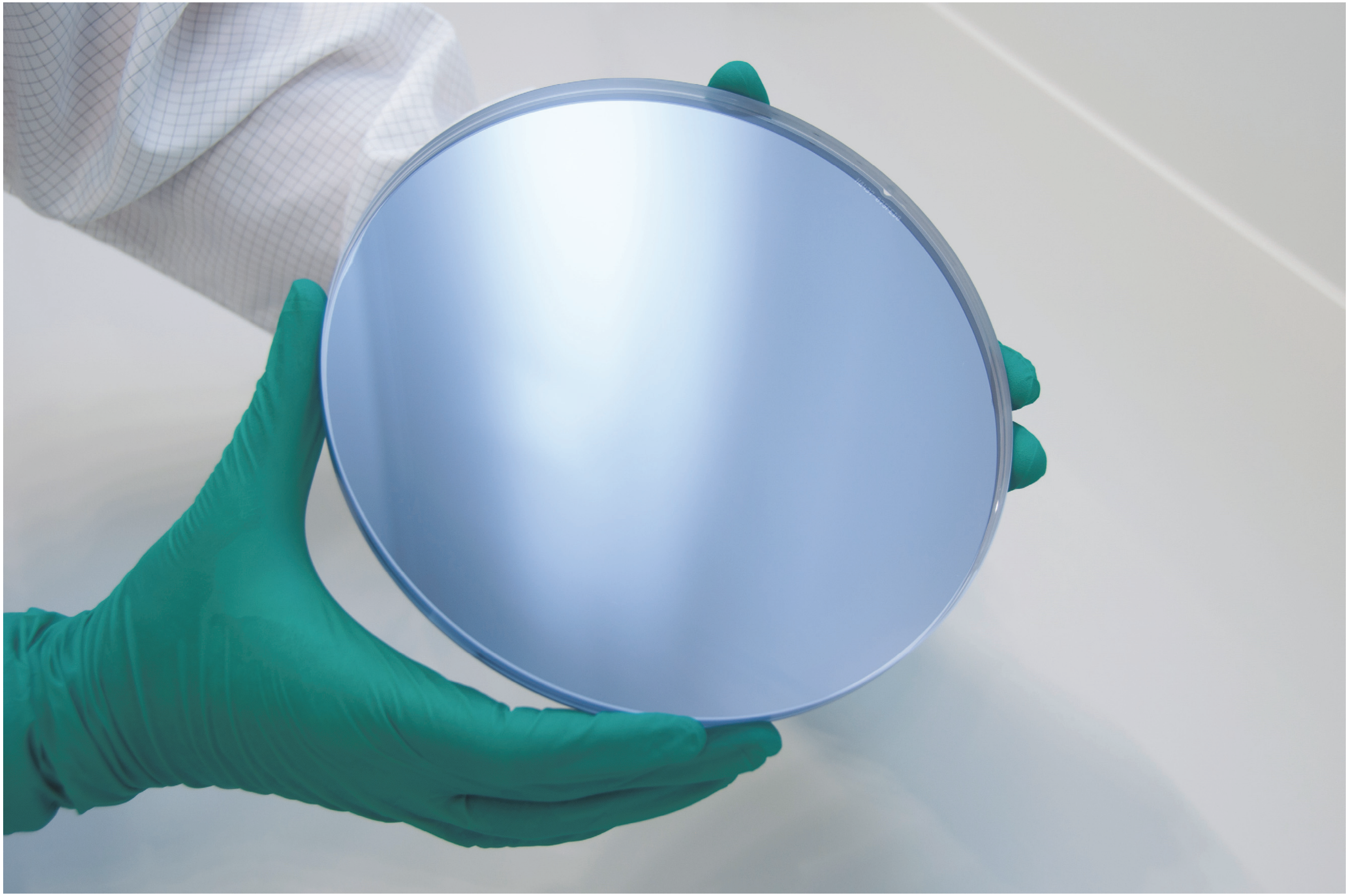
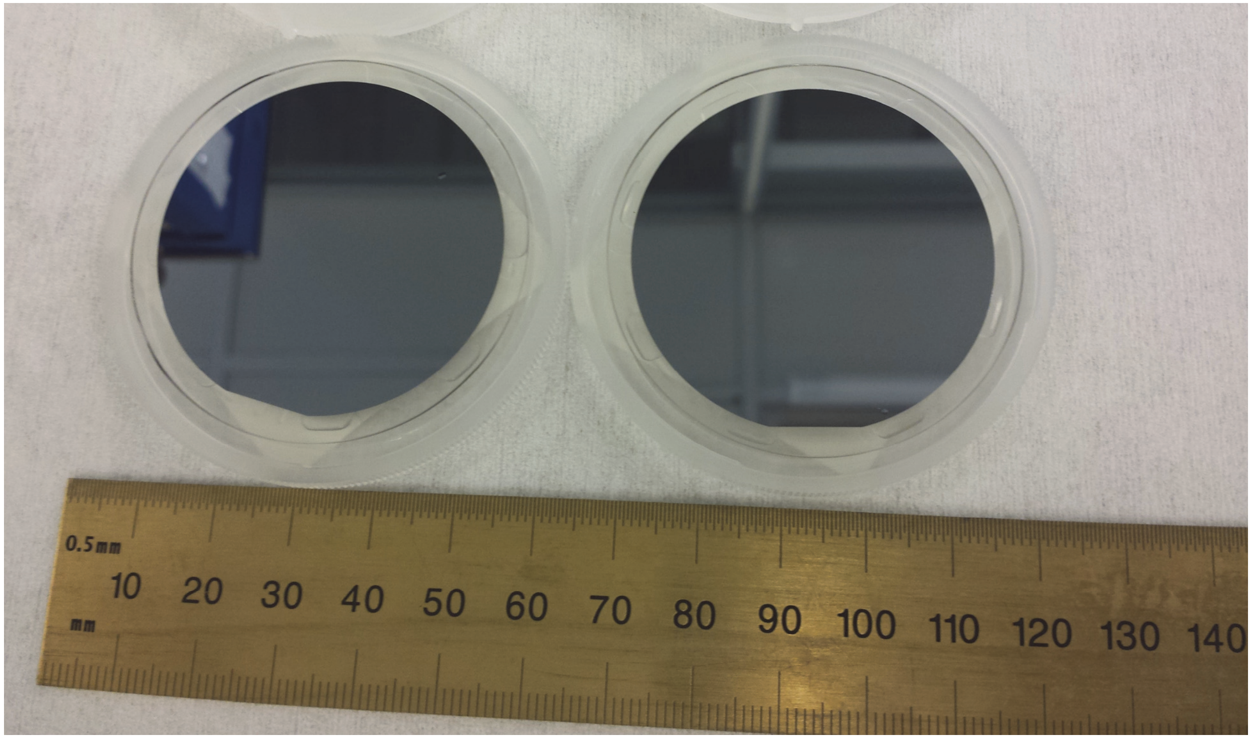
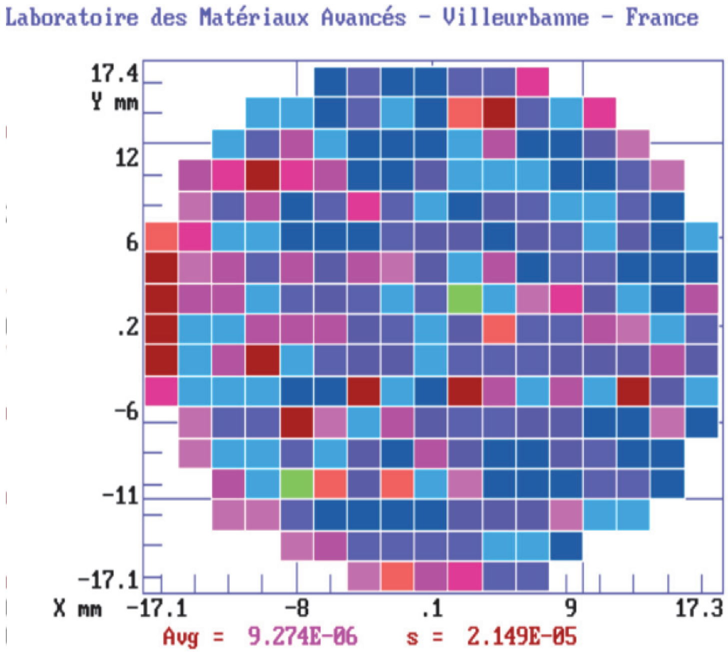
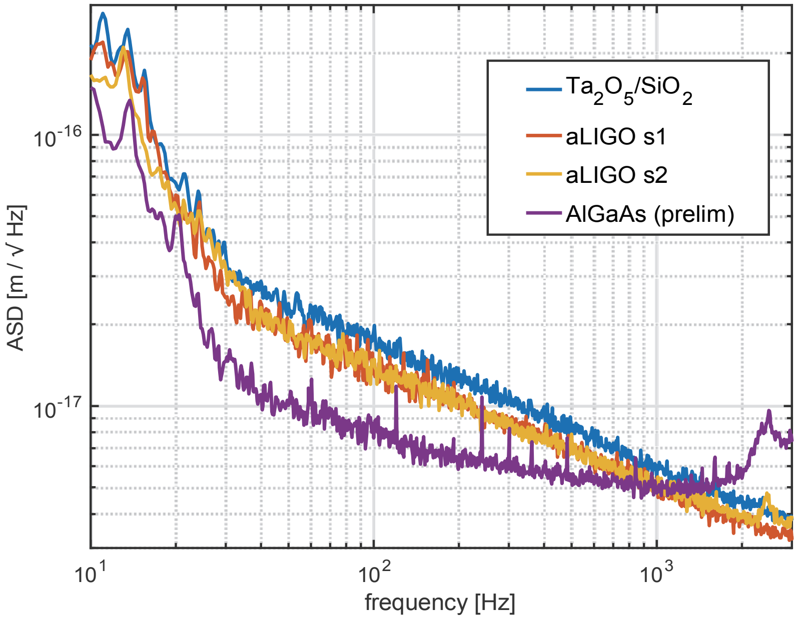
20-cm Diameter Bonding Demonstration





- High reflectivity 1064 nm crystalline coatings on fused silica wafers
  - 35.5 period mirror, target transmission of 10 ppm at normal incidence
- Samples used for process evaluation and in-depth characterization
  - properties of interest include optical scatter and thickness uniformity



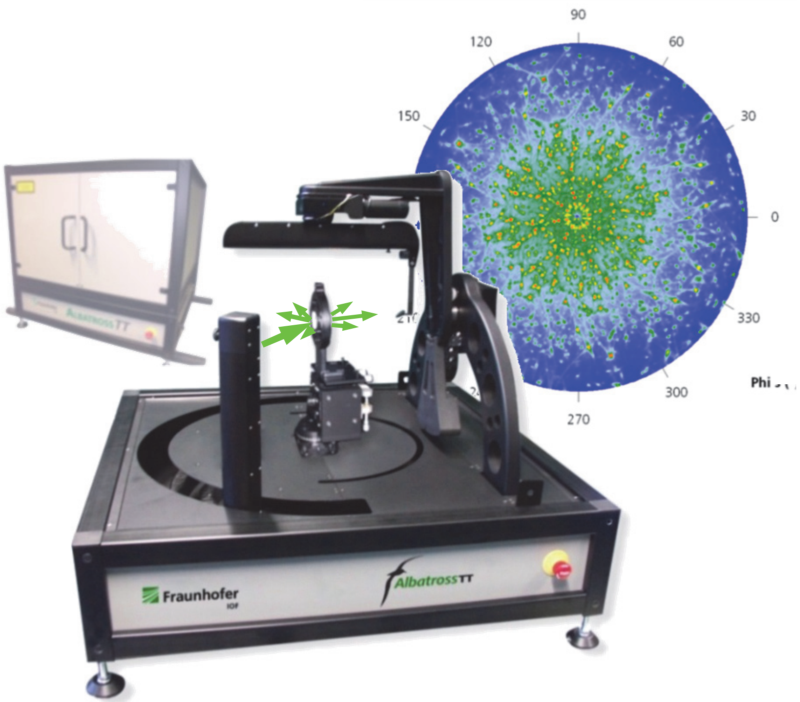


Measurement	Coating on silica substrate	Coating on sapphire substrate
Transmission @1064 nm	6 ppm	6 ppm
Absorption @1064 nm	≤ 0.8 ppm	below the noise floor
Scattering @1064 nm	9.5 ppm	6 ppm
Coating Roughness	7.7 Å RMS	1.1 Å RMS
Substrate Roughness	9.1 Å RMS	1.1 Å RMS

Marchio et al., Optics Express, vol. 26, no. 5, 6114 (2018)

- Table top system, w/ housing $0.8 \times 0.8 \times 0.8$ m³
- In-plane, out-of-plane, or full 3D-spherical measurements of ARS, BSDF, R, T
- 1064 nm probe wavelength
- Dynamic range: 13 orders of magnitude
- Noise equivalent ARS: $<10^{-8}$ sr^{-1}
- Roughness sensitivity < 0.1 nm

Fraunhofer IOF

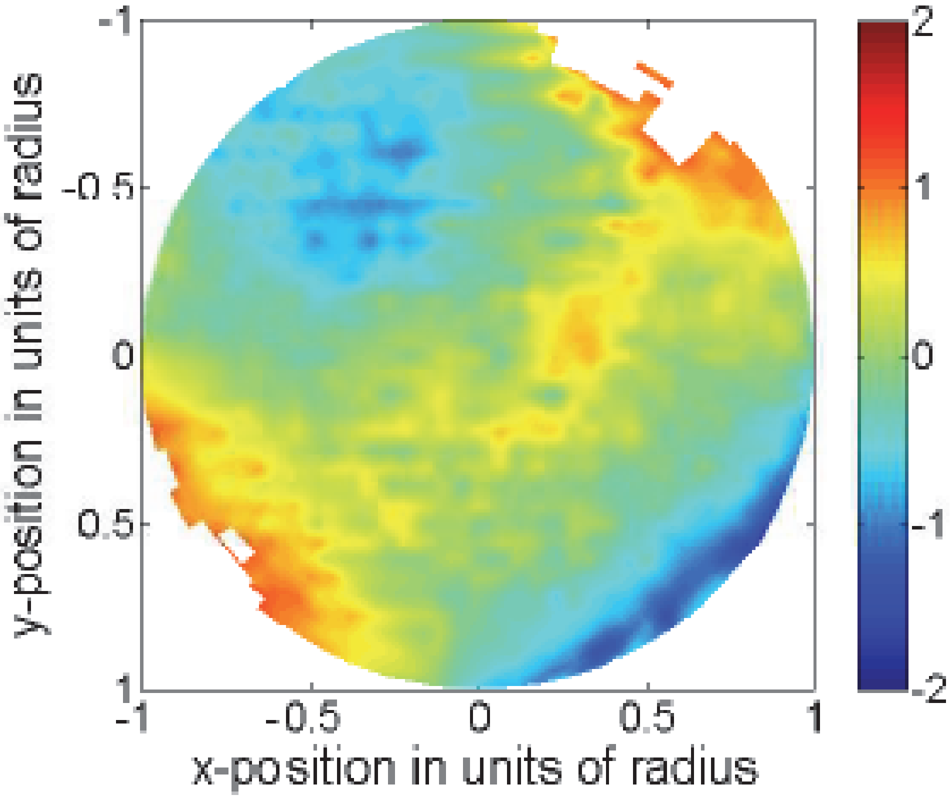


Compact table-top system
ALBATROSS TT

	T	TS_b	TS_f	R+A= 1-T-TS
Pos1	8.8×10^{-6}	12×10^{-6}	$<5.6 \times 10^{-8}$	99.9979%
Pos2	8.9×10^{-6}	4.2×10^{-6}	$<5.3 \times 10^{-8}$	99.9987%
Pos3	9.3×10^{-6}	3.8×10^{-6}	$<4.7 \times 10^{-8}$	99.9987%
Pos4	8.4×10^{-6}	6.6×10^{-6}	$<5.7 \times 10^{-8}$	99.9985%
Pos5	9.1×10^{-6}	4.1×10^{-6}	$<4.9 \times 10^{-8}$	99.9987%
AVG	8.9 ppm	6.1 ppm	<0.05 ppm	99.9985%

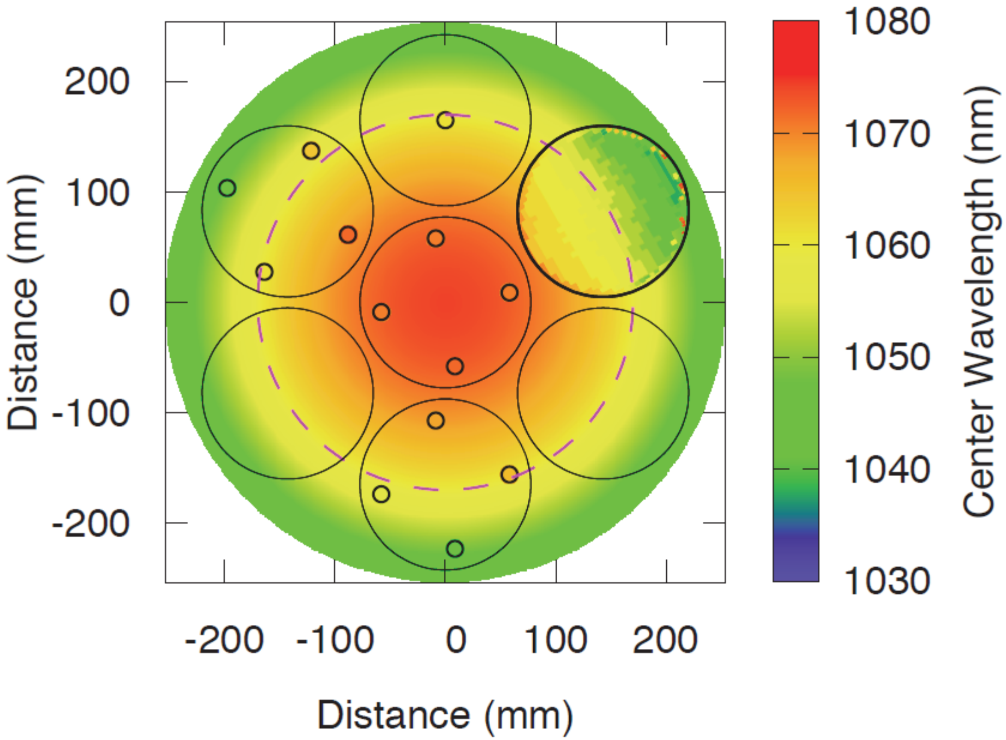
TS_f … forwards total scattering
TS_b … backwards total scattering
T … Transmission
R … Reflection
A … Absorption

Fraunhofer
IOF

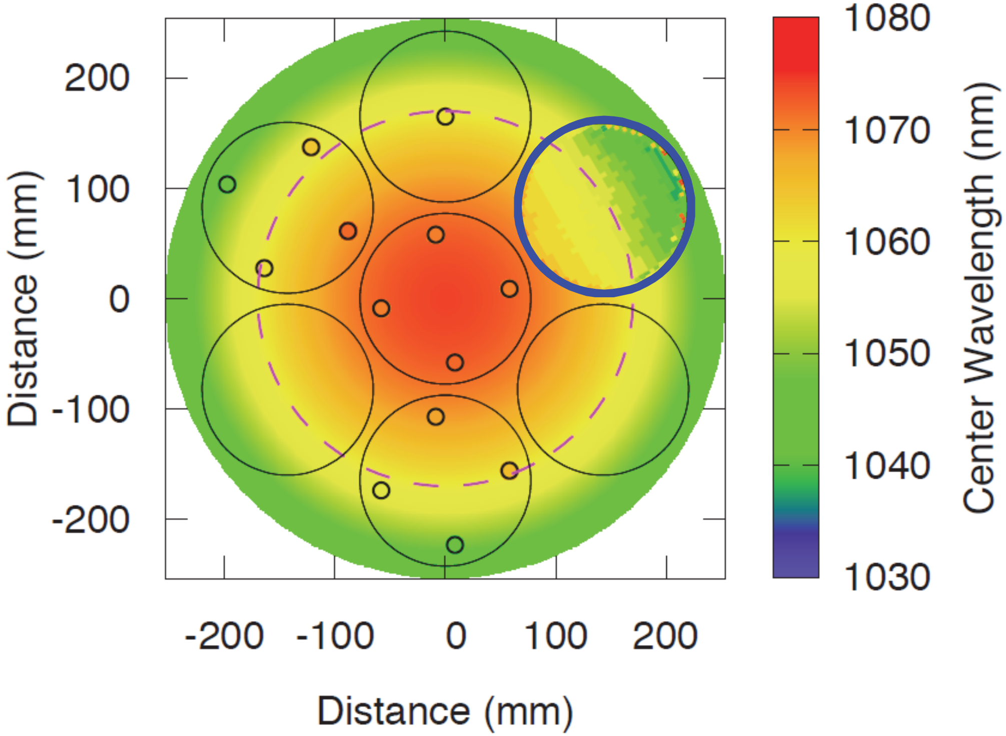


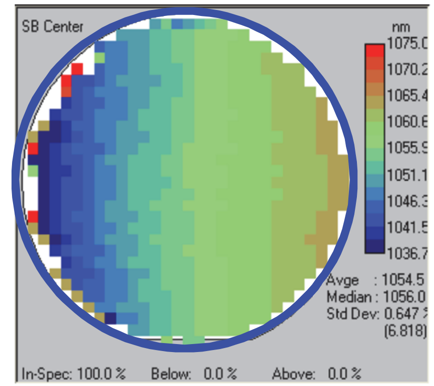
RMS = 0.41 +/- 0.05 nm

- Thickness mapping of sample successfully realized
  - rear surface reflections, defects, and outer 4 mm removed
  - corrected for Zernike polynomials of first, second, and fourth order
- RMS of 0.41 nm results in a negligible transmission variation of <<1 ppm
  - astigmatism of 1 nm_{pp} is major contribution
  - uncertainty of ±0.05 nm due to fluctuating laser power



- 7 x 6" wafer growth platen geometry
  - orbital wafer mapped with spectrophotometer
  - HRXRD measurements on 13 witness pieces





Full Wafer Reflectivity Spectrum

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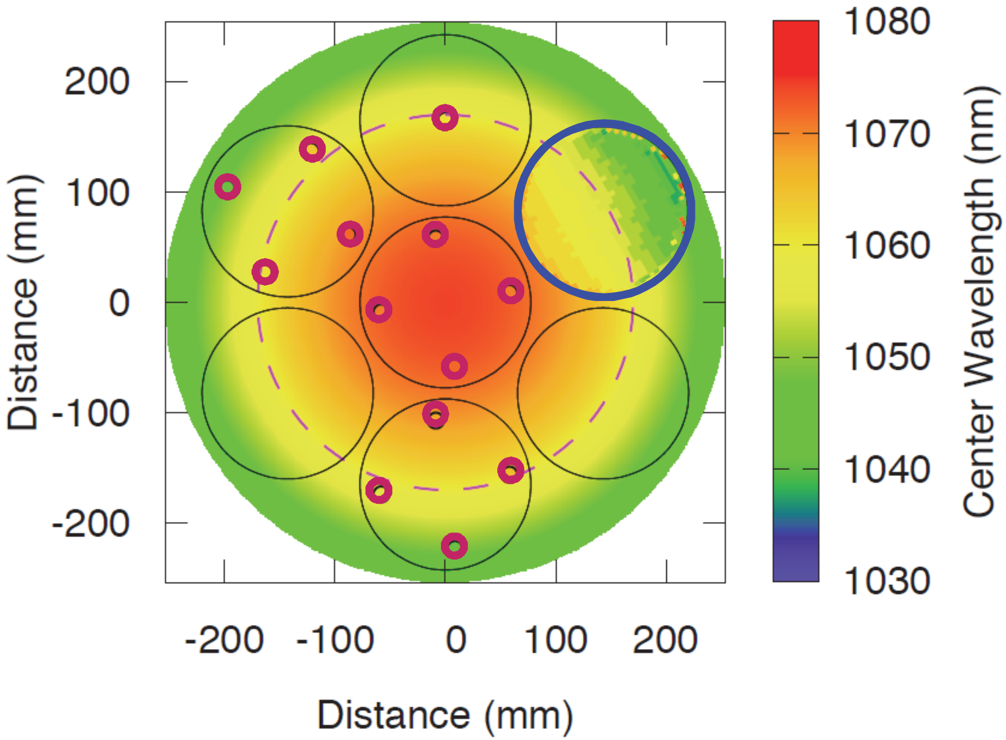
  - HRXRD measurements on 13 witness pieces

Mapping the Full Growth Platen



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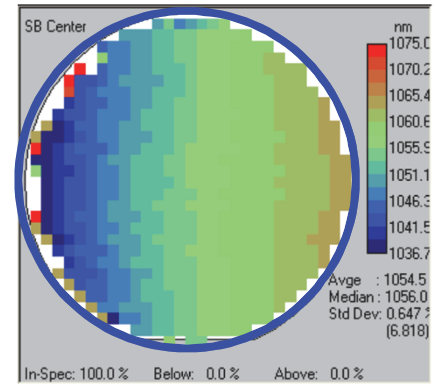

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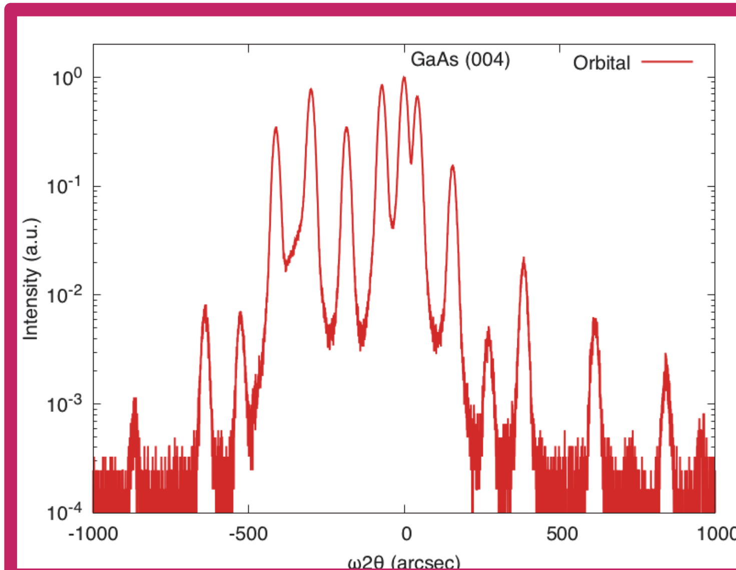
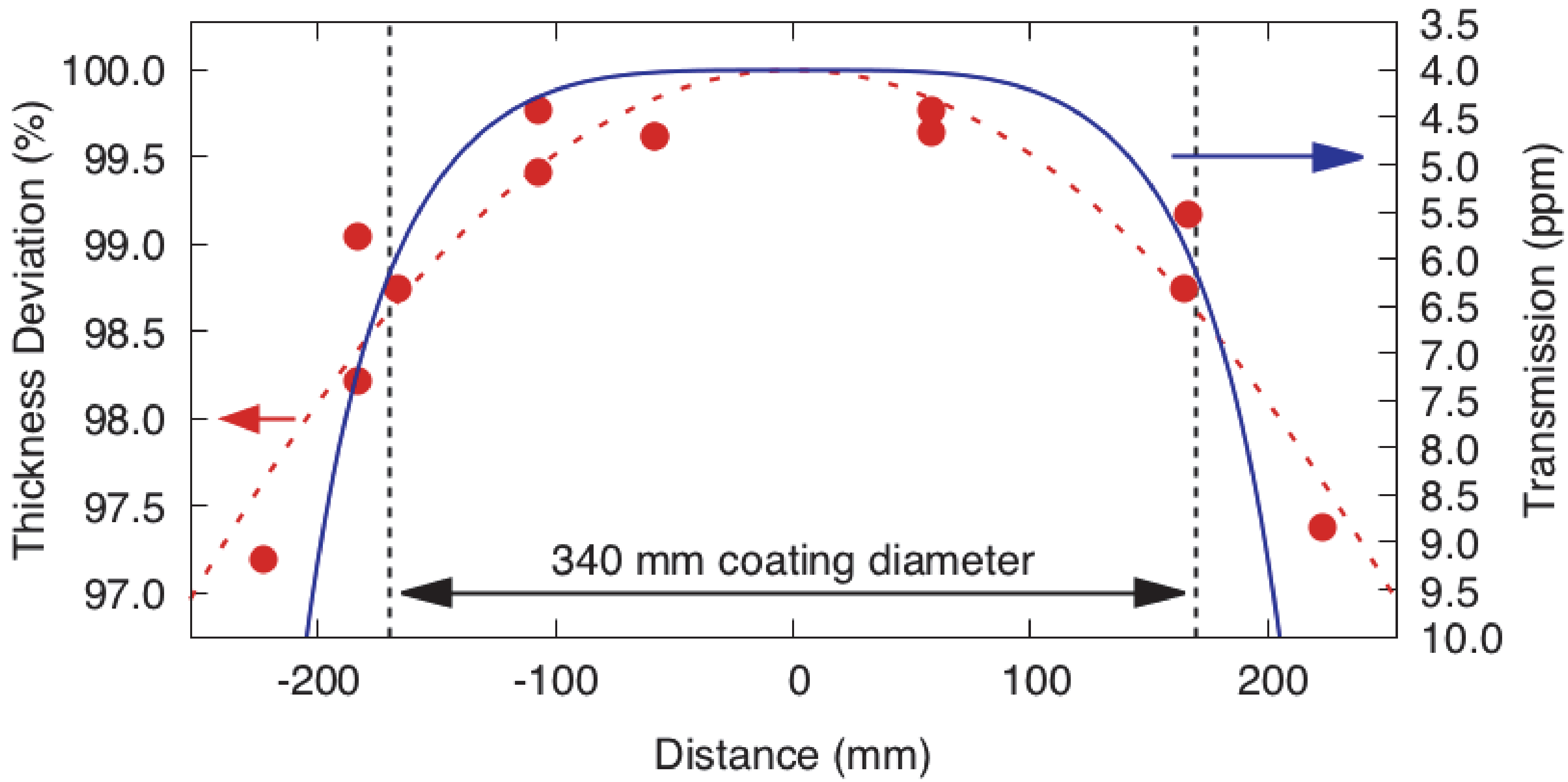


HRXRD Thickness Measurement



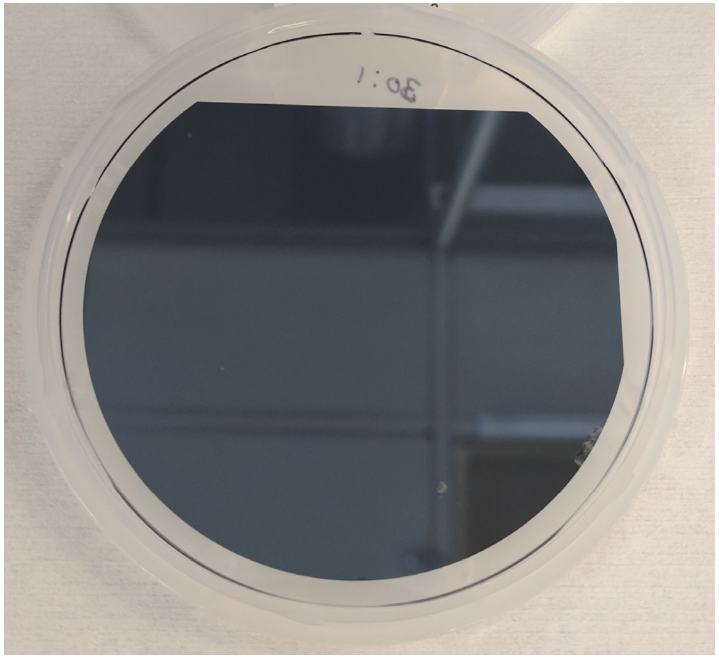
- Measured Uniformity (Gen2k): < 3% across platen (50 cm diameter)
- Transmission of aLIGO equivalent: ~2 ppm variation (34-cm diam.)
  - end test mass (ETM) transmission specification: 5 ±1 ppm
- aLIGO uniformity achieved w/ commercially available MBE tool

Elastic Loss of ~70-mm Diameter Multilayer

JOSA B Special Issue on Fluctuations in Photonic Systems

Mechanical Ringdown Studies of Large-Area Substrate-Transferred GaAs/AlGaAs Crystalline Coatings

STEVEN D. PENN[1,*], MAYA M. KINLEY-HANLON[2], IAN A. O. MACMILLAN[2,3], PAULA HEU[4], DAVID FOLLMAN[4], CHRISTOPH DEUTSCH[5], GARRETT D. COLE[4,5], AND GREGORY M. HARRY[2]

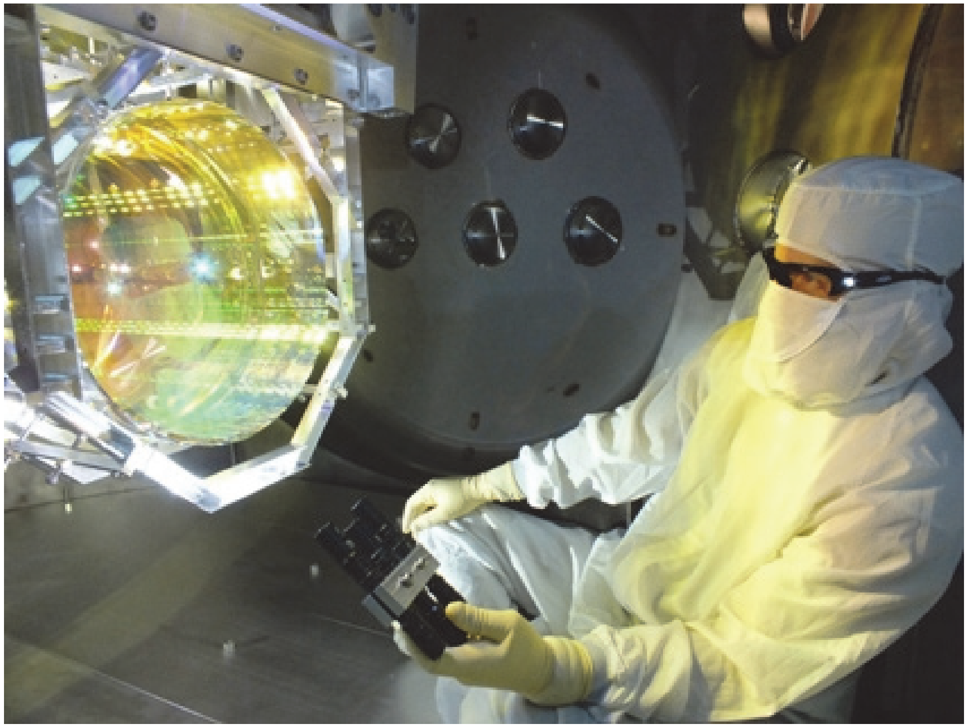


The elastic loss, when decomposed into bulk and shear contributions, was shown to arise primarily from the bulk loss

$$\varphi_{bulk} = (5.33 \pm 0.03) \times 10^{-4}$$

$$\Phi_{shear} < 5.2 \times 10^{-7}$$

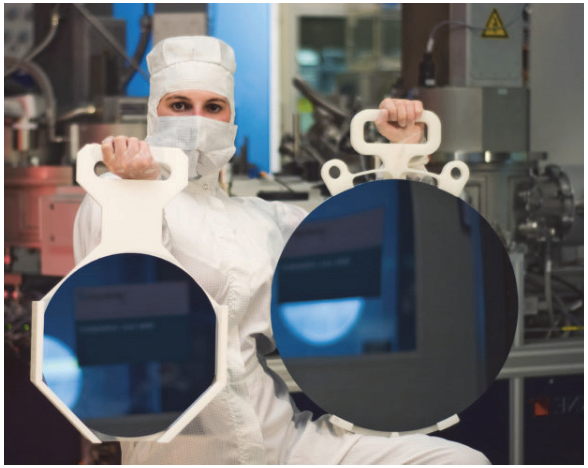
S. Penn, et al., JOSA B, vol. 36, no. 4, C15-C21 (2019)



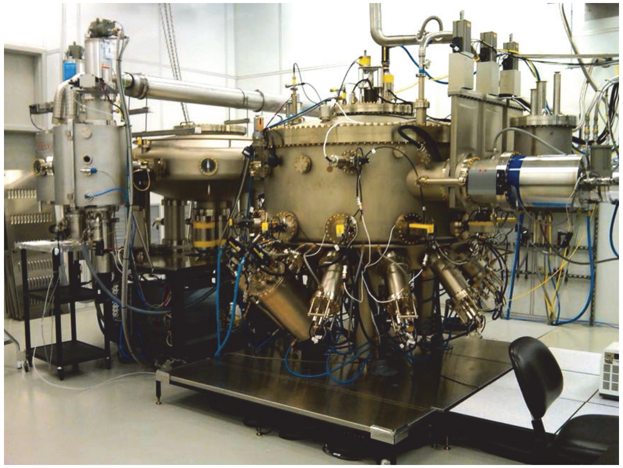
Can we maintain the excellent performance of crystalline coatings at GWD-relevant size scales?

- Optomechanical performance of crystalline coatings has now been explored up to 3″
  - 20-cm diameter coatings possible now in principle
- aLIGO test masses are 35 cm in diameter with demanding coating specifications
  - < 1 ppm absorption
  - scatter at the < 10 ppm level
  - thickness variation < 1% (trans. variation < 1 ppm)

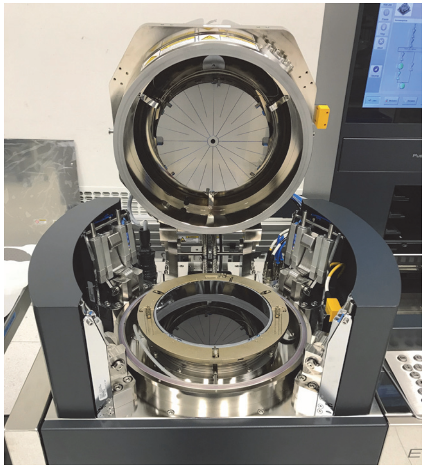
GaAs wafers: 20 → 40 cm



Epitaxy: 30 → 40 cm



Bonding: 45 cm



- Crystalline coatings limited to ⌀20 cm, three areas to scale
  - commercial GaAs wafers currently available up to 20-cm diam.
  - epitaxy qualified for wafer sizes of 30 cm (~50-cm chamber diam.)
  - semiconductor direct bonding demonstrated to diam. of 45 cm

Significant progress has been made in last 5-6 years, but a number of important questions still remain:

- What are the individual loss angles of GaAs and AlGaAs?
  - thus far this has only been measured for multilayers
  - components to be determined and temp. dep. to be explored
- Ultimately, what limits the loss angle in epi materials?
  - measurements at Jena show Qs in the 10^7 range for bulk GaAs
  - surface issues seem to be a significant factor in this material
- A number of efforts underway for scaling mirror sizes
  - Q-GWD effort in Europe (collab. w/ Hannover and DTU)
  - Caltech 10-cm diam. optics (using TO-optimized coating design) currently in progress

Thank You!