Crystalline AlGaAs coatings for future gravitational wave detectors

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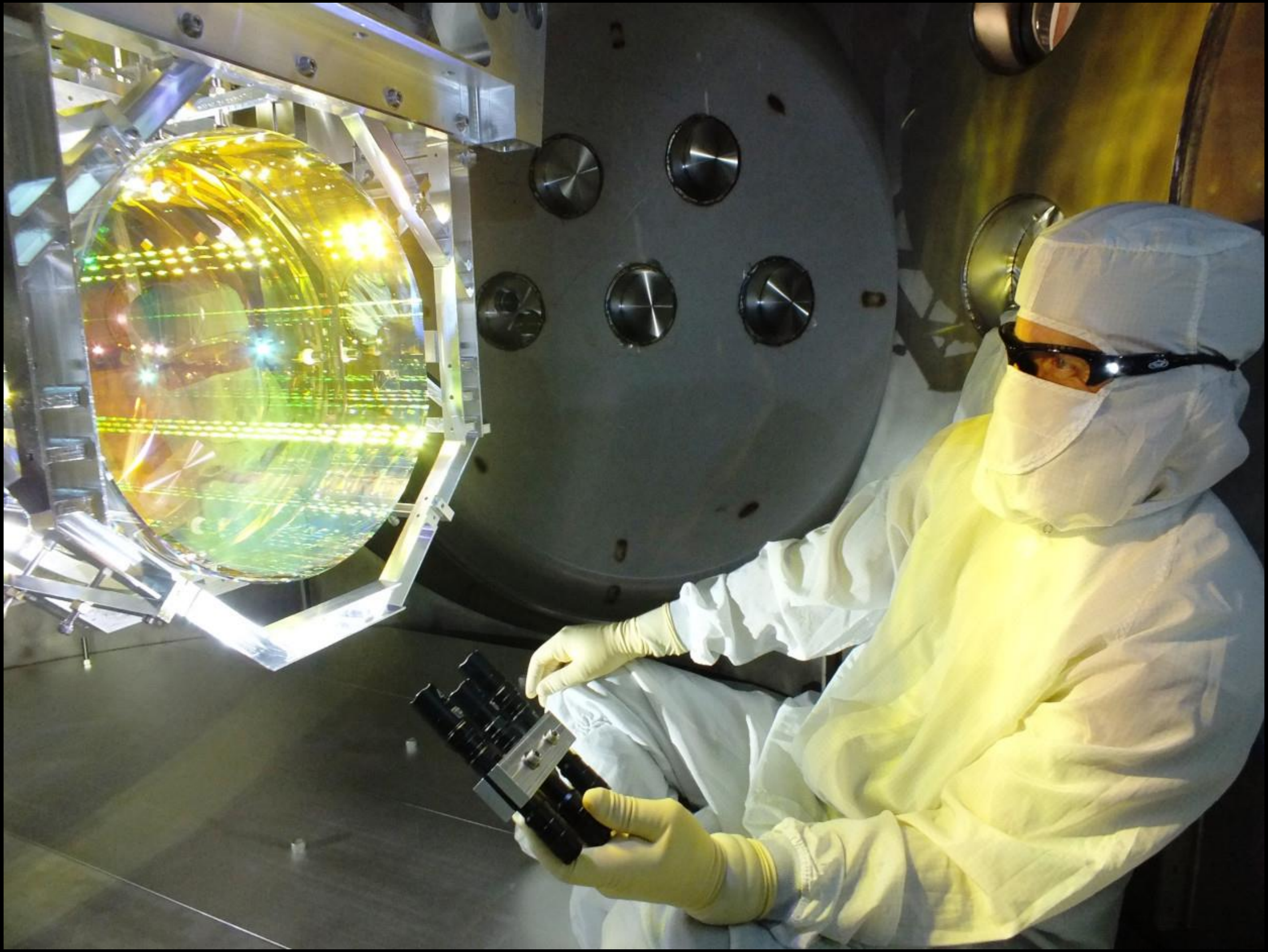
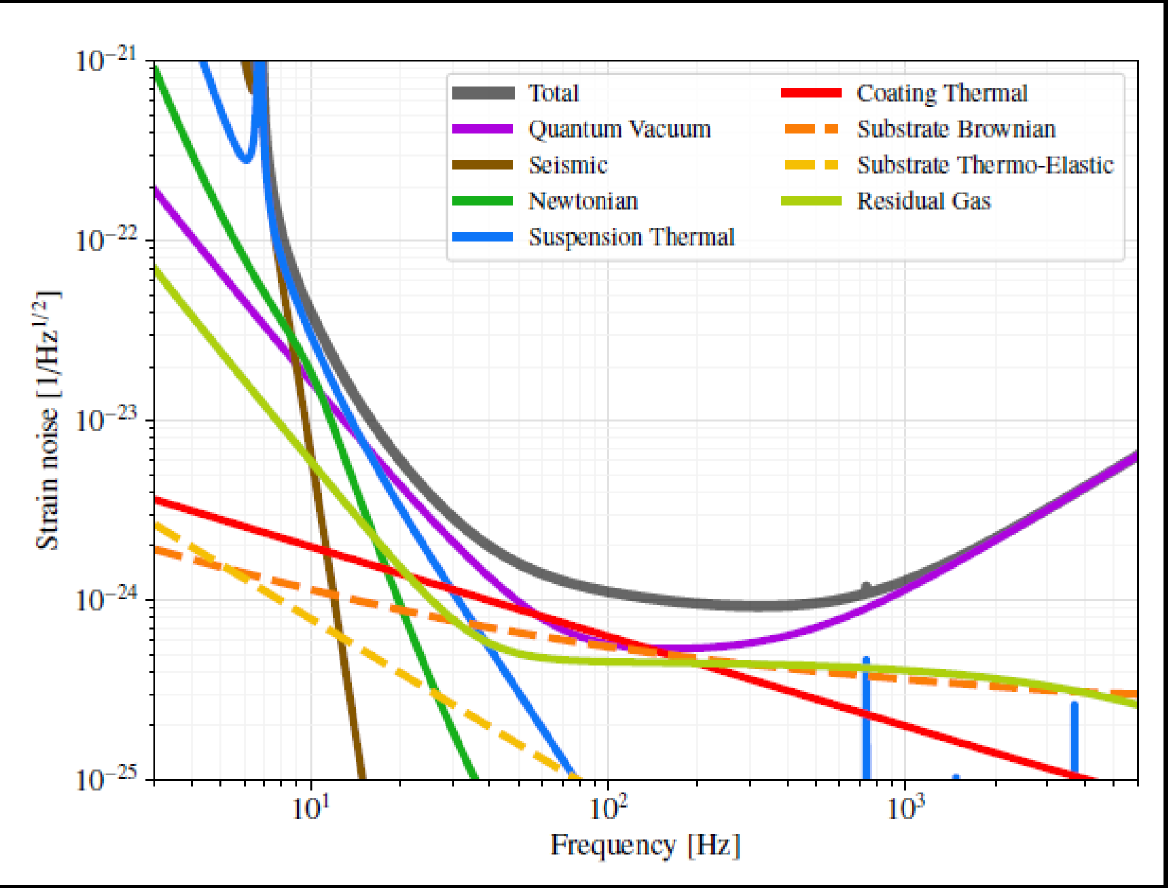


- Thermal noise in amorphous coatings limits the sensitivity of current detectors.

A# design sensitivity



- ✓ 100 kg test masses
- ✓ Better seismic isolation
- ✓ 1.5 MW arm power
- ✓ Reduced coating thermal noise (AlGaAs coating thermal noise is assumed)

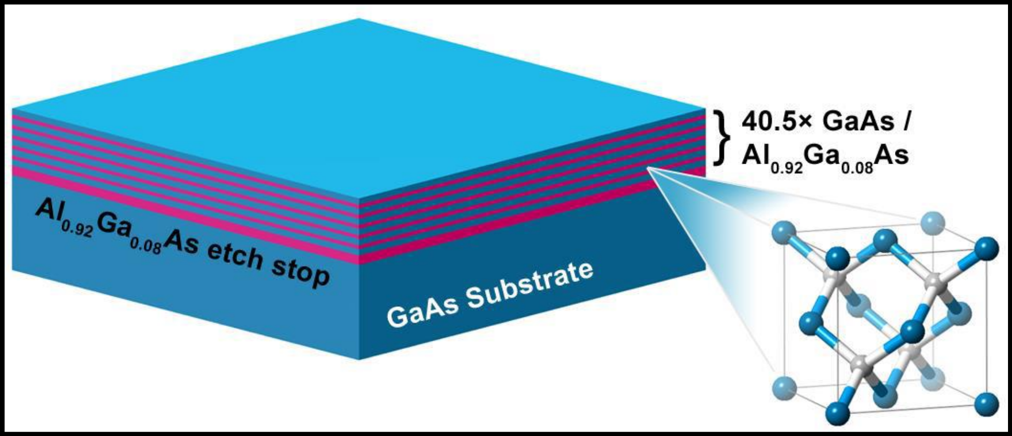
LIGO-T2200287

Important stepping stone toward 3G detectors

Crystalline AlGaAs coatings

- The crystal is grown via Molecular Beam Epitaxy (MBE) on a single-crystal GaAs wafer.
- Alternating the Al alloy composition forms a Bragg reflector from layers of $Al_{0.92}Ga_{0.08}As$ (n=2.89) and GaAs (n=3.30).
- Limited to $\lambda > 870\mathrm{nm}$

G. Cole 2013



https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=14069

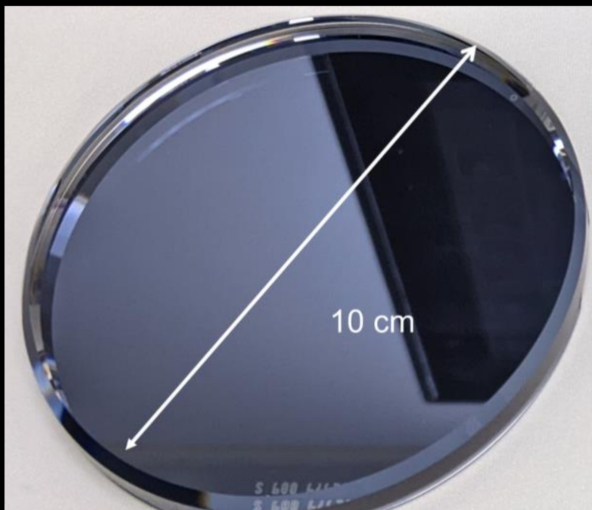
Demonstrated

- ✓ Low optical losses
  - ➢ typically <5ppm scattering (A. Gleckl LIGO-G2000376)
  - ➢ typically <1ppm absorption (M. Marchio 2019)
- ✓ Mechanical loss
  - ➢ $\leq 2.5 \times 10^{-5}$ (S. Penn 2019)
- ✓ Electro-optic noise
  - ➢ well below the design sensitivity (S. Tanioka 2023)
- ✓ High laser damage threshold
  - ➢ >64 MW/cm^2 (P. Koch 2019)

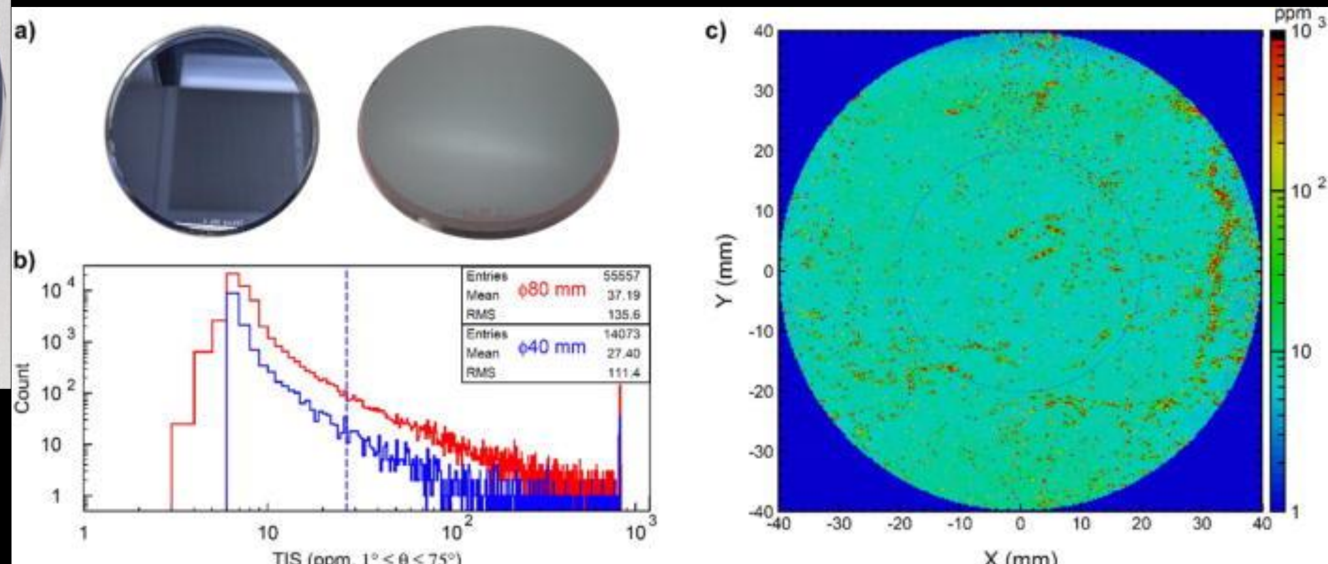
On going

- ❑ Surface characterization @Caltech
- ❑ Direct measurement of coating thermal noise @MIT
- ❑ Arm length stabilization @Syracuse
- ❑ Birefringence @Embry-Riddle Aeronautical University
- ❑ Scaling up

Surface characterization



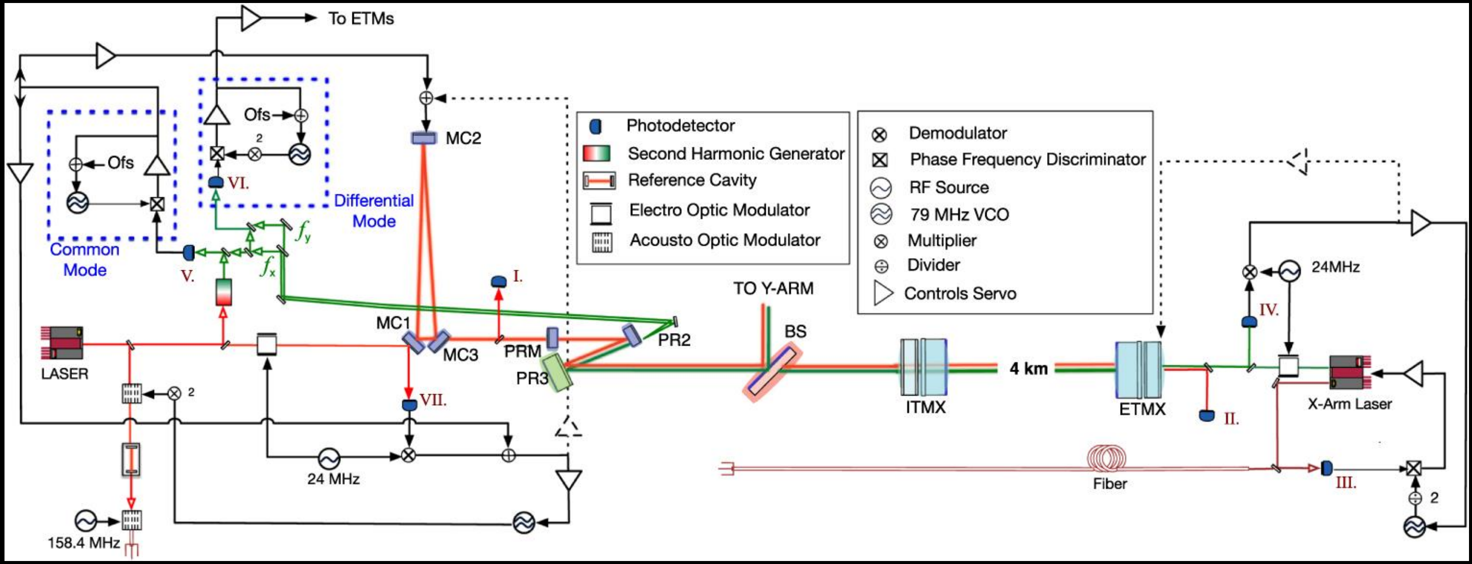
G. Cole 2023



- Studying surface quality and uniformity
  - defects, absorption, scattering, etc.
- 20 cm diameter plan is in progress.

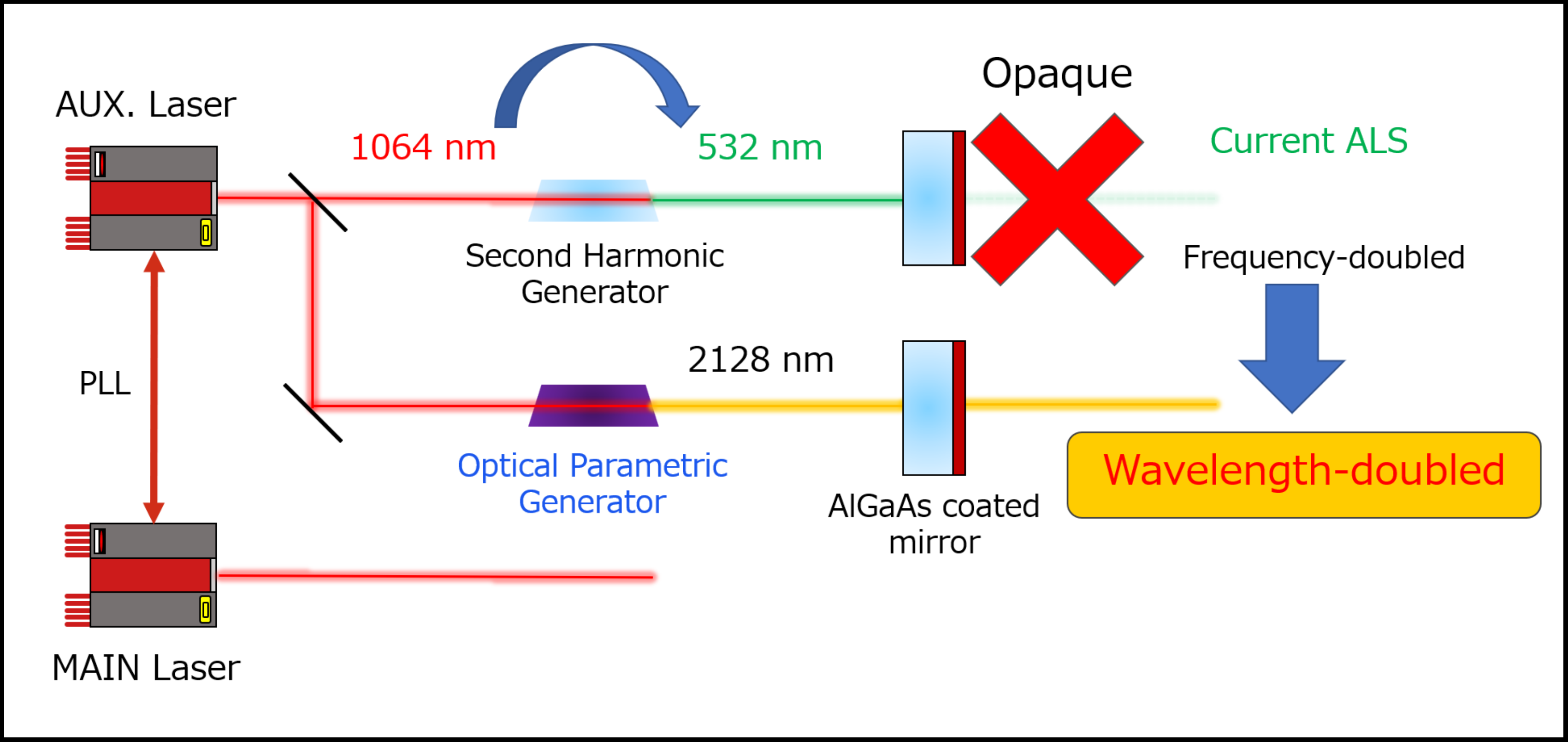
Arm length stabilization (ALS)

Layout of the ALS system.
Image adapted from A. Staley et al. 2014



- Current green lock is no longer an option due to the bandgap of GaAs.
- Need to develop an alternative locking scheme.

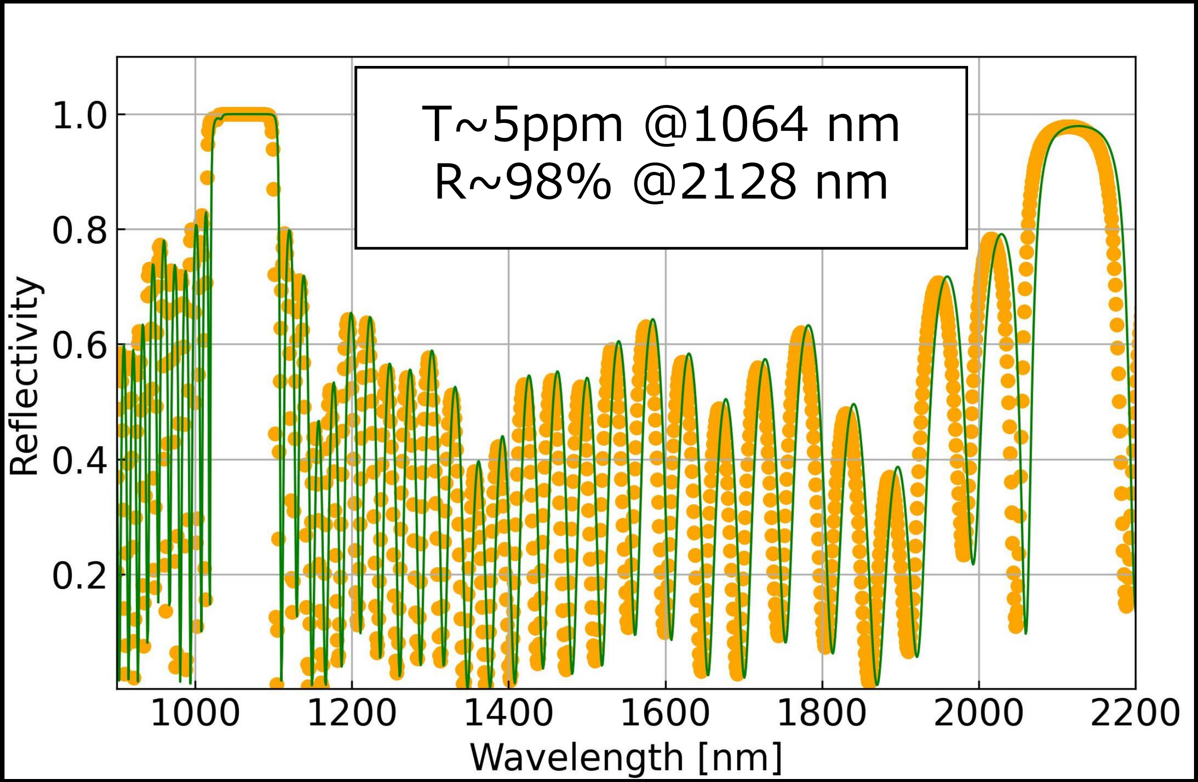
Wavelength-doubled ALS



- The wavelength of main laser remains 1064 nm.
- Construction of demonstrator has been started.

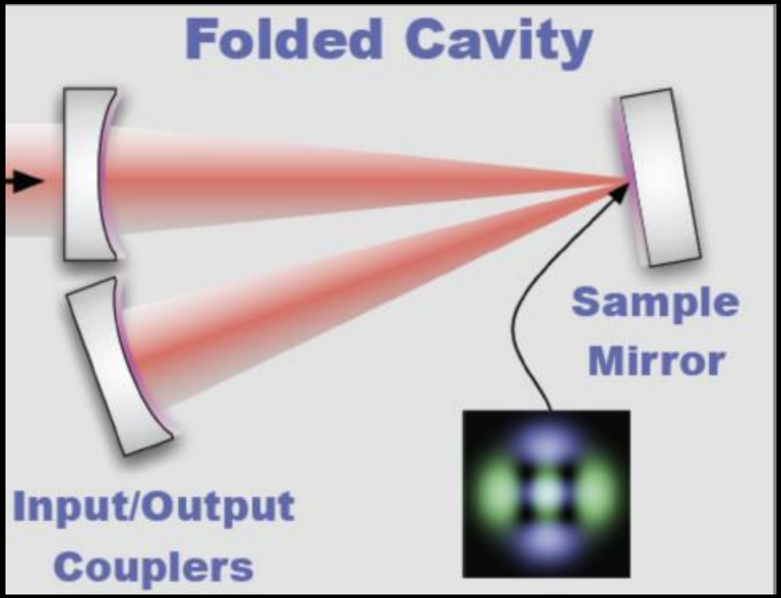
Dichroic AlGaAs coatings

- AlGaAs coatings should be dichroic.
  - High-reflectivity both at 1064 nm and 2128 nm
- ETM-like dichroic AlGaAs mirrors have been manufactured.

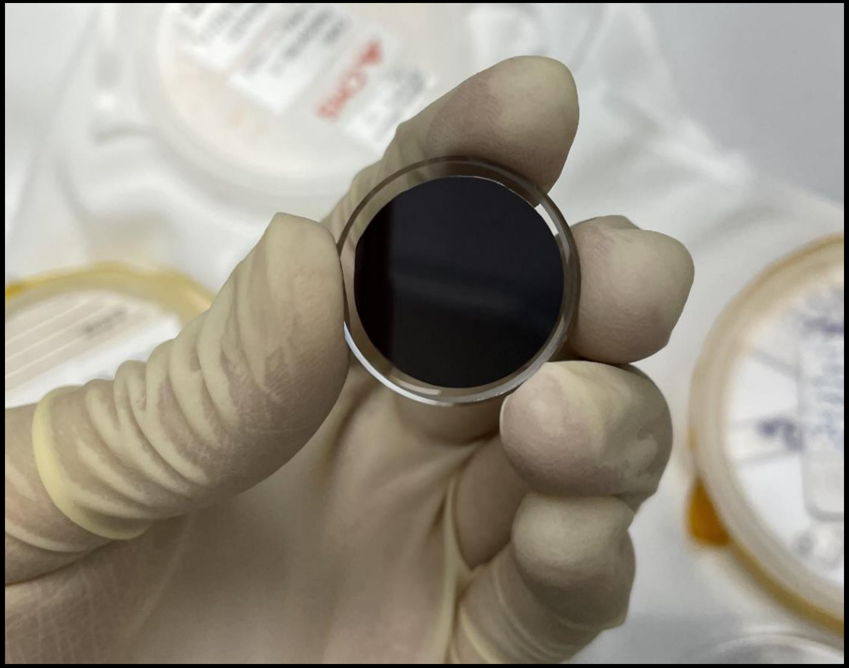


Dichroic AlGaAs coatings

- Coating thermal noise of dichroic AlGaAs mirror will be measured @MIT.
- More precise coating thermal noise level will be provided soon.

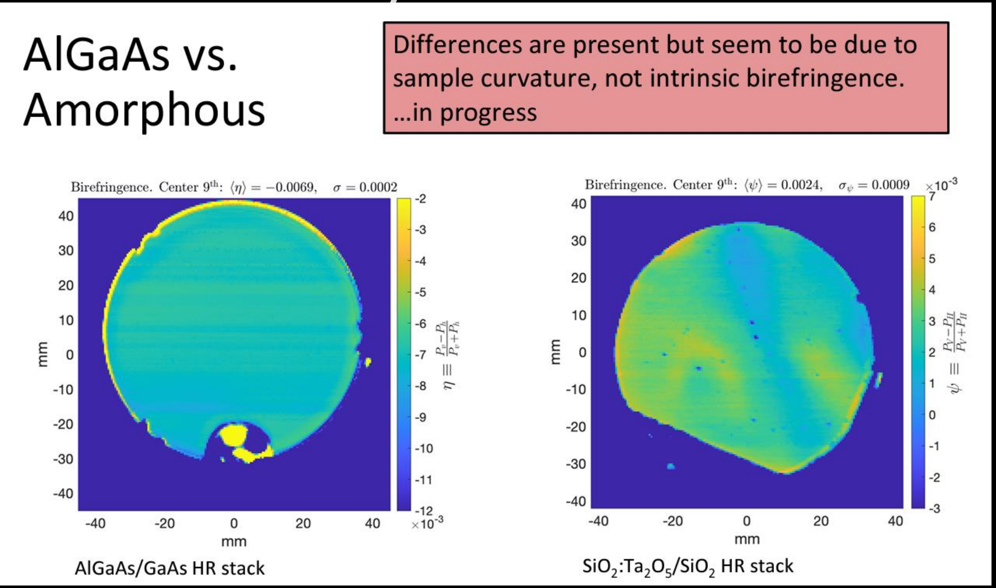


S. Gras 2017



Birefringence

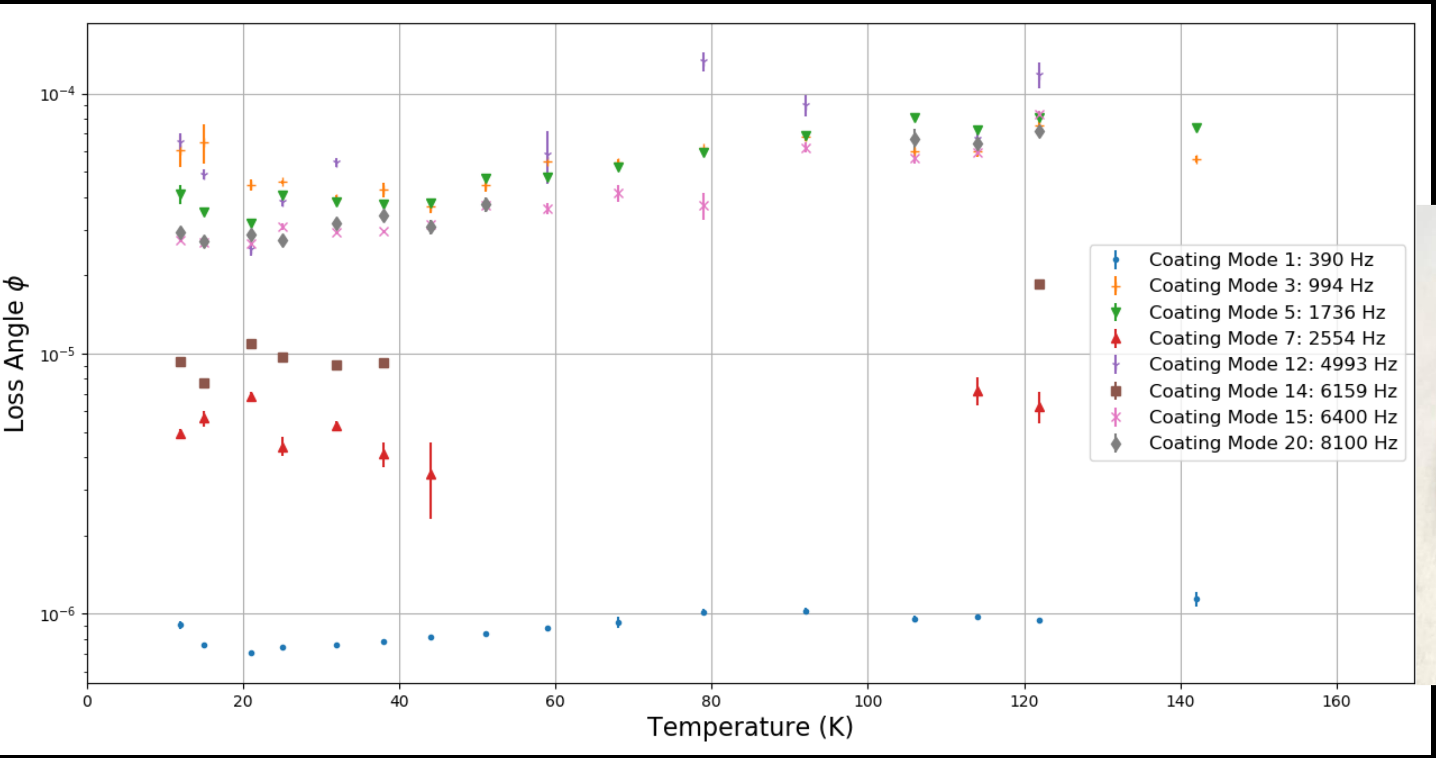
- AlGaAs coatings have large birefringence.
  - typically ~2 mrad -> ~25 Hz mode splitting in 4 km cavity
    - G. Cole 2013, G. Cole 2016, S. Tanioka 2023, etc.
  - high-end amorphous coatings: ~10 μrad
- Birefringence study at Embry-Riddle Aeronautical University



https://dcc.ligo.org/LIGO-G2201607

Cryogenic mechanical loss

LIGO P-2300050



- Precise characterization is ongoing.
- The upper limit of coating thermal noise level in ET-LF is $\sim 2.5 \times 10^{-21}$ [m/rtHz] @10 Hz.
  - requirement: $\sim 3.6 \times 10^{-21}$ [m/rtHz]

Implications for the ET-LF

- The thermal noise level of AlGaAs coating can meet the requirement of the ET-LF.
- Becomes an option even with the limited size.
    - e.g. cryogenically cooled ETMs with a 13 cm beam and 70 cm diameter amorphous coatings and ITMs with a 4 cm spot size with 20 cm diameter AlGaAs coatings (G. Cole 2023)
- If larger diameter coatings are available, AlGaAs coatings would be more attractive.

Scaling

Scale Coatings to 30 cm

★ **Freiberger Compound Materials:**
- 30 cm GaAs wafers
- 2.6 years: Grow, Cut, Etch, Polish
- 8.2 M€ = $9.94M

★ **IQE, NC:** MBE coating facility
- Retooling to 30 cm = $300k
- $300k/month rent of MBE chamber
- $4 M to grow and process coatings

★ **EV Group:** Robotic Bonder
- $5M for bonder for 30 cm coating
- 12-16 month delivery time

Total: 3–5 years, ≈$20M

LIGO G-2300674

- More details will be given by Steve Penn's talk tomorrow morning.

Summary

- A# will be an important milestone toward 3G detectors.
  - AlGaAs coatings are one of the candidates for A# because of their low coating thermal noise.
- Coating thermal noise level with more realistic layer structure will be measured directly soon.
- Other important technologies are being developed and efforts are underway to scale up toward A# and 3G detectors.
  - e.g. ALS, dichroic coatings, ...

Extra slides

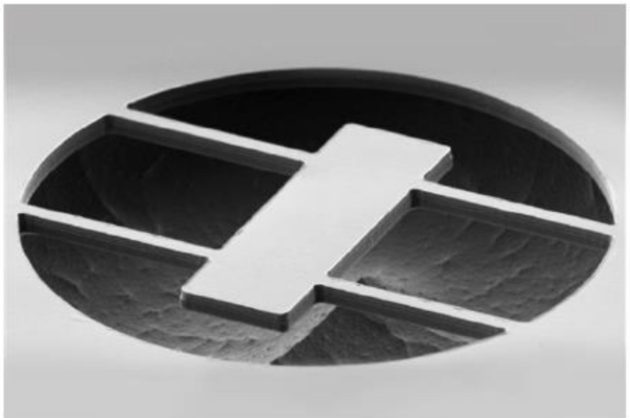
A#

A Detector parameters

Parameter	Units	A+	A$^\sharp$	iVoy	STO	VoyD	VoyW
Arm power	kW	750	1500	3000	1500	4000	4000
Laser wavelength	µm	1	1	2	1	2	2
Test mass material		Silica	Silica	Silicon	Silica	Silicon	Silicon
Temperature	K	295	295	123	295	123	123
Test Mass	kg	40	100	200	200	200	200
Total susp. mass	kg	120	400	520	520	520	520
Final stage susp. length	cm	60	60	80	80	80	80
Total susp. length	m	1.6	1.6	1.6	1.6	1.6	1.6
Observed squeezing	dB	7	10	9	10	9	9
Rayleigh wave suppression	dB	0	6	6	20	20	20
Test Mass Coatings		A+	AlGaAs	Ta/aSi/SiO_2	AlGaAs	aSi	aSi
Horiz. susp. pt. at 1 Hz	pm/$\sqrt{\text{Hz}}$	10	10	10	0.1	0.1	0.1
Final susp. stage blade		None	None	Aluminum	Silica	Silicon	Silicon
ETM beam radius	cm	6.2	5.5	8.0	5.5	8.4	8.4
ITM beam radius	cm	5.3	4.5	5.2	4.5	5.9	5.9
Cavity stability $g_i g_e$		0.83	0.71	0.62	0.71	0.73	0.73
Transverse mode spacing	kHz	32.5	30.7	29.6	30.7	31.0	31.0
Filter cavity linewidth	Hz	48	42	28	30	36	13
Arm finesse		450	450	3100	450	2000	2000
SRM transmission	%	32.5	32.5	4.6	32.5	9.2	1.1
Arm length	m	3995	3995	3995	3995	3995	3995
Filter cavity length	m	300	300	300	300	300	300
SEC length	m	55	55	55	55	55	55
RT arm cavity loss	ppm	75	75	20	75	20	20
RT filter cavity loss	ppm	40	30	10	20	10	10
RT SEC loss	ppm	3000	500	500	500	500	500
Exc. gas damp.		2.0	2.6	2.5	3.1	2.5	2.5
Diffusion time	µs	800	1500	1400	2300	1400	1400

Table 6: Defining parameters of detectors (aSi: amorphous silicon; AlGaAs: aluminum gallium arsenide; RT: round trip). The parameters needed to reach these squeezing levels are given in Table 2. Detailed coating parameters are given in Table 8. The excess gas damping is the squeezed film enhancement to residual gas damping as described in [48] and calculated in LIGO-T0900582. As described in Appendix A of [48], the details of the sticking time for molecules in the TM/ERM gap depend on the mirror temperature and the AR coating's sticking energy. These are not well characterized for our amorphous oxides at 123 K, and so while we expect the squeezed film damping to be less for Voyager, we use the standard room temperature formula as a conservative upper limit for now.

Epitaxial AlGaAs micro resonators



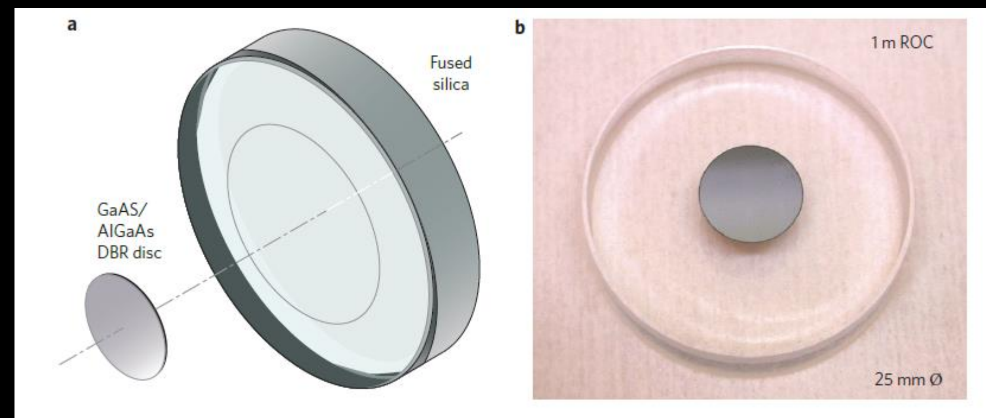
free-standing epitaxial AlGaAs

reflectivity >0.9999 (ppm losses)

loss angle $<4\times10^{-5}$ to $<5\times10^{-6}$

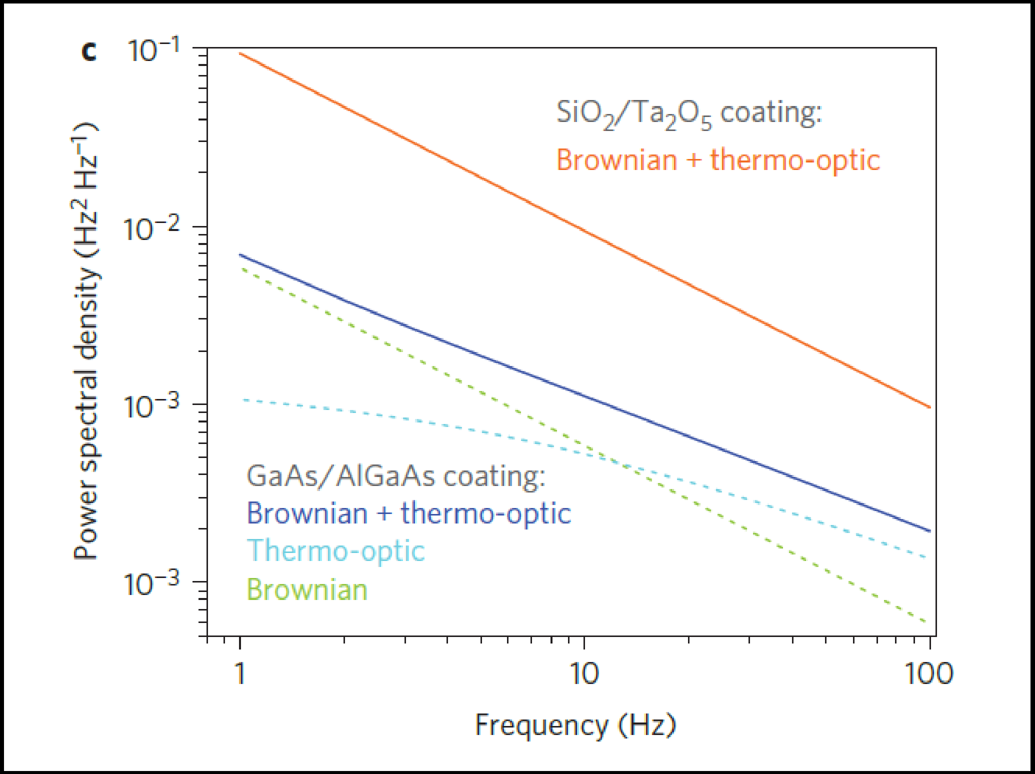
a) Cole, et al., *Appl. Phys. Lett.* 92 (2008)
b) Cole, *Proc. SPIE.* 8458–07 (2012)
c) Aspelmeyer et al., *RMP* 86, 1391 (2014)

originally used to micro resonators
-> applied to HR mirror coatings



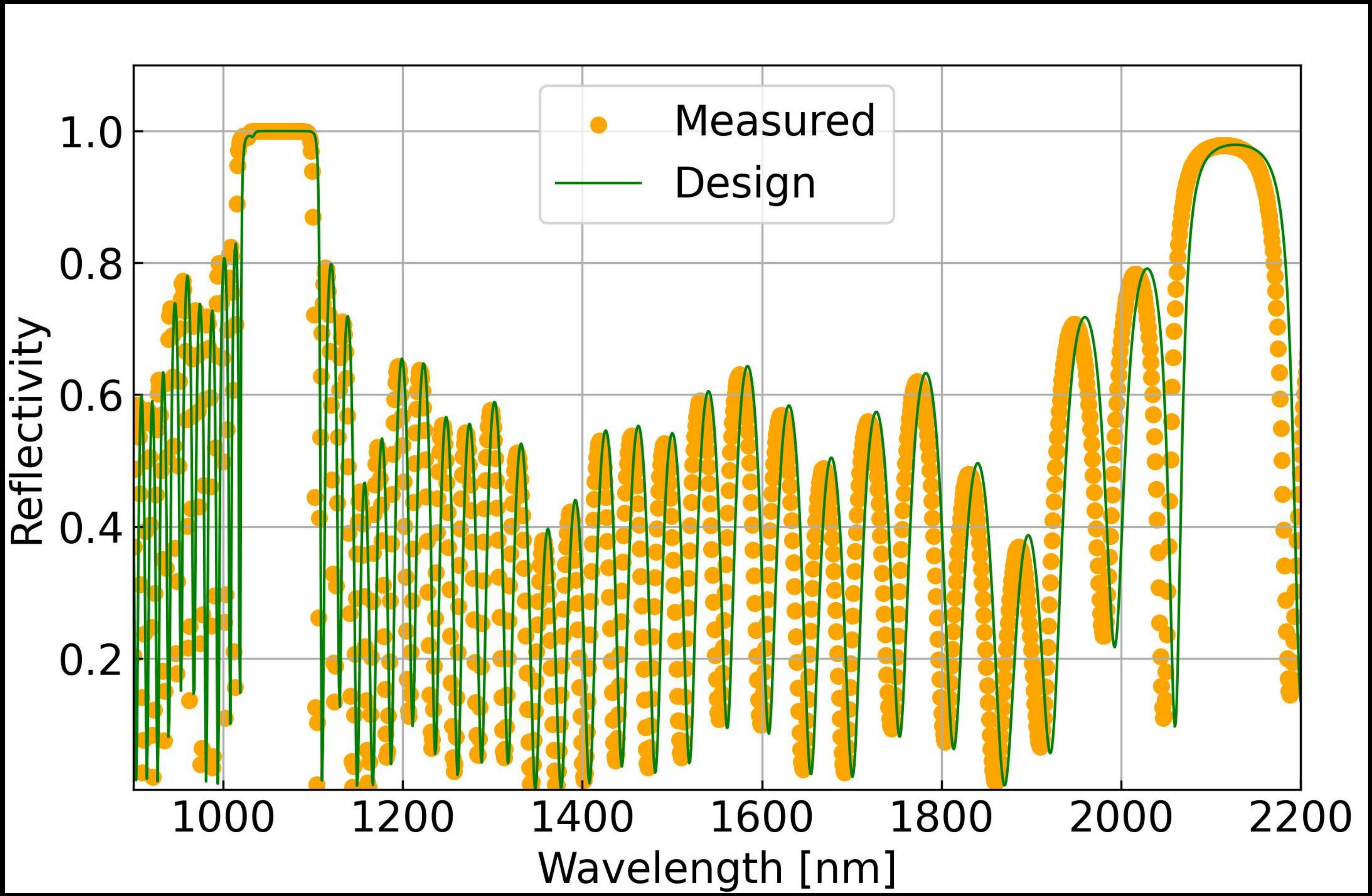
Cole+ 2013

Cited from G. Cole's presentation @AlGaAs workshop



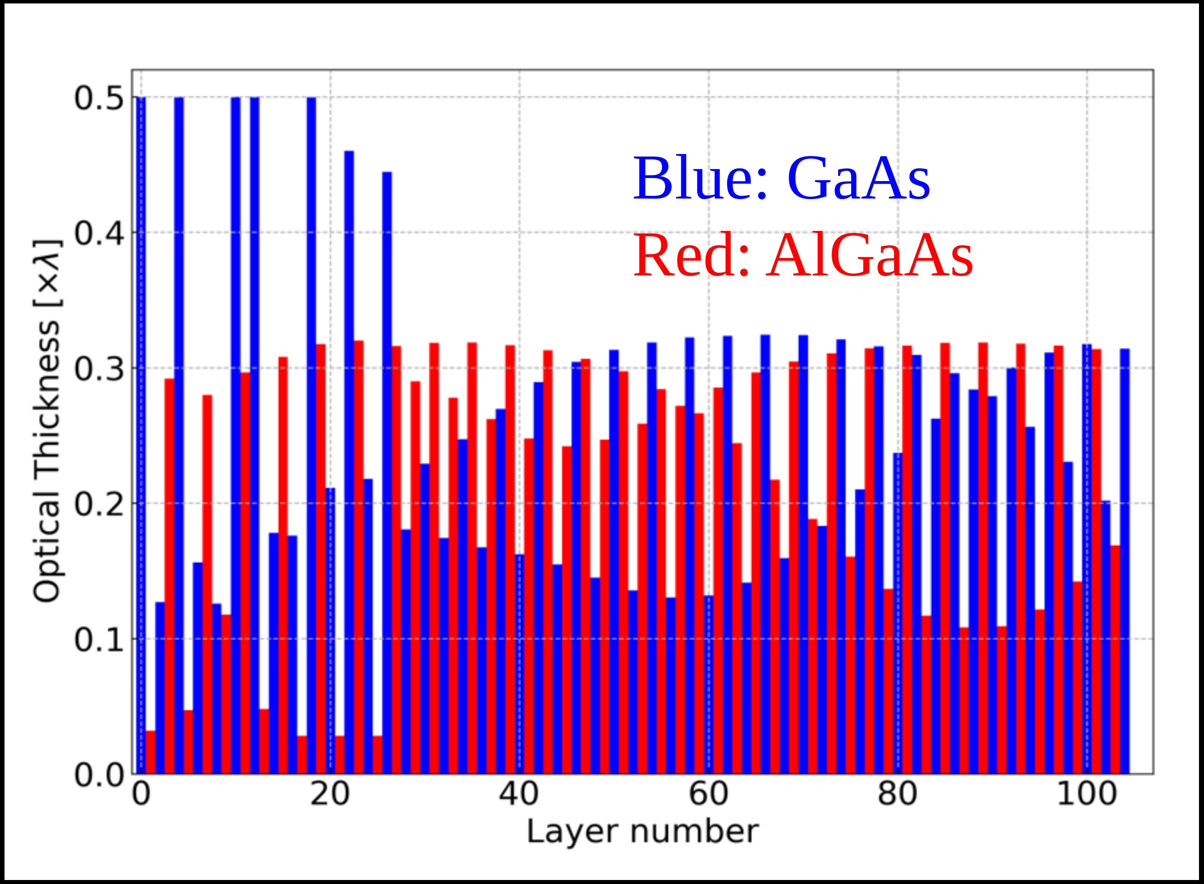
Cole+ 2013

$\phi = 4 \times 10^{-5}$ -> one order of magnitude smaller than typical amorphous coatings



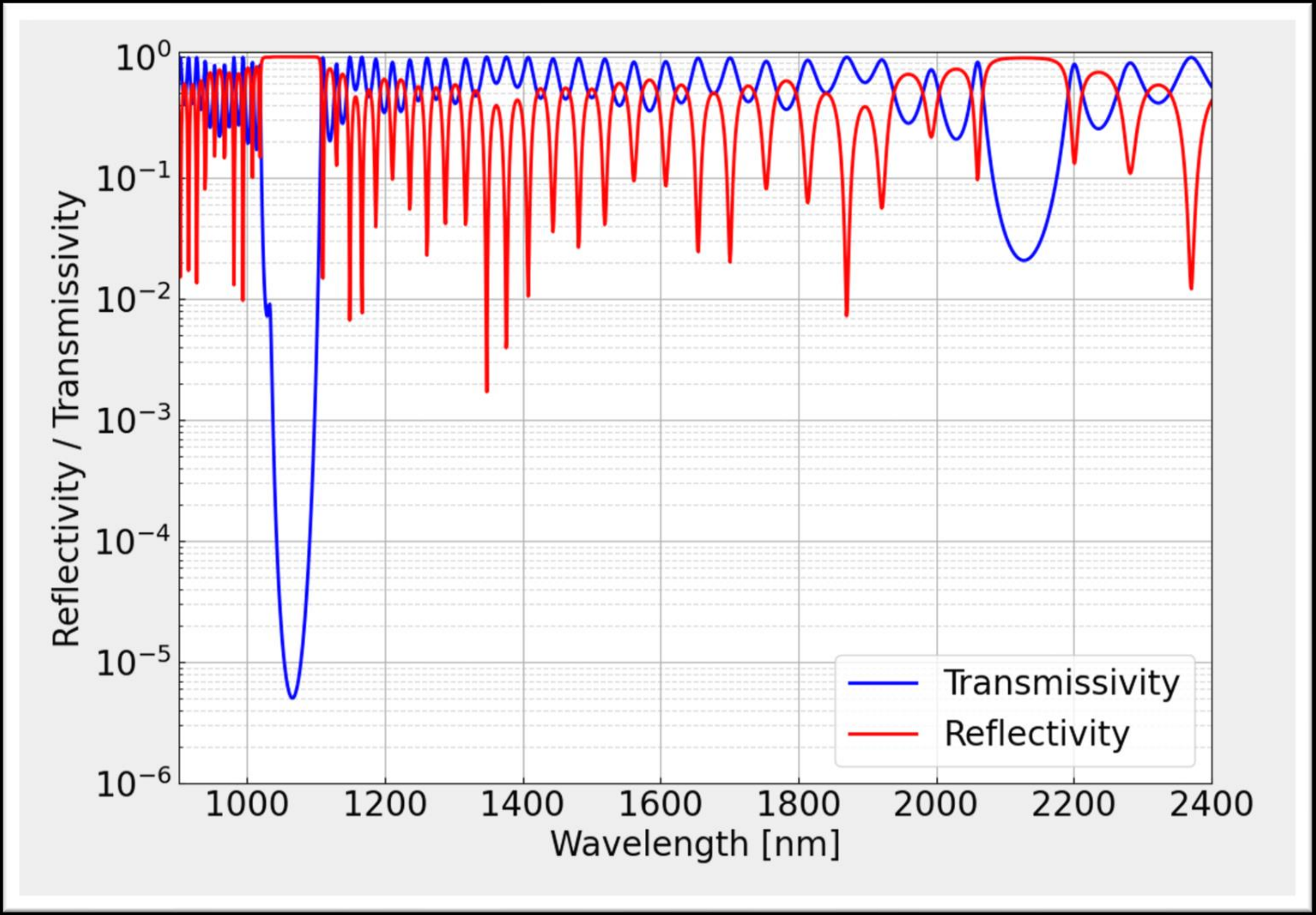
Measured
Design
Reflectivity
1.0
0.8
0.6
0.4
0.2
1000
1200
1400
1600
1800
2000
2200
Wavelength [nm]

Layer



Blue: GaAs
Red: AlGaAs
Optical Thickness [×λ]
0.0
0.1
0.2
0.3
0.4
0.5
0
20
40
60
80
100
Layer number

Design



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Reflectivity / Transmissivity
1000
1200
1400
1600
1800
2000
2200
2400
Wavelength [nm]
Transmissivity
Reflectivity

Demonstrator