Future of mirror characterization towards next KAGRA mirrors

Marc Eisenmann

Outlook

- Current situation
- What mirrors are we aiming for ?
- How can we improve current mirrors
- New birefringence characterization

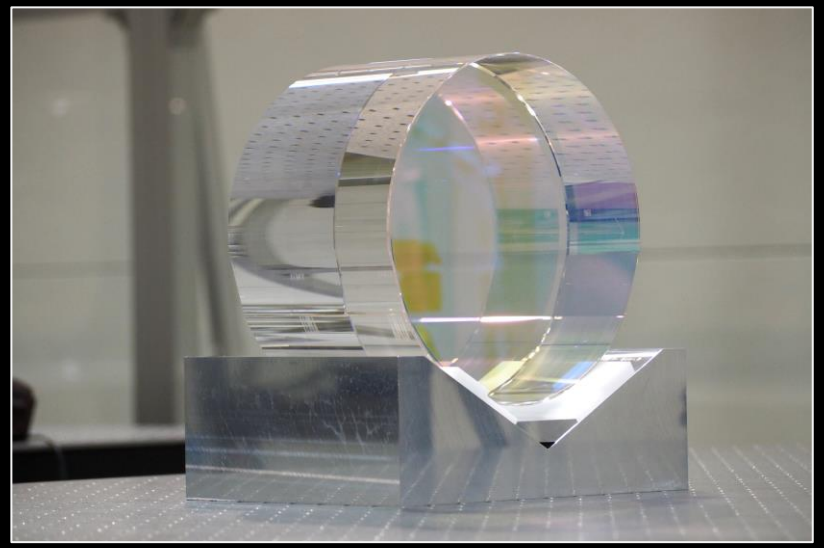
KAGRA mirrors

- KAGRA ITMs and ETMs are 22 kg sapphire at cryogenic temperature

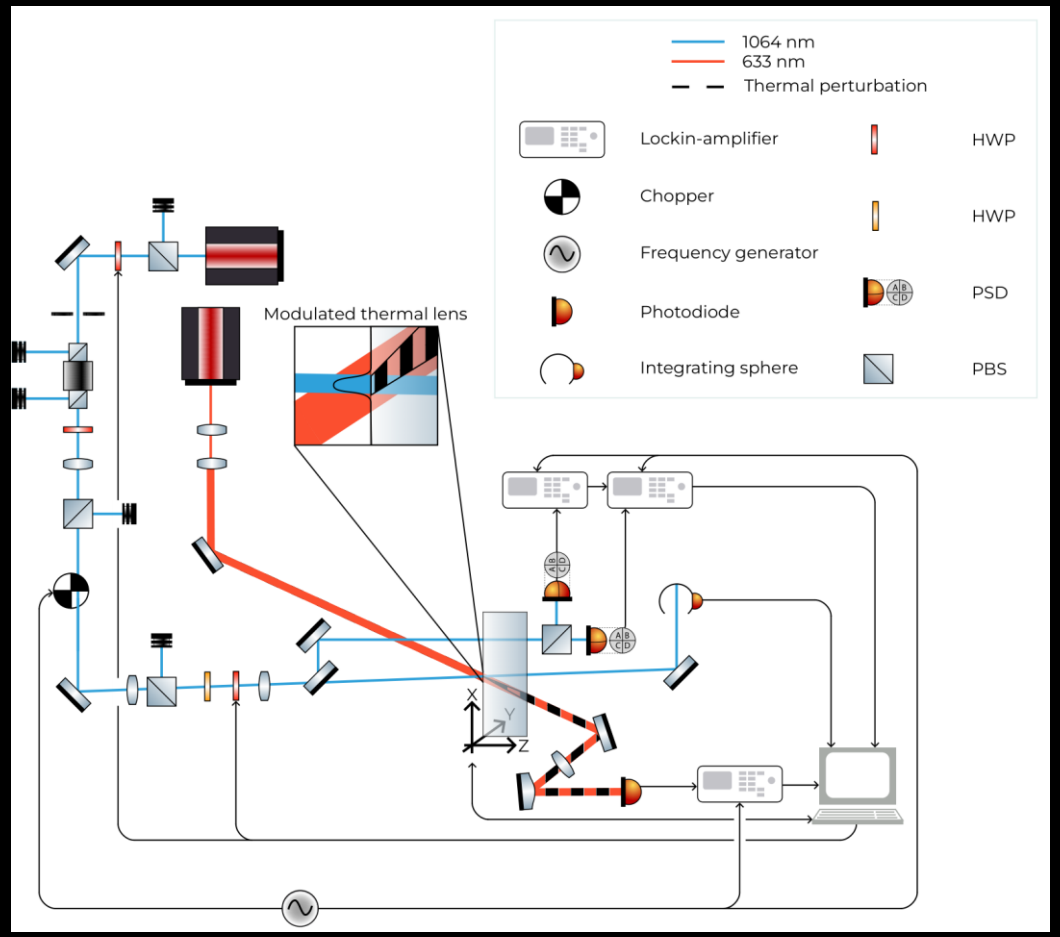
- ITMs substrate properties are critical for KAGRA performances

  - ITMs **absorption** must be <= 50 ppm/cm to operate at cryogenic temperature with high laser power
    - Lower absorption will allow to reduce the suspension thermal noise

  - ITMs have high and non-uniform **birefringence** :
    - Higher losses (ie higher quantum noise)
    - Higher laser frequency & intensity noise
    - Complex coupling to alignment signal



Characterization setup at NAOJ



- Modified PCI measurement setup :
  - Can measure absorption at 1064nm with probe at 633nm & 1310nm
  - 3D resolution of absorption
- Added polarization control & readout :
  - Can measure polarization & birefringence at 1064 nm
  - 2D resolution of birefringence (integrated along Z)
  - It is a linear-polarizer setup (ie indirect birefringence measurement)

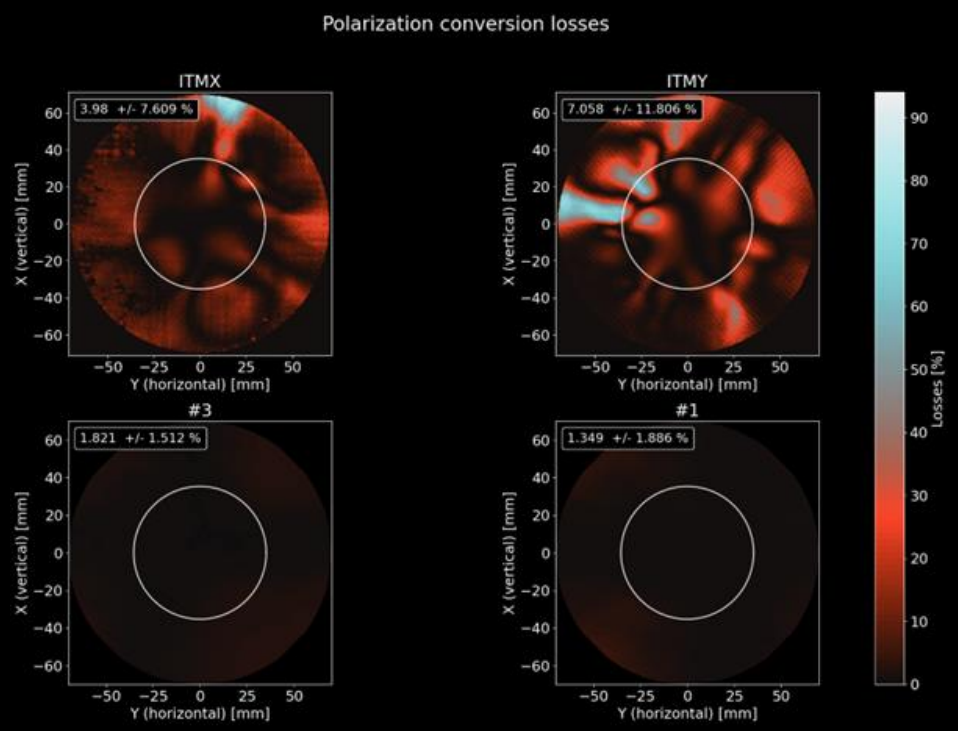
3D characterization of low optical absorption structures in large crystalline sapphire substrates for gravitational wave detectors

Manuel Marchiò[1,2], Matteo Leonardi[2], Marco Bazzan[3] & Raffaele Flaminio[2,4]

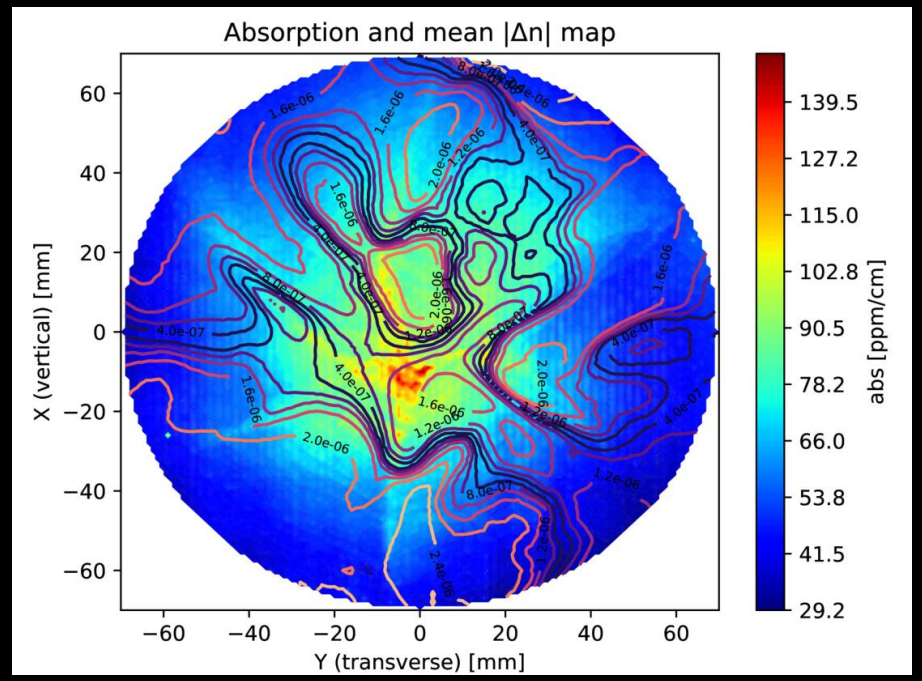
Simultaneous Birefringence and Absorption Mapping in Large-Size Sapphire Substrates for Gravitational-Wave Interferometry

Simon Zeidler (s.zeidler@rikkyo.ac.jp)
Rikkyo University
Pengbo Li
National Astronomical Observatory of Japan (NAOJ)
Marc Eisenmann
National Astronomical Observatory of Japan (NAOJ)
Marco Bazzan
UniversitàUniversit`Università di Padova
Matteo Leonardi
National Astronomical Observatory of Japan (NAOJ)

KAGRA future mirrors



New KAGRA ITMs have far better birefringence



Absorption & birefringence seem to share similar origin

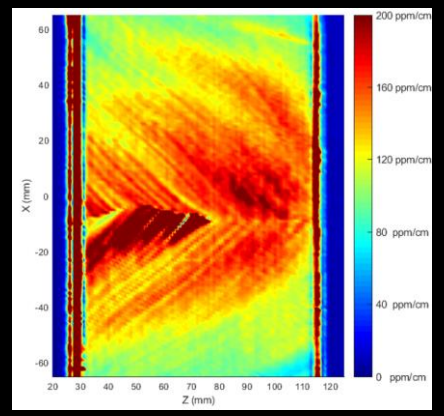
If we can understand the origin of the absorption, we should be able to reduce both absorption and birefringence !

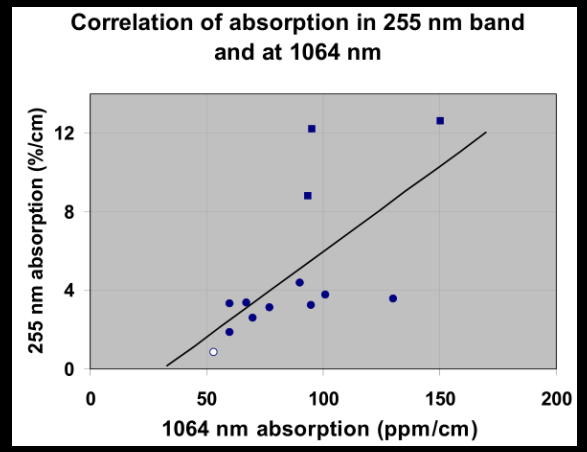
Possible common origin ?

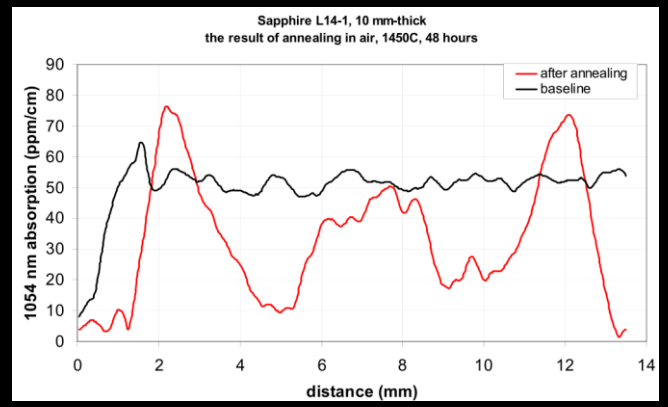
Two strong candidates :

- Impurities (eg Fe, Cr, Ti, etc ...)
- Crystalline structure defects

Growth direction

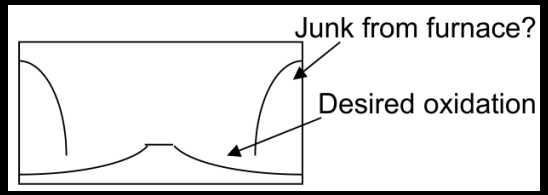






- **Spectro-photometry** allows us to probe impurities
  - Interesting correlation with 255 nm absorption

- **Annealing** allows us to heal the crystalline structure
  - Require tuning of temperature profile, environments conditions



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Next KAGRA mirrors?

Survey of the current technologies (price and readiness)	Relevance (necessity)				Significance						5-yr Feasibility						total score	"oo" in upgrade options			
	LF	40kg	FDsq	HF	KS	SH	YM	ML	KK	avg.	KS	SH	YM	ML	KK	avg.	avg.	LF	40kg	FDsq	HF
Squeezing (squeezing level, losses)	x	o	oo	oo	5	5	5	5	5	5.0	5	5	5	5	5	5.0	25.0			25	25
Filter cavity (losses)	x	o	oo	o	4	5	5	5	5	4.8	5	4	5	5	5	4.8	23.0			23	
High quantum efficiency PD	o	o	oo	oo	5	5	5	5	5	5.0	5	4	4	5	4	4.4	22.0			22	22
Low-loss output faraday isolator	x	o	oo	oo	4	5	5	5	5	4.8	4	4	4	5	4	4.2	20.2			20.2	20.2
High power laser (how much power? stability?)	x	o	o	oo	5	5	5	5	5	5.0	5	4	3	4	4	4.0	20.0				20
Parametric instabilty vs power, mitigation schemes	x	o	o	oo	5	5	5	4	5	4.8	5	5	3	3	4	4.0	19.2				19.2
Large Sapphire Mirror	x	oo	x	x	5	4	5	5	5	4.8	3	3	5	4	3	3.6	17.3		17.3		
Balanced homodyne detector	oo	o	oo	o	4	4	5	4	4	4.2	4	4	4	4	4	4.0	16.8	16.8		16.8	
Suspension design for suspension thermal noise reduction	oo	o	o	oo	4	5	5	5	4	4.6	2	4	5	4	3	3.6	16.6	16.6			16.6
Improving heat conductivity of sapphire fibers	o	o	o	o	4	5	5	4	5	4.6	2	4	5	4	3	3.6	16.6				
Low absorption Sapphire Mirror	x	oo	o	o	5	5	5	5	5	5.0	3	3	3	4	3	3.2	16.0		16		
Extreme RSE (high SRM reflectivity possible?)	x	x	x	oo	4	4	4	4	5	4.2	4	4	4	3	4	3.8	16.0				16
Better Coatings	o	oo	oo	o	4	5	5	5	4	4.6	4	4	3	3	3	3.4	15.6		15.6	15.6	
Suspending larger mirror	x	oo	x	x	4	4	5	5	5	4.6	3	3	4	4	3	3.4	15.6		15.6		
Thermal compensation system (BS/PRMs)	x	x	x	oo	5	4	4	4	3	4.0	4	4	4	3	4	3.8	15.2				15.2

- Significant technological improvement will be needed to achieve better sensitivity of low frequency region and to have broadband sensitivity upgrades. Heavier mass option (40 kg) and studies on the low-frequency noises should be pursued for the middle term upgrades (~10 years)

JGW-G1910098-v3

Next KAGRA mirrors?

What should we aim for ?

- 40 kg mirror & 50ppm/cm absorption
- 40 kg mirror & 20ppm/cm absorption

- 100 kg mirror & 40ppm/cm absorption
- 100 kg mirror & 20ppm/cm absorption

- 200 kg mirror & 20ppm/cm absorption

- Is it still reasonable to ‘only’ have 40 kg mirrors from O6+?

- Should we focus on larger mirror ?

- Should we demonstrate & use 3G-size mirror?

Next KAGRA mirrors and sensitivity

Mirror size affects several fundamental noises :

$$S_{susp} \propto \frac{d_f^2}{l_f^2 * r}$$

$$S_{QN} \propto \frac{1}{P_{BS}} + \frac{P_{BS}}{r^6}$$

$$S_{sub} \propto \frac{1}{r}$$

$$S_{coat} \propto \frac{1}{r^2}$$

$$P_{\mathrm{BS}}^{max} \propto \frac{d_f^3}{l_f . absorption . r . \frac{15}{22}}$$

r : mirror radius
l_f : fiber length
d_f : fiber diameter
P_{BS} : power at BS

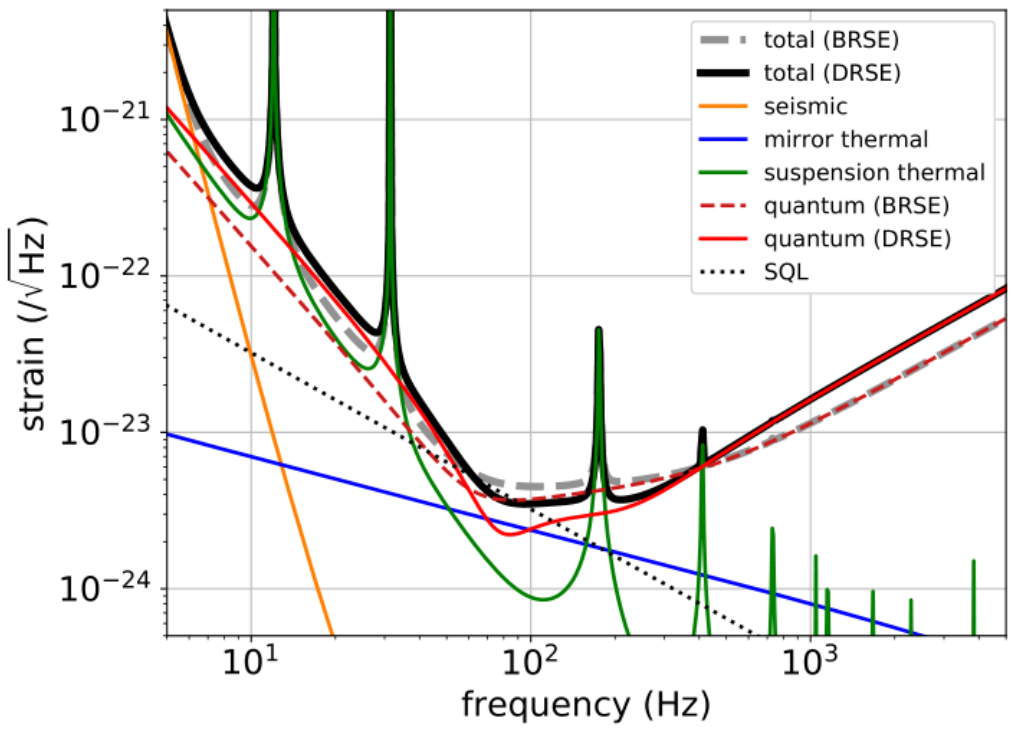


Figure 11: KAGRA design sensitivity and noise contributions which were approved as the official design by KSC and EO in September, 2017 [385, 383]

Next KAGRA mirrors (tentative) schedule

Mass [kg]	Radius increase	Absorption measurement duration	Birefringence measurement duration	Samples	Total absorption	Total birefringence	Coating [year]	Installation before run [year]	Total [year]
20	=	1 week	2 weeks	2 out of 5	5 weeks	10 weeks	2	2	4.3
40	*1.2	1.4 weeks	2.8 weeks	6 out of 15	5.3 months	10.6 months	2	2	5
100	*1.7	2.9 weeks	5.8 weeks	6 out of 15	11 months	22 months	3?	4?	9.8
200	*2.1	4.4 weeks	8.8 weeks	6 out of 15	16.5 months	33 months	3?	4?	11.1

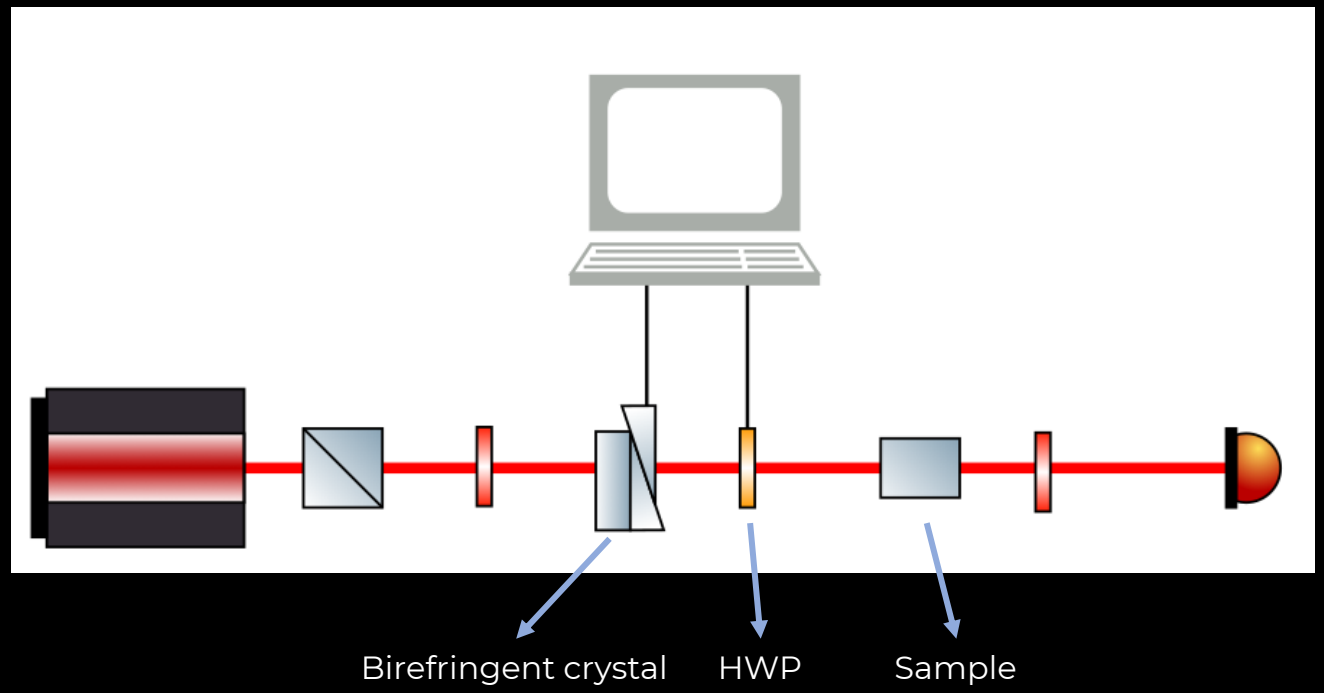
* Does not take into account R&D to find good mirrors, time to take decision on which mirror to go for, time to get budget, etc..

Adding R&D duration, decision making, budget approval etc .. it seems that KAGRA next mirror could be on the critical path for future upgrades

(also with this setup and the need of 3 times more mirrors for ET it might also be tricky for them...)

Other way to measure birefringence

- Soleil-Babinet compensator



Development of an automatic birefringence measuring device of mirror substrates for gravitational wave detectors

M Tokunari, H Hayakawa*, K Yamamoto, T Uchiyama, S Miyoki, M Ohashi, K Kuroda
Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan
E-mail: tokunari@icrr.u-tokyo.ac.jp

- Sample placed between 2 cross-polarizers
- Birefringent crystal w/ variable thickness acts as variable polarization retarder
- Motorized HWP acts as variable polarization rotator
- Tune both of them to get no light at the photodetector : ie direct measurement of sample birefringence

Issues

- Uses step-motor to shift the birefringent crystal
- Uses step-motor to rotate the HWP
- Requires to scan a large parameter space (several tens of points / measurement
- Sapphire measurements using this technique had 10* smaller resolution than NAOJ polarimeter and same order of magnitude sensitivity

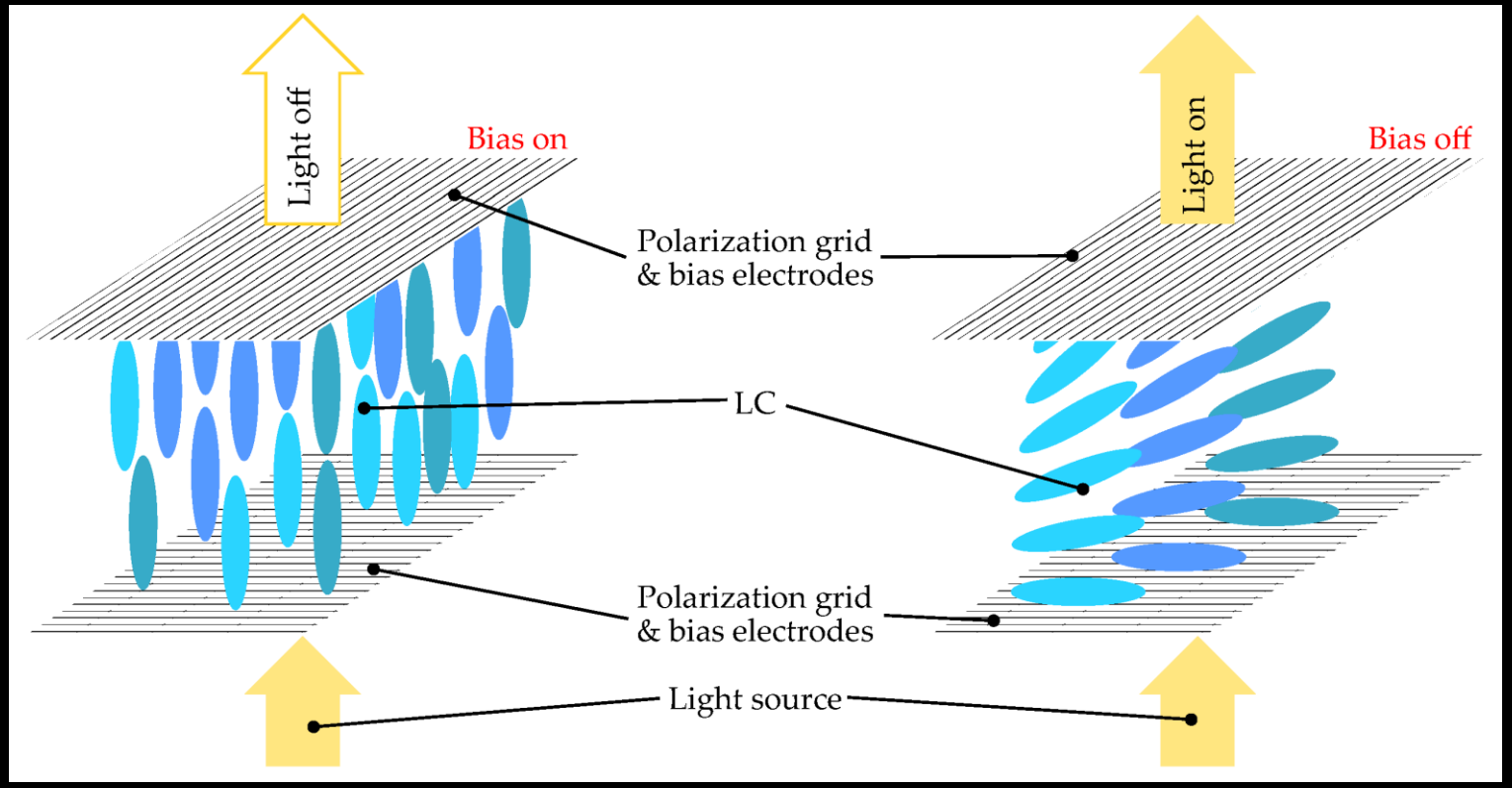
Fast & direct birefringent measurement?

- Requires variable polarization rotator and retarder
- Electrically tunable could insure fast measurement

KAGRA uses already such component : EOM are electrical variable polarization retarder !

This should work but today is about Future plans so I will present another component

Liquid crystal

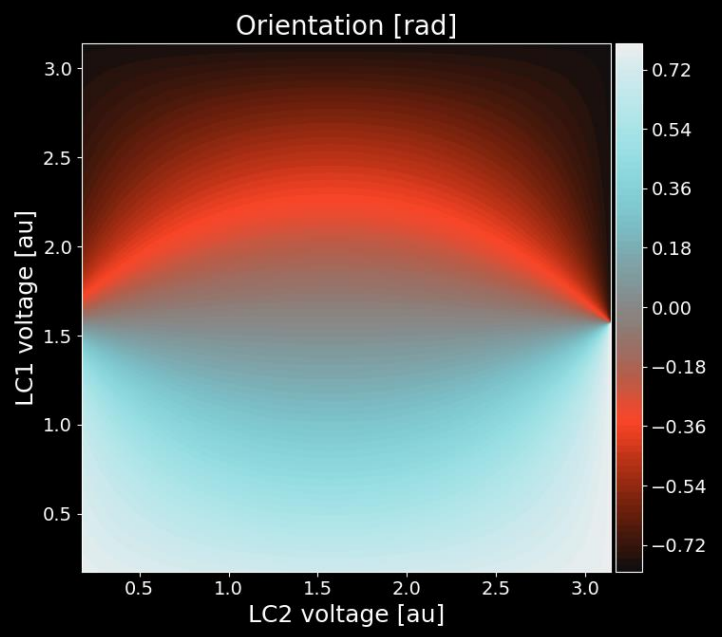


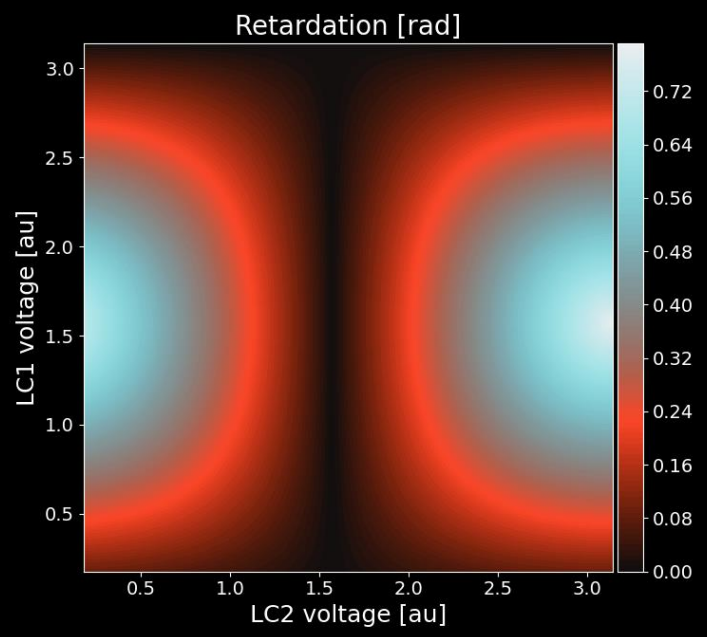
Liquid crystal are voltage based polarization controller

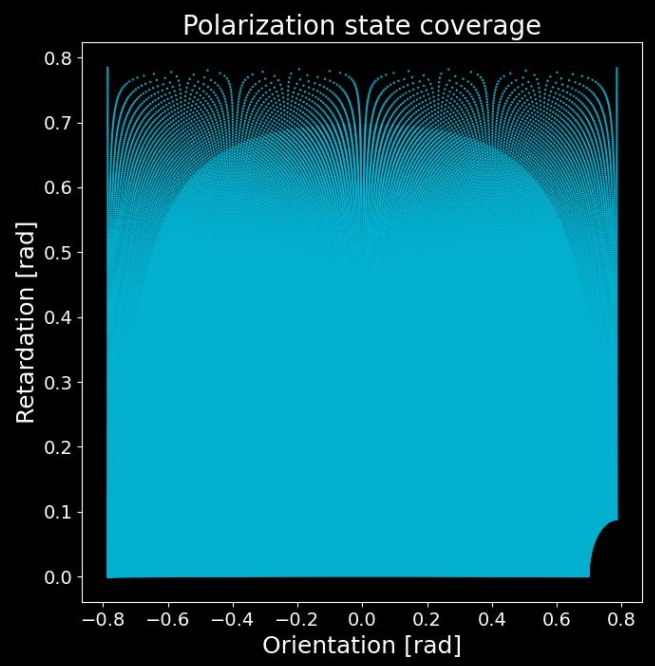
- Polarization retarder
- Electrically controlled
- Really cheap
- Large aperture available
- Requires low voltage

Arbitrary polarization state generation

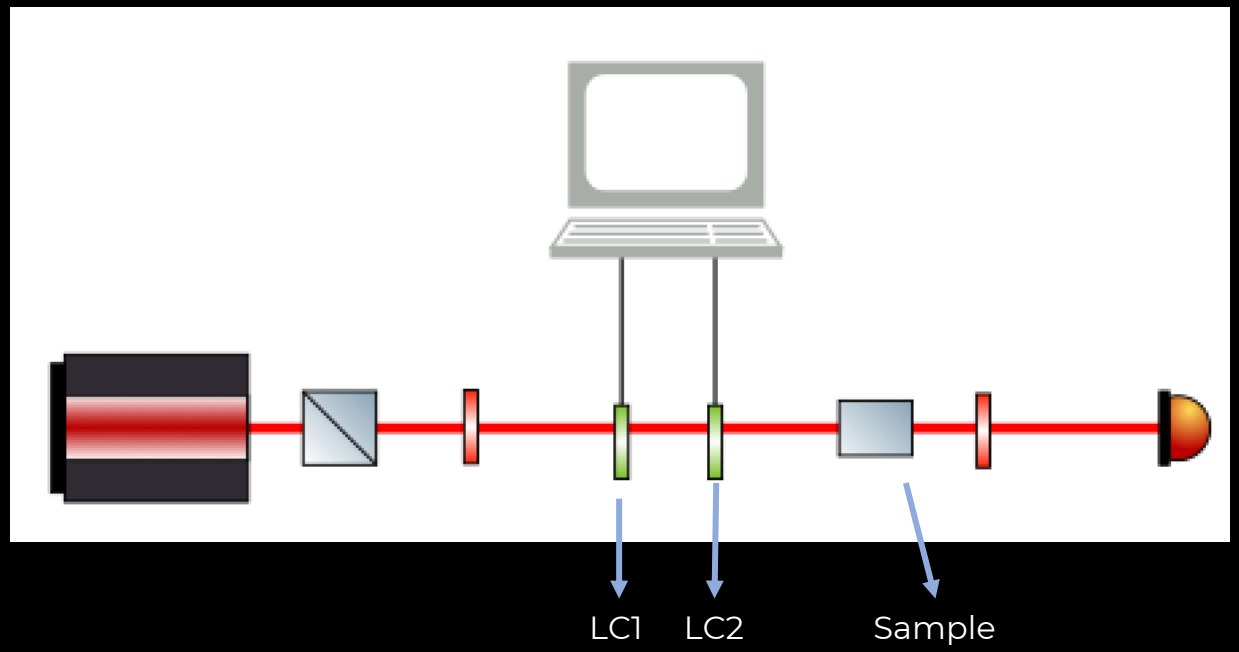
With a pair of Liquid Crystal, it is actually possible to generate any polarization state !







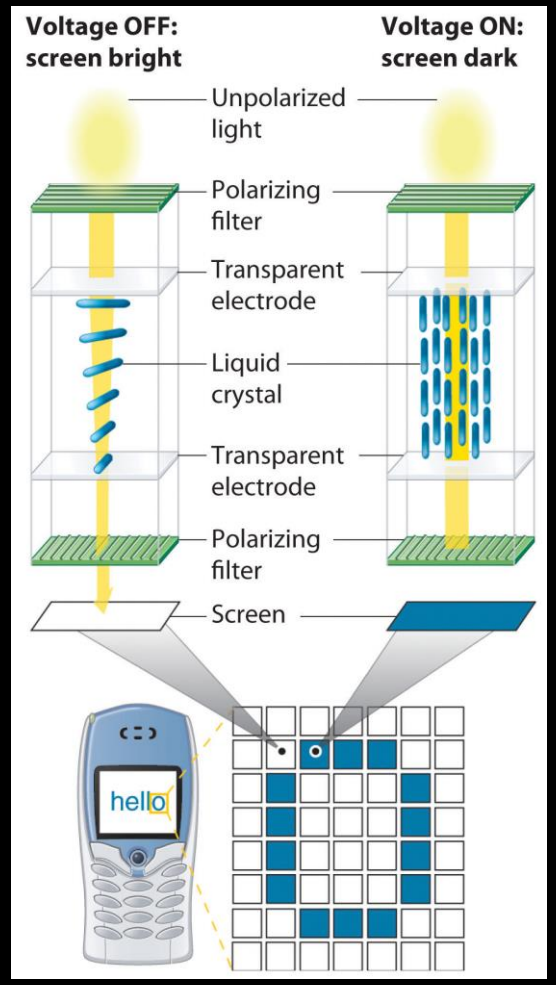
New birefringence setup



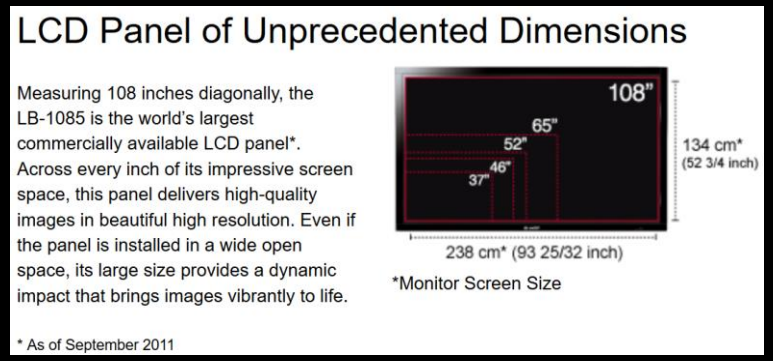
The birefringence characterization duration can be reduced by a factor 50 !

But can we go even faster ?

LCD !



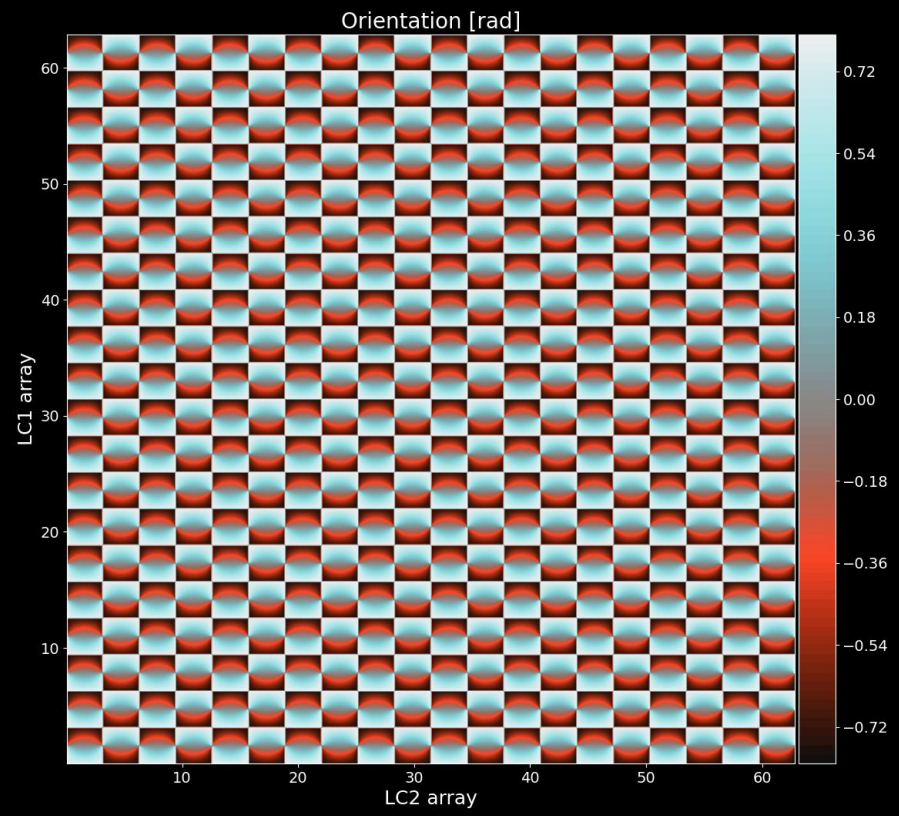
- Liquid Crystal Display (LCD) are large array of Liquid Crystals (eg 4K UHD is 3840 × 2160 pixels)
- Can reach size larger than 3G mirrors
- Each pixel is contains small Liquid Crystal

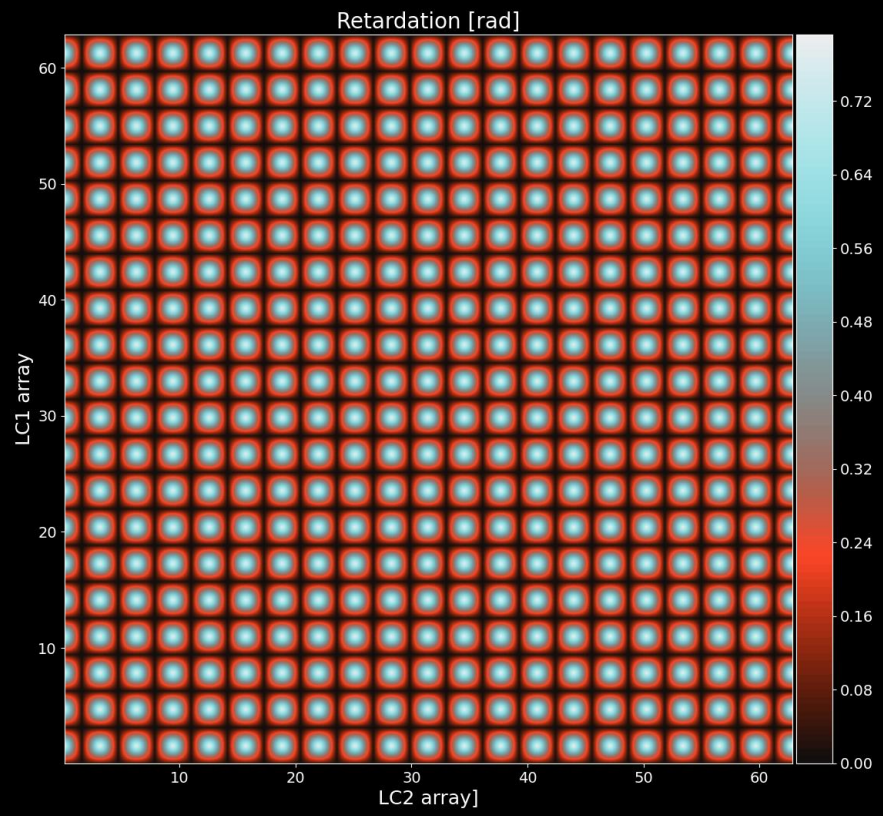


Sharp

https://saylordotorg.github.io/text_general-chemistry-principles-patterns-and-applications-v1.0/s15-08-liquid-crystals.html

LCD and birefringence





- Using 2 LCDs is a 2D electrical Soleil-Babinet compensator
- No need to have ANY mechanical motion
- Instantaneous birefringence measurement
- Full compensation of birefringence

New characterization setup status

- Purchased all components
- Received half of what we need (remaining arrives next week)
- Tests will start from tomorrow
- Hopeful first KAGRA size measurements within few months

- LCD requirements and simulation on-going
- Plans to play with LCD at the beginning of next year

Conclusion

- We need to decide somehow soon what is the future of KAGRA : should we aim for the best allowed by our infrastructure or maximize the observation time with smaller mirror ?

- We plan to investigate the origin of absorption and birefringence
  - If understood we could have 20 ppm/cm absorption ; negligeable birefringence sample

- We have plan for a new birefringence setup
  - At least 50 times faster ; maybe soon ‘instantaneous’
  - Also acts as birefringence compensator

- We have several other MIR related plans :
  - At next F2F we will present a new Automatic Alignment scheme able to be used with birefringent mirror
  - (and more to come)