Development of birefringence characterization and compensation techniques for gravitational wave detectors.

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Gravitational waves and detector

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Birefringence issue

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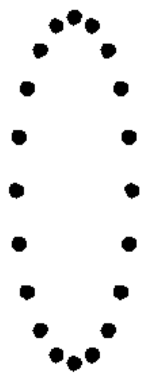
Tackling birefringence

- **Choosing the best mirror**
- **Birefringence monitoring**
- **Birefringence compensation**

Gravitational waves

- Ripples in space-time
- Sources: Black hole mergers, Neutron star mergers
- First direct detection: GW150914 (binary black hole merger)



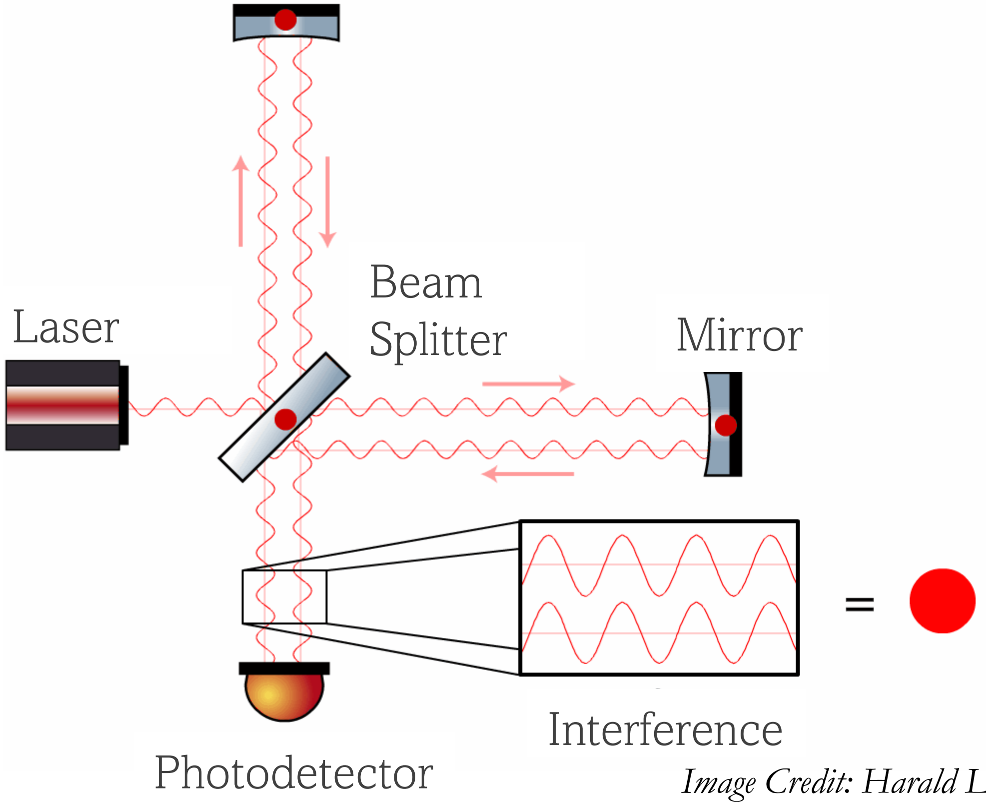


Image Credit: Harald Lück

Gravitational wave signal in time

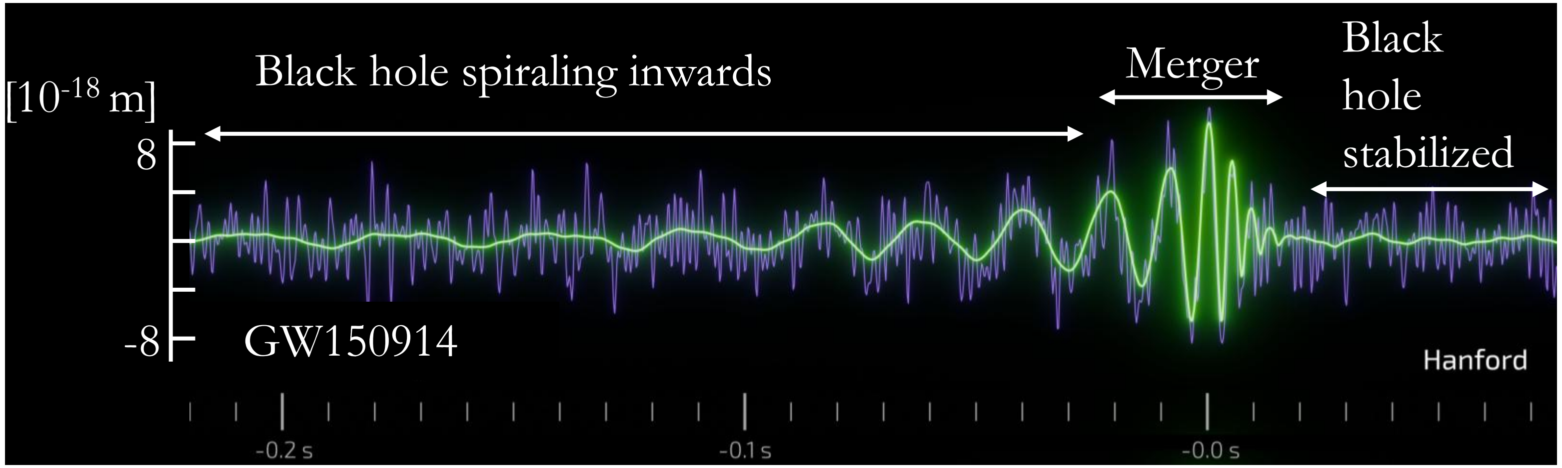
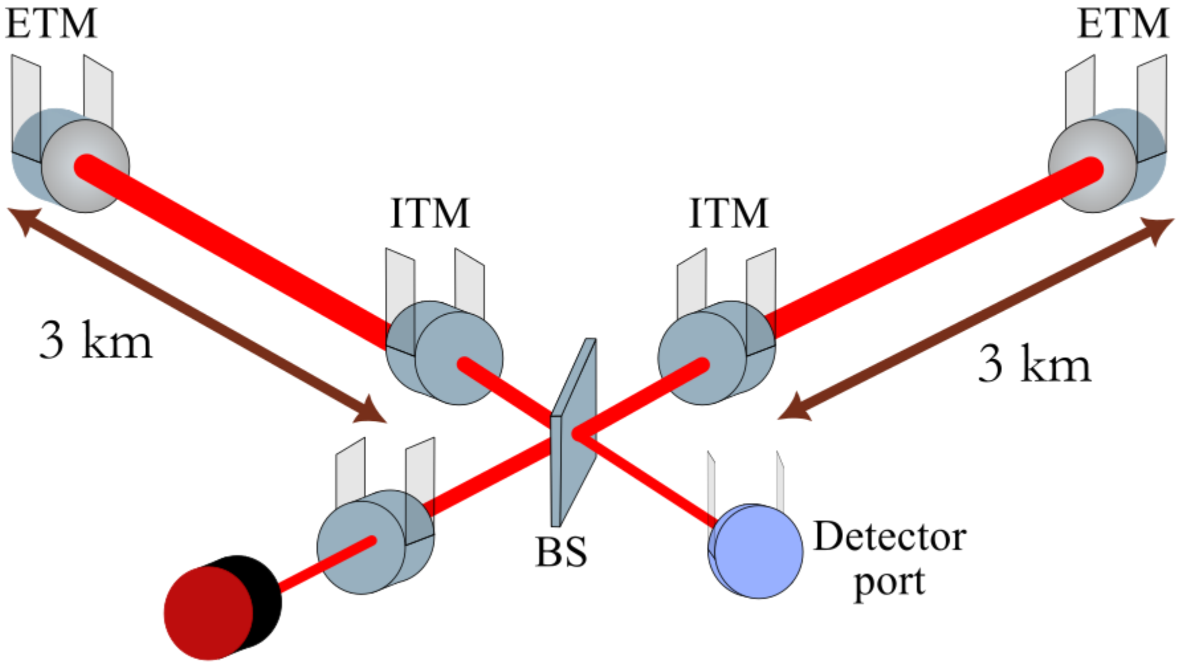
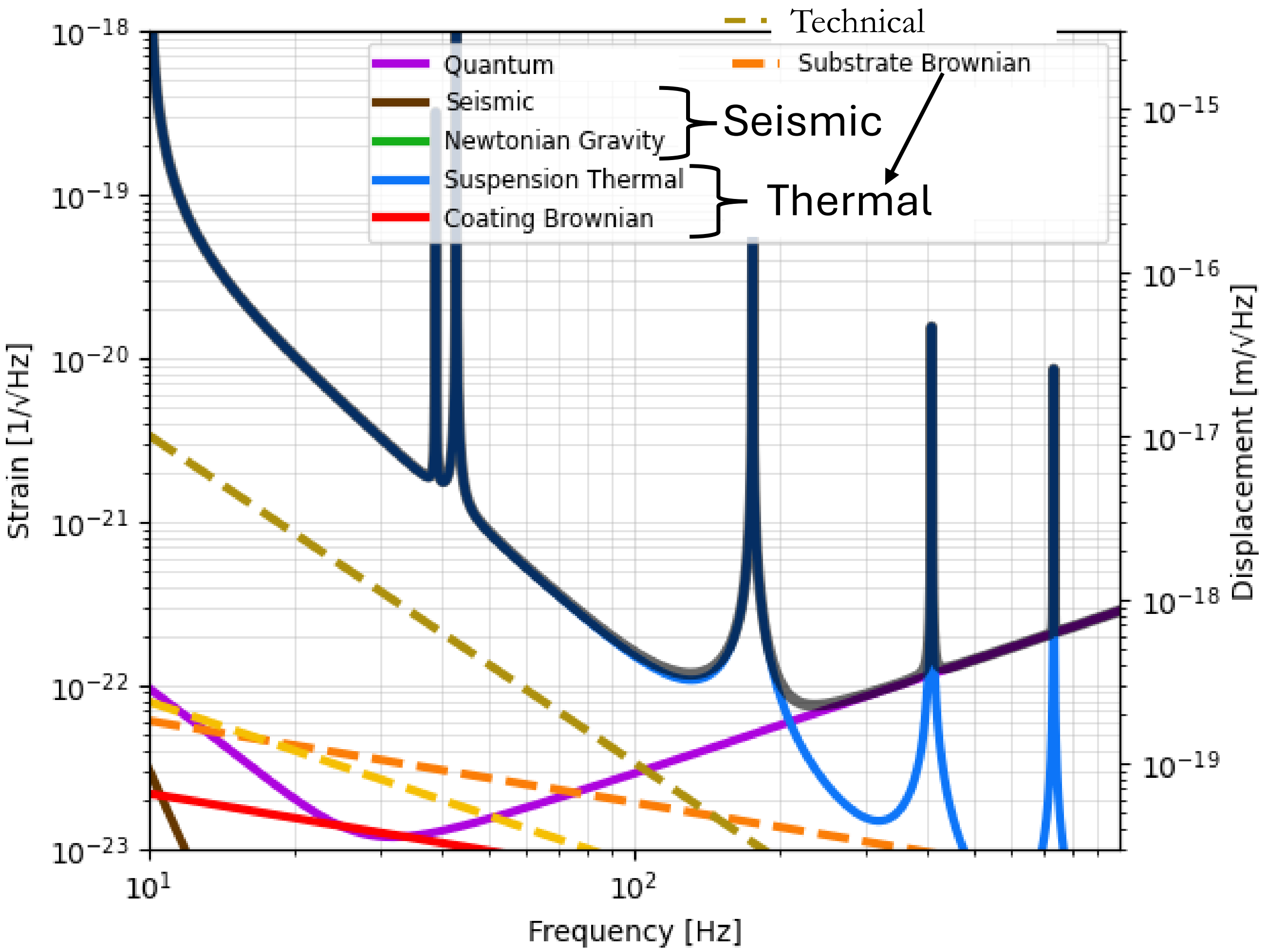


Image credit: LIGO/J. Tissino (GSSI)/R. Hurt (Caltech-IPAC)

Gravitational wave detector

- It has complicated configuration using vacuum, vibration isolation, with kilometer long (3-4km) arms.
- Increasing effective length using input test mass (ITM) and using recycling techniques to increase gain, etc. ….





Potential of detector with increased sensitivity

- Till date 391 gravitational waves emitting events have been observed.
- Increasing the sensitivity increases detection rate & helps to observe signal more clearly.

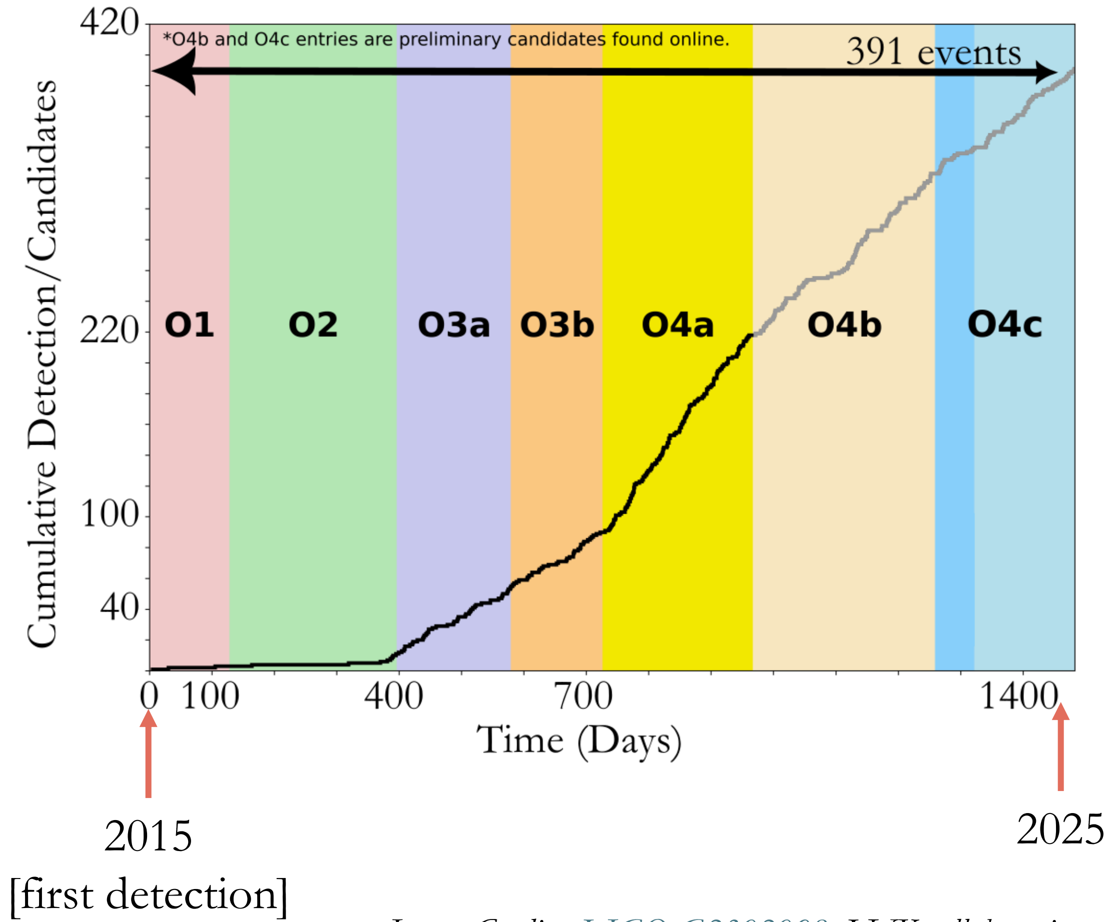


Image Credits: LIGO-G2302098, LVK collaboration

Sensitivity is improved in 10 years

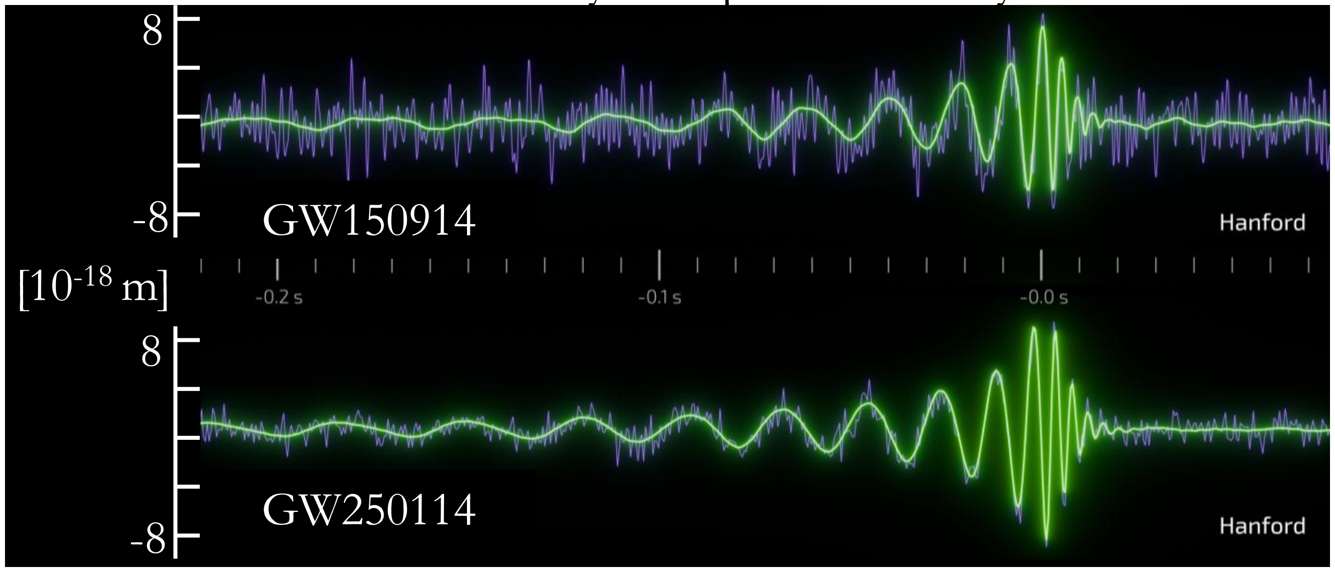
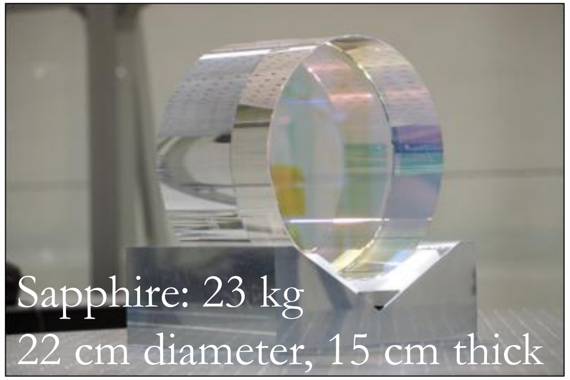
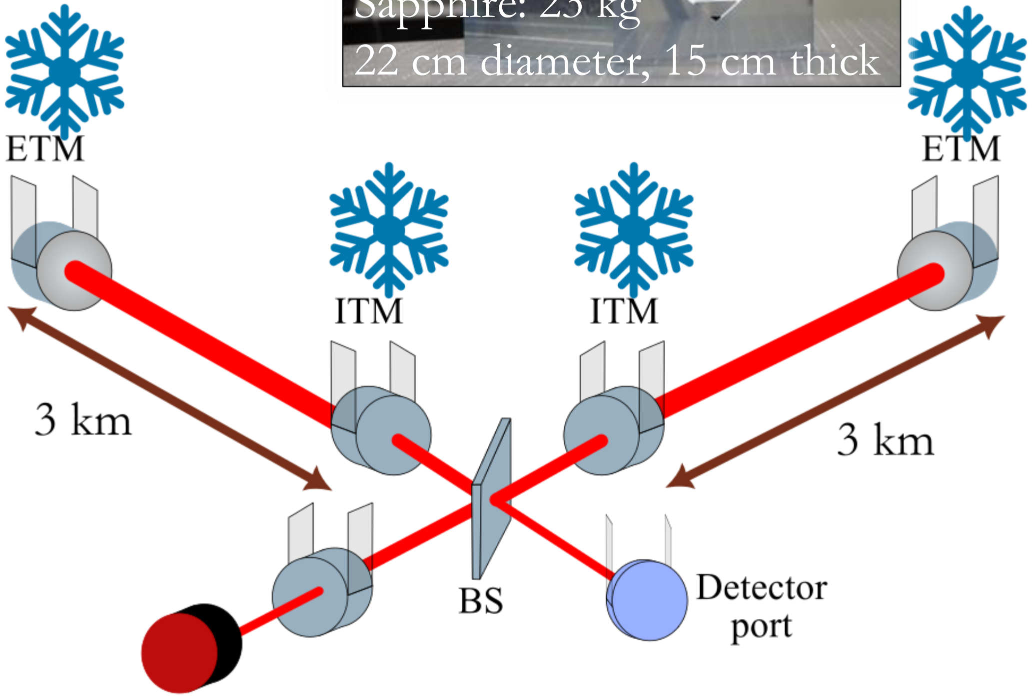


Image credit: LIGO/J. Tissino (GSSI)/R. Hurt (Caltech-IPAC)

KAGRA, detector in Japan

- Underground in a mine to reduce Newtonian and seismic noise
- Mirrors cooled to 20K to reduce thermal noise
- Crystalline mirrors are required at low temperature
  - Sapphire: low mechanical loss, high thermal conductivity
- Choosing best quality Sapphire
  - Low absorption
  - Low scattering
  - **Low birefringence**

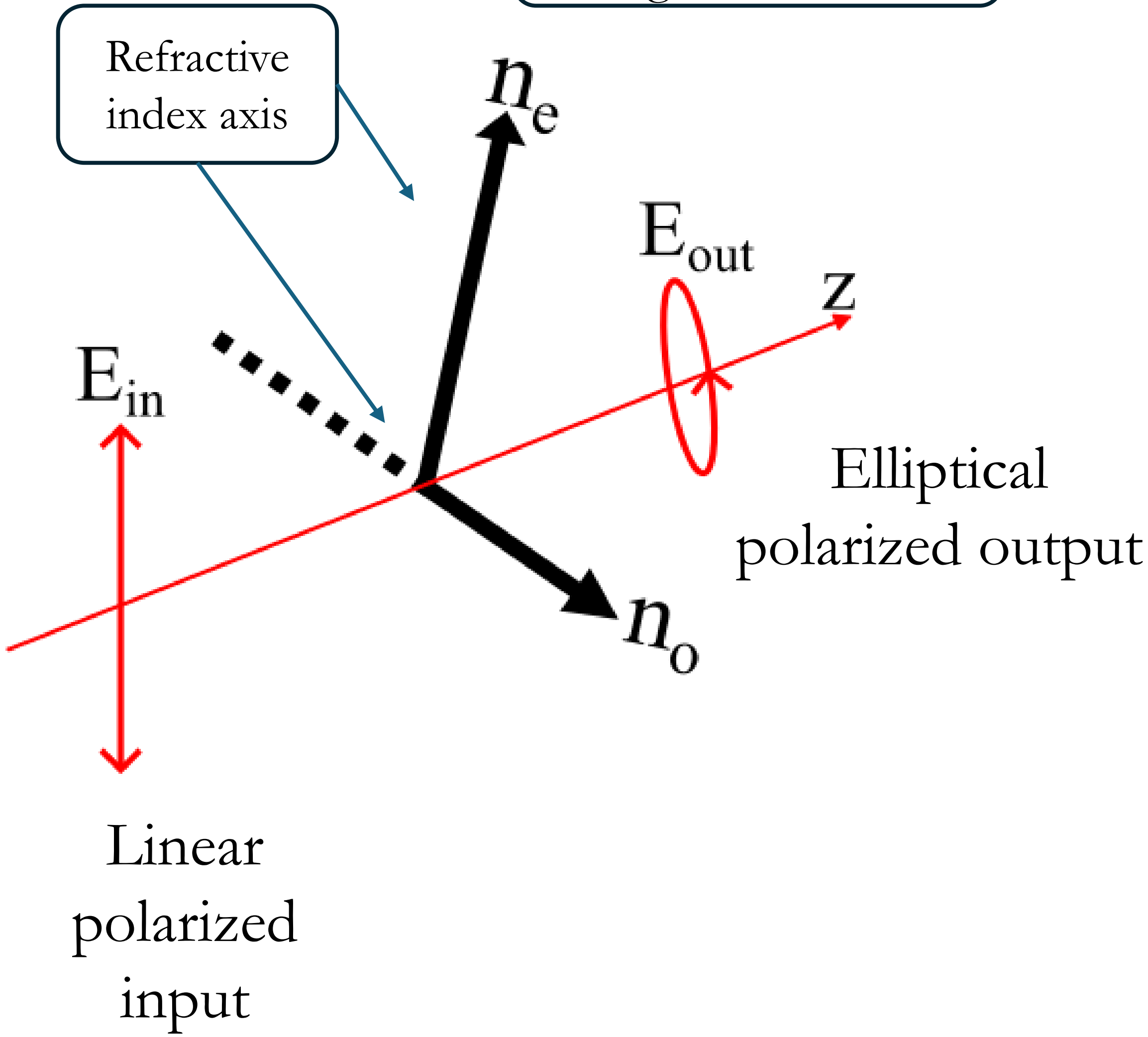




What is Birefringence?

$\boldsymbol{\Delta n = n_e - n_0}$

Δn can be positive or negative.

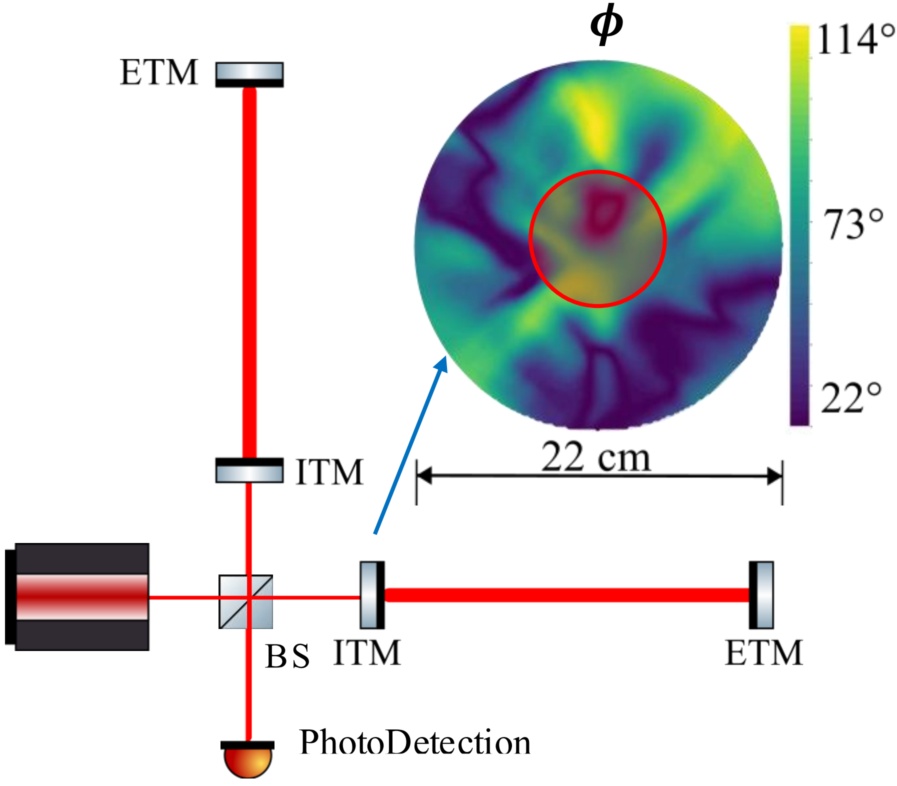


Retardation: polarization-dependent change in phase, $\phi \propto \Delta n d$.

Diattenuation: polarization-dependent change in amplitude

Why study Birefringence?

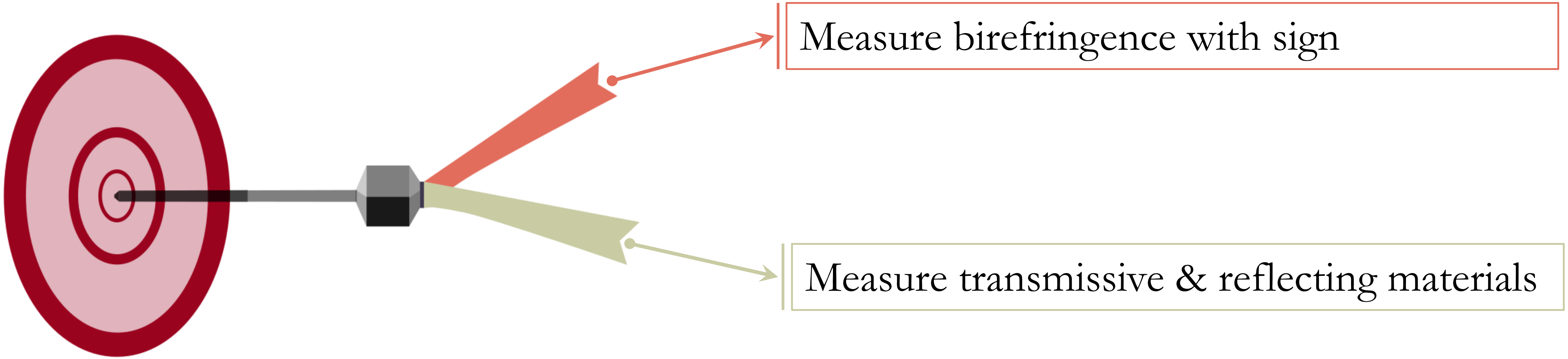
- The current Sapphire test masses in KAGRA have imperfections
- Non-uniform birefringence can spoil sensitivity of KAGRA
  - Increase quantum noise (by 16% at high frequencies),
  - Decreased contrast defect & increase technical noise (by factor 10),
  - Reduced duty cycle.



- A real time monitoring of birefringence in KAGRA is required as the laser beam moves on the test mass.
- Birefringence characterization is required for new test mass of KAGRA.

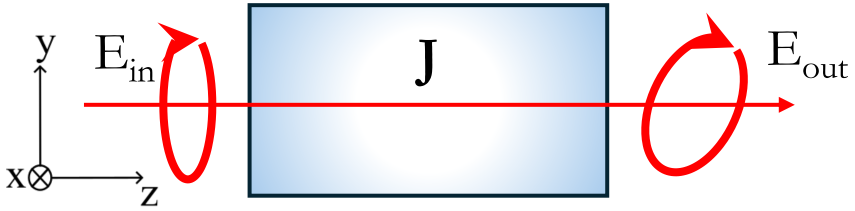
Part 1: Complete birefringence characterization

Motivation: Know birefringence better to choose the best mirror



Jones Calculus

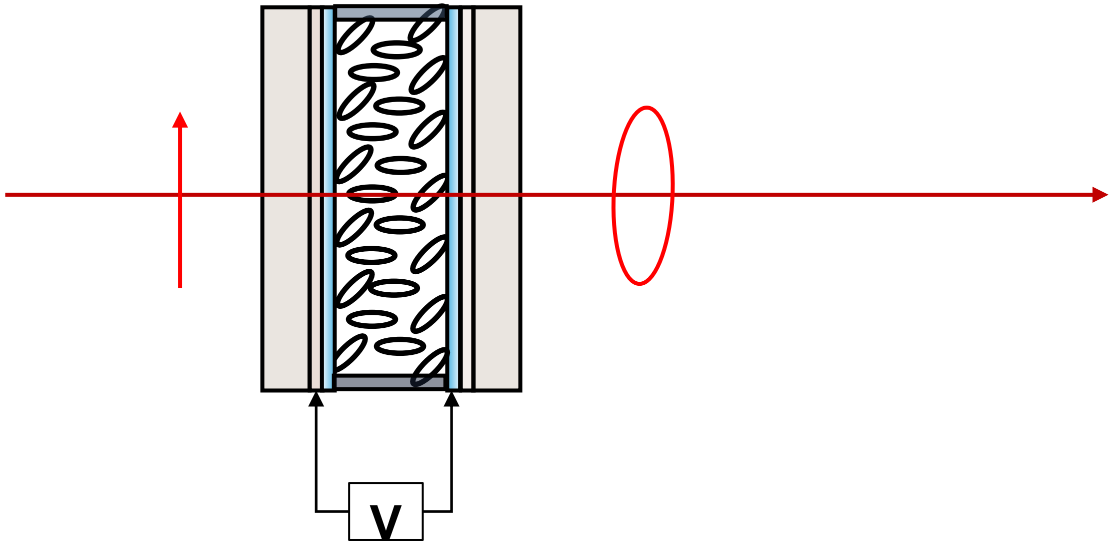
- Any polarization can be represented in vector form as, $\begin{pmatrix} E_x \\ E_y \end{pmatrix}$
- Polarization elements can be represented using Jones matrix, $J = \begin{pmatrix} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{pmatrix}$
- $E_{out} = J \cdot E_{in}$



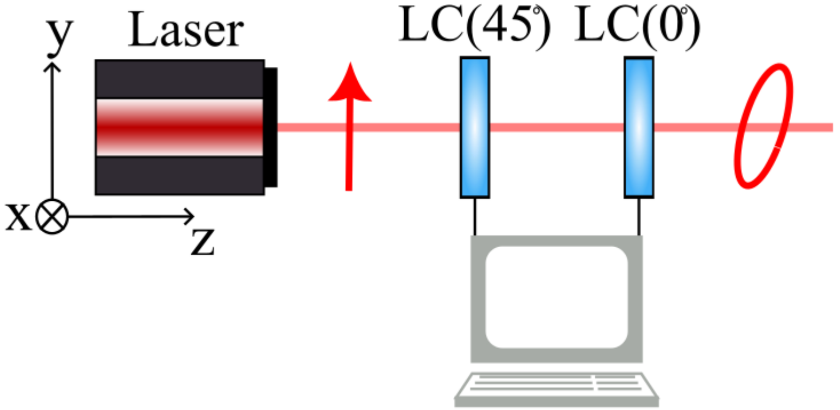
- Jones matrix contains all information on complete birefringence.
- Jones matrix has 4 unknowns, so two input and output measurements are needed.
- Measurement of several arbitrary input and output polarizations provide good estimation of the Jones matrix.

Polarization Generation

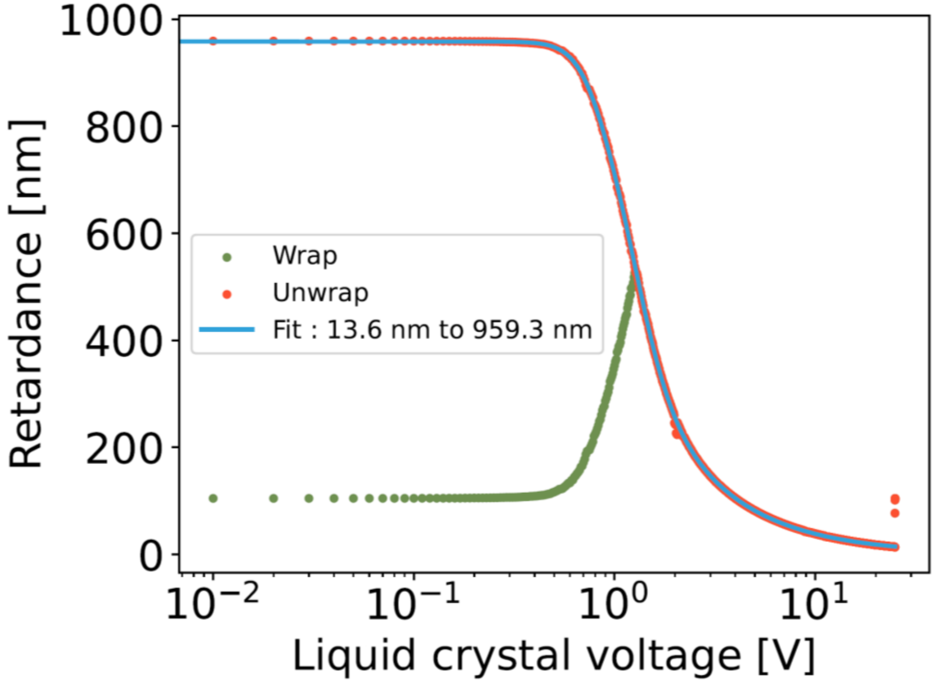
Liquid crystals (LC) are voltage-controlled retarders. They are commonly used in display monitors.

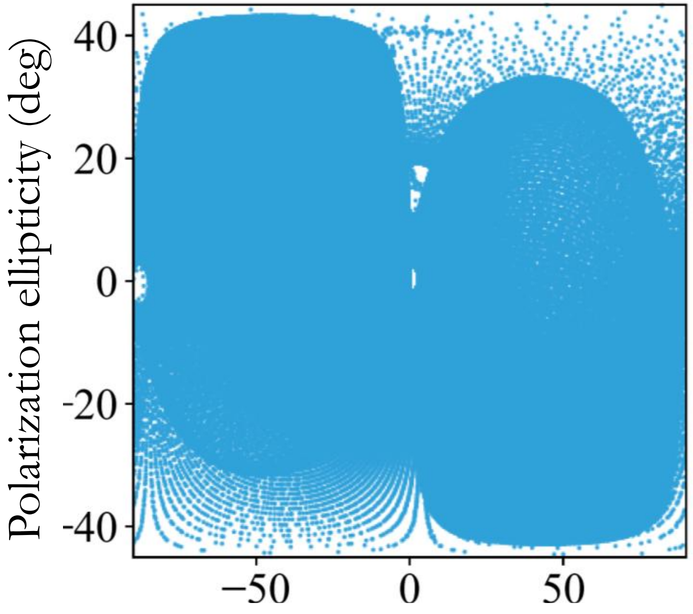


Retardation control using one liquid crystal

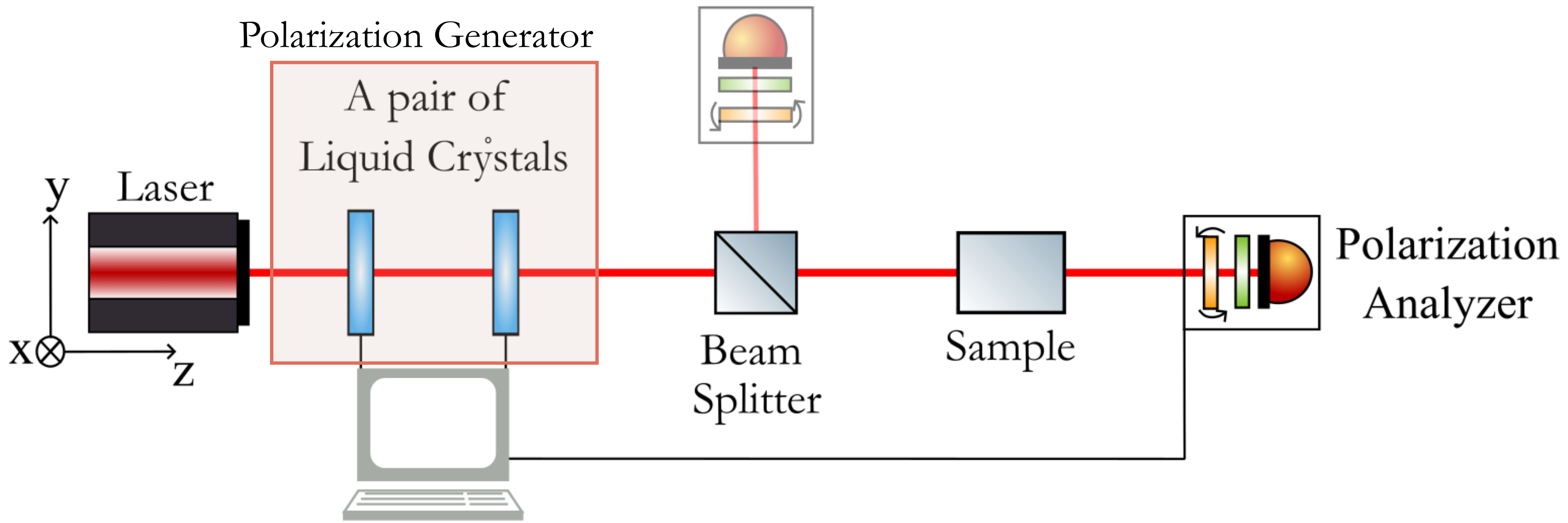


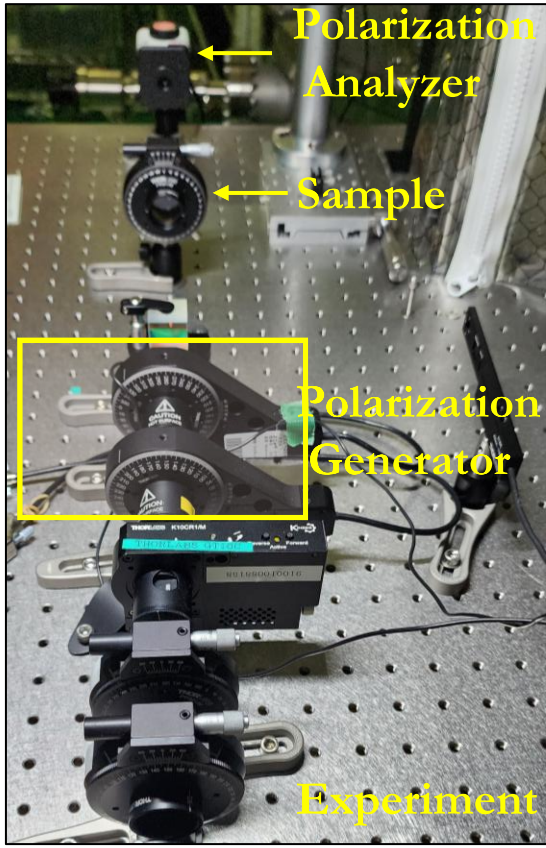
Polarization control using a pair of liquid crystals.





Generating & Measuring Arbitrary Polarization

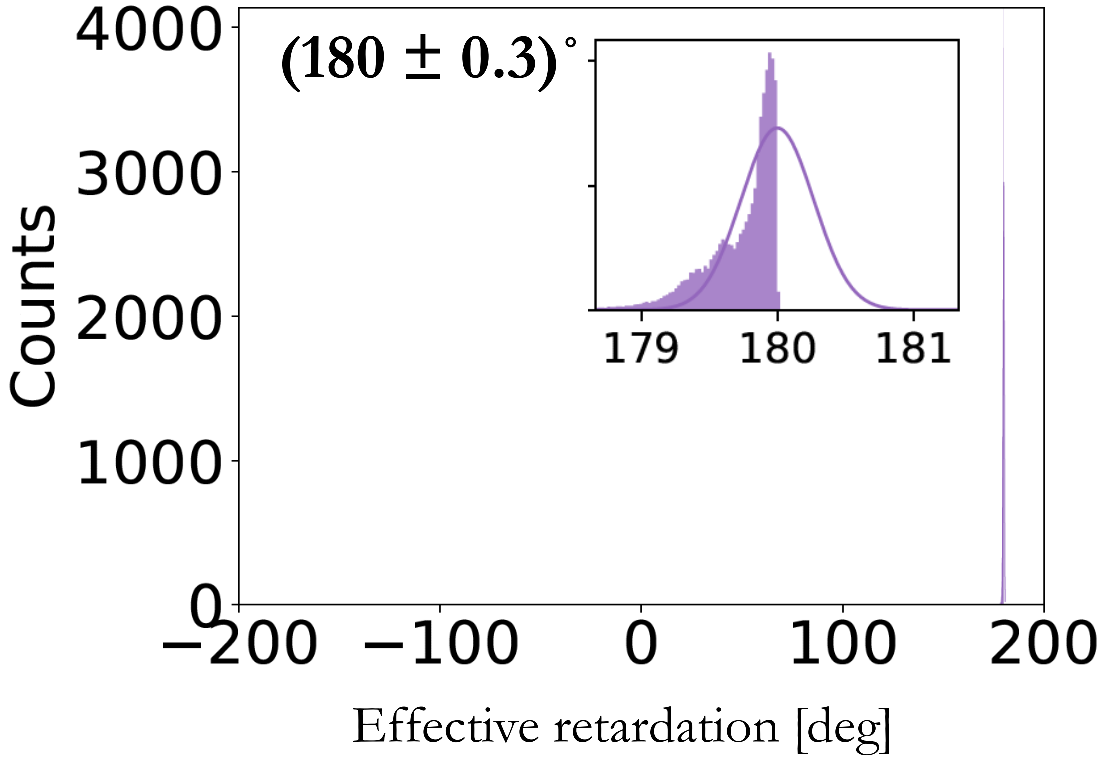




- Measured polarization optics: Half-wave plate, polarizer, beam splitter, dielectric mirror.
- The measurement technique was later adapted to make birefringence maps using translation stage.

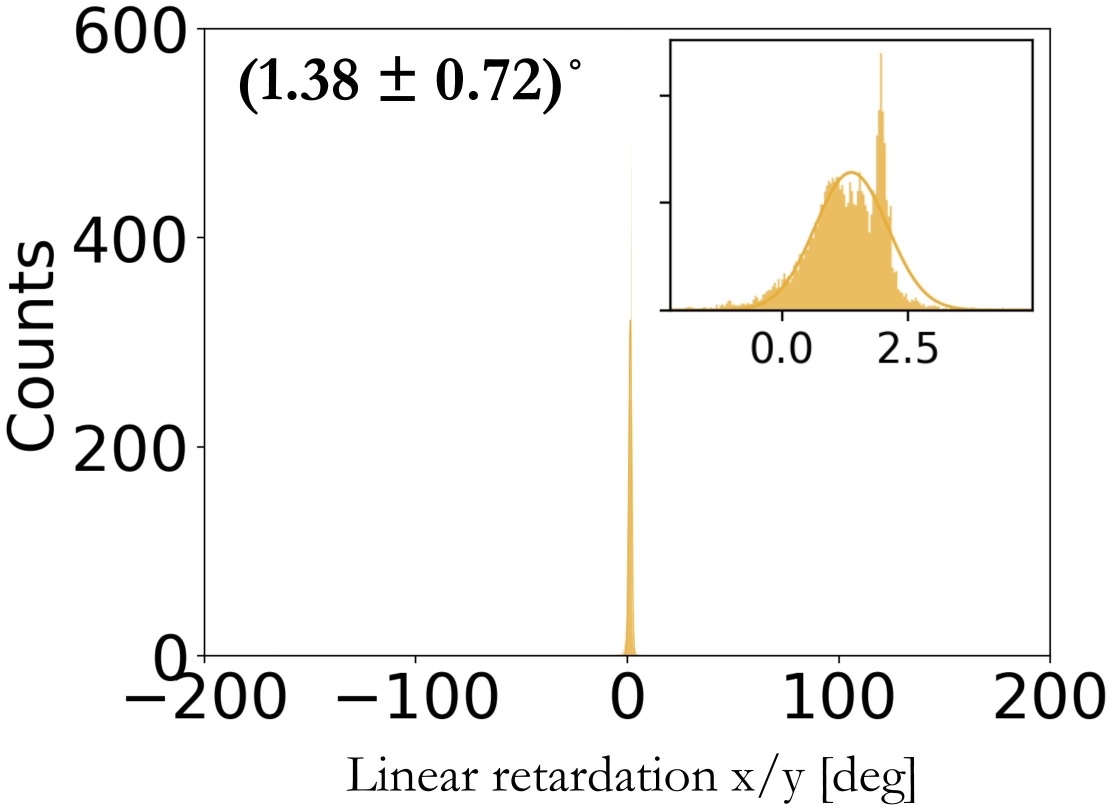
'Complete birefringence and Jones matrix characterization using arbitrary polarization'. *Optics Express, 2025.*

Half-wave plate



In agreement with manufacturer

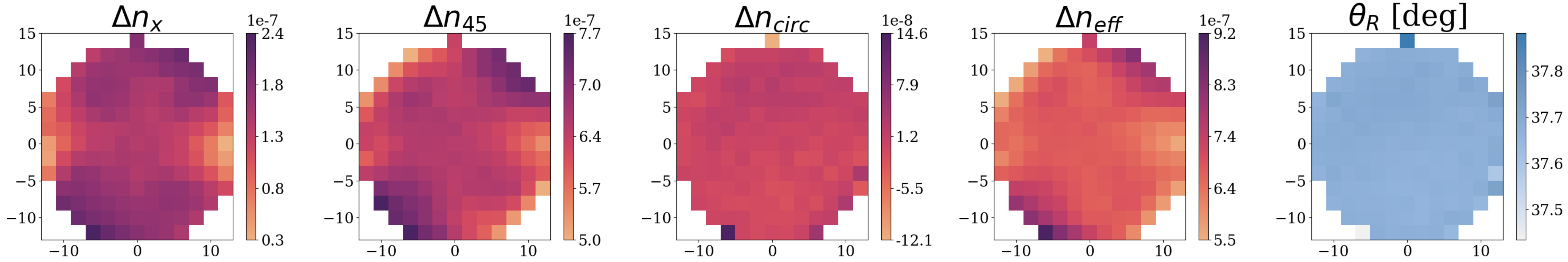
Dielectric mirror



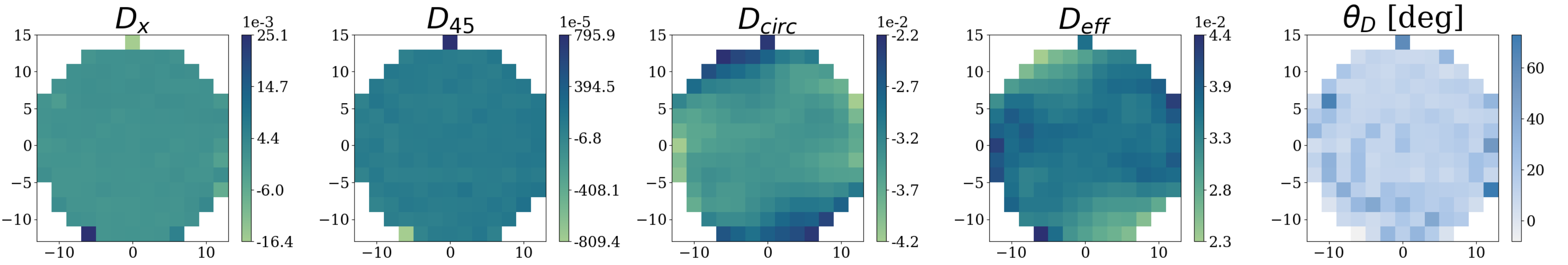
In agreement with Univ. of Florida measurement

Sapphire, 30mm(diameter.)-20mm(thick)

Retardation



Diattenuation



Part 1: Summary

Developed Polarization generator

Developed analysis to get Jones matrix & complete birefringence

Measured with transmissive & reflective sample

Measure birefringence with sign

Measure transmissive and reflective materials

More retardation and diattenuation information than before

Measure birefringence of polymer

'Programming the Photoelasticity of Hydrogels for Label-Free Mechanosensing by a Simultaneous Birefringence-Stress Reader (SiBRe),' ***Chem. Commun.***, 2026

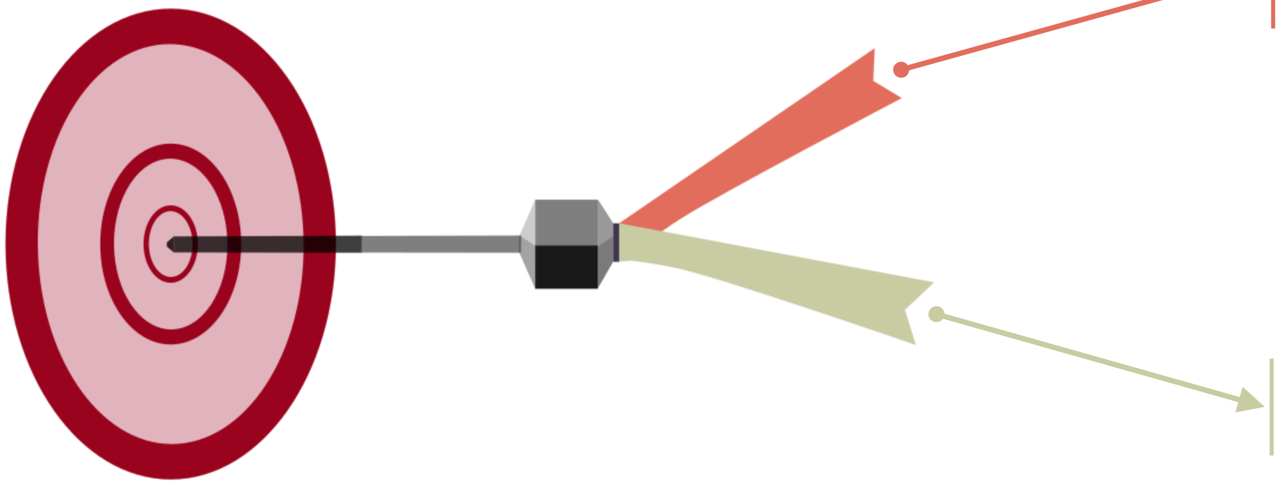
Understand origin of non-uniform birefringence

Applications of Complete birefringence

Measure birefringence of KAGRA input test mass

Part 2: Polarization control at MHz speed

Motivation: Prepare for real-time birefringence monitoring in detector.



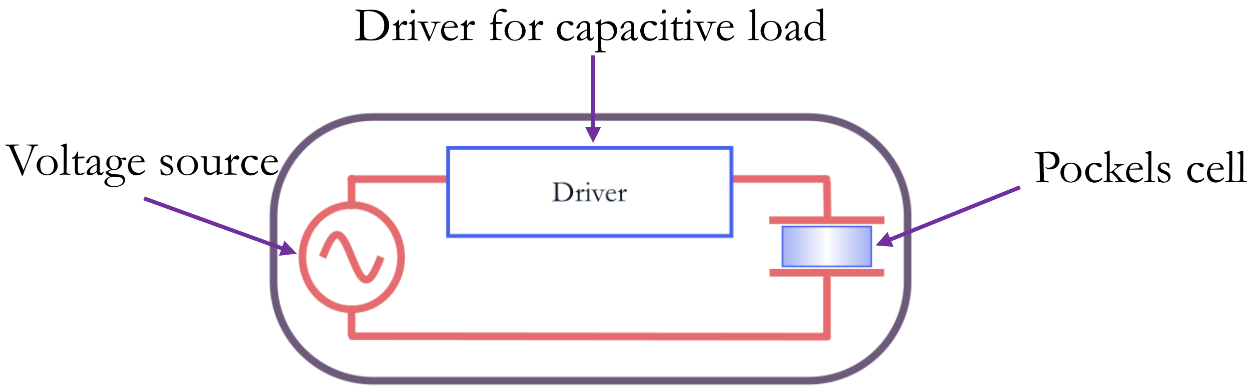
Increase speed of retardation generation

Increase stability

Pockels cell

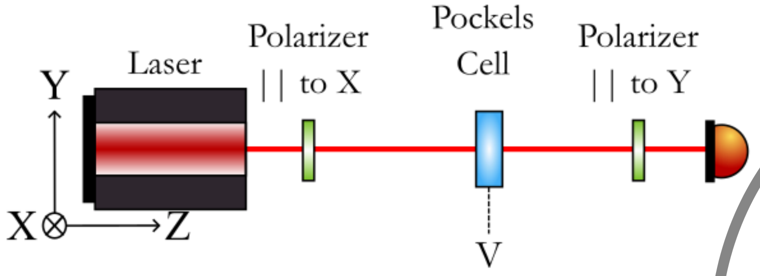
- Electrooptic crystal that can be actuated at MHz speed. Increase in speed leads to faster measurement with more statistics.
- It can tolerate higher laser power ($4W/mm^2$). Increase in laser power helps to increase the sensitivity of measurement.
- It has stable response in comparison to Liquid Crystals over long periods of time.

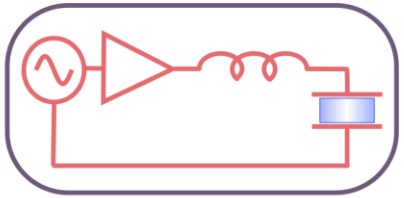
- Pockels cell need 420V to produce 180° (π) retardation.



- Having large retardation range offers large variety of polarization generation.
- A custom driver is required to provide large voltage at MHz.

High Voltage Driver

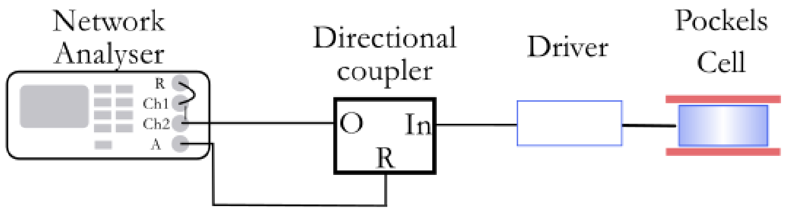




Circuit

Impedance

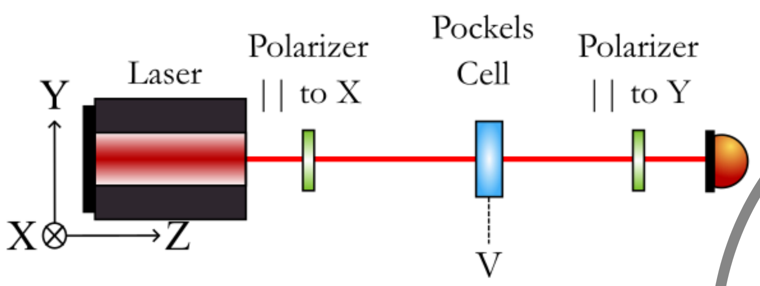
To reduce loss at resonance
Re(Z)~50Ω & Im(Z)~0



Optical Response
[To see ~180˚]

High Voltage Driver

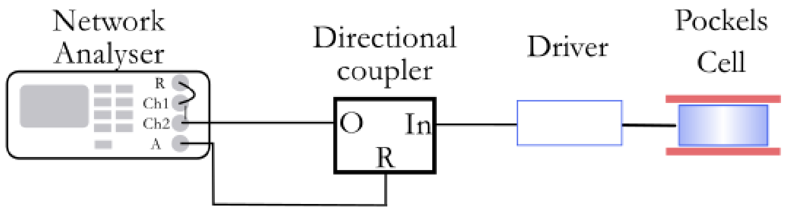
- Different Opamps:
  Low voltage, high current
- Different Inductor:
  Lead, Air core
- PCB design



Circuit

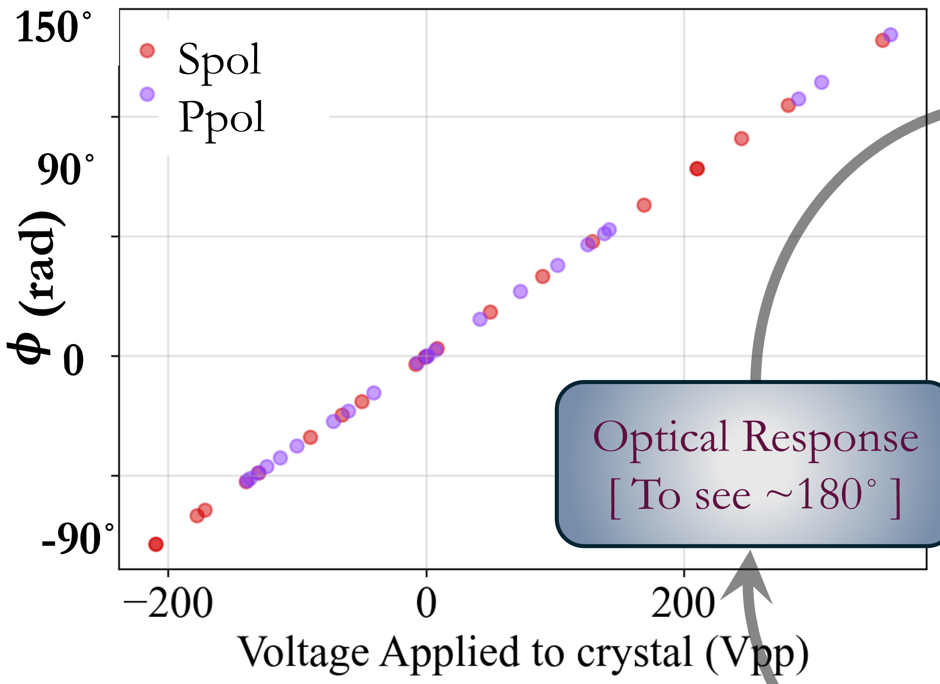
Impedance

To reduce loss at resonance
$Re(Z) \sim 50\Omega$ & $Im(Z) \sim 0$



Optical Response
[To see ~180˚]

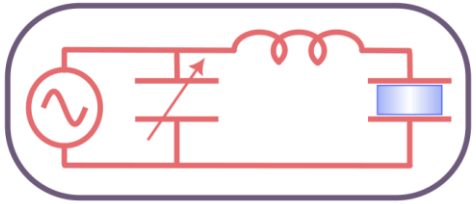
High Voltage Driver

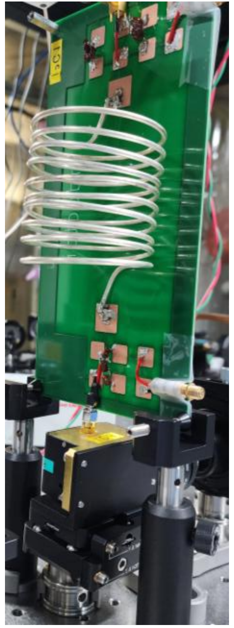


Circuit

Impedance

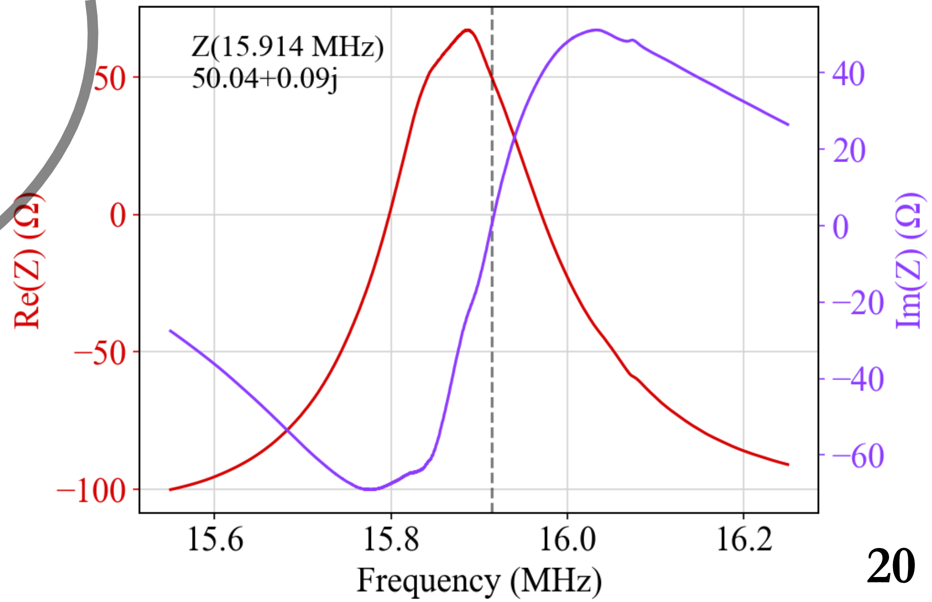
Optical Response
[To see ~180°]





Air-core inductor with Pockels cell

To reduce loss at resonance
Re(Z)~50Ω & Im(Z)~0



Part 2: Summary

Developed driver for Pockels cell

Optimized driver components to achieve >350 V at 15MHz.

Tested Pockels cell to generate >150° retardation

Stability increased by using Pockels cell

Large Retardation generation at MHz speed

Measure birefringence fluctuations

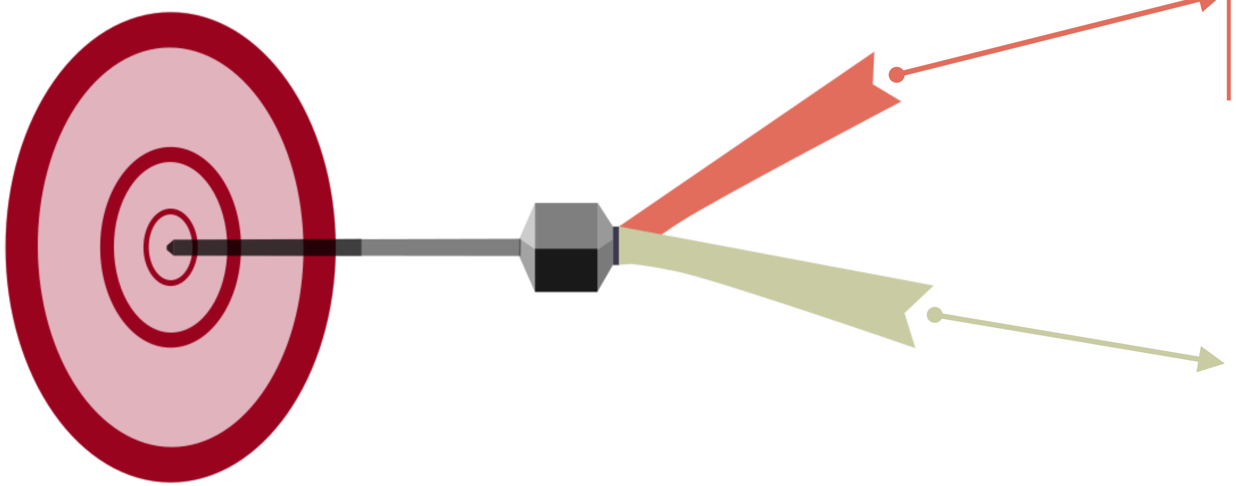
Real-time birefringence monitoring in KAGRA

Applications of Pockels cell

Measure birefringence of future-generation of coatings

Part 3: Birefringence Compensation

Motivation: Birefringence compensation of test mass in detector

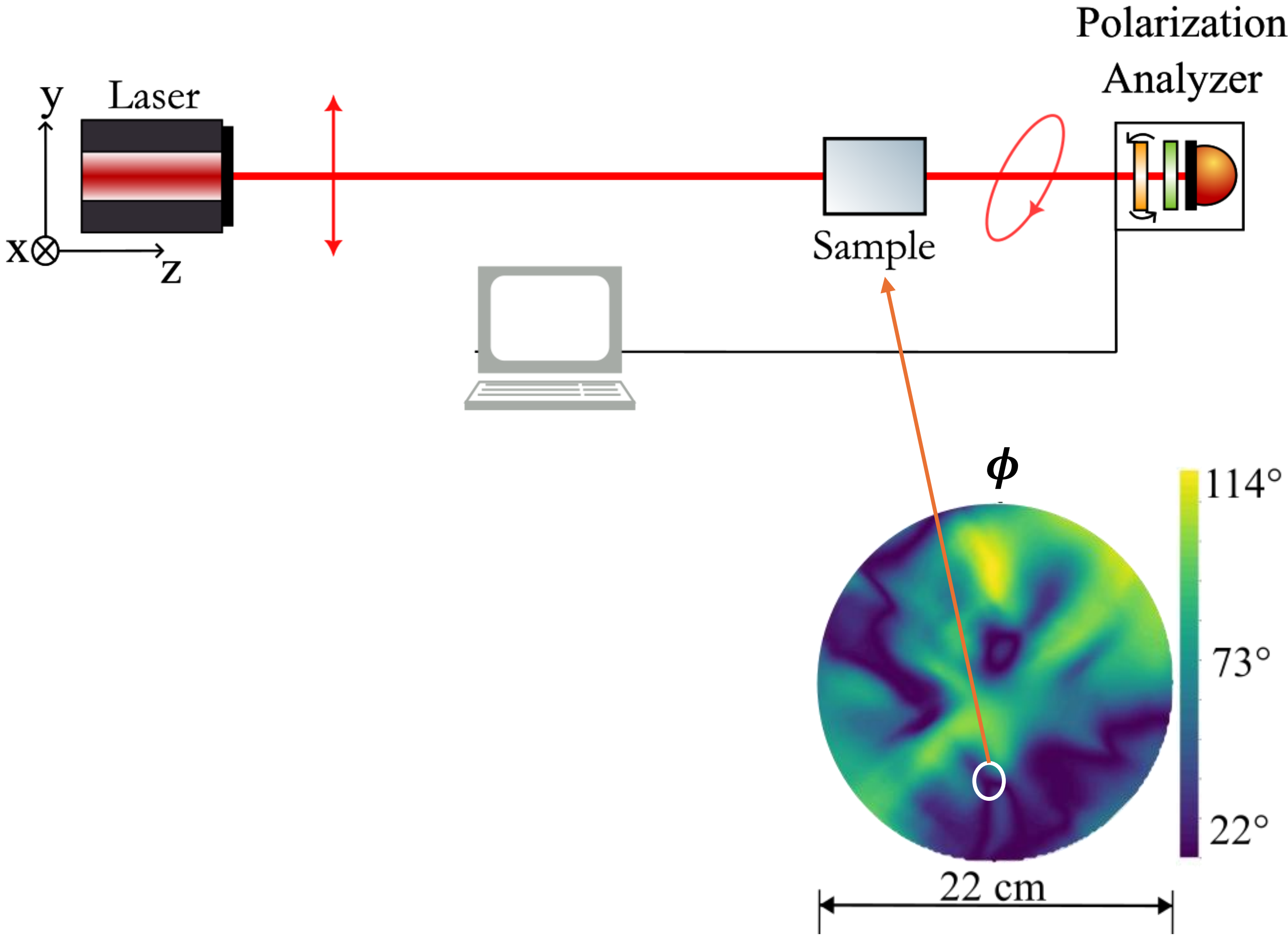


Demonstrate birefringence compensation using polarization generator in 1D.

To identify the material compatible for use in detector for 2D compensation.

1D Birefringence compensation with Liquid Crystals

- Birefringent sample changes the polarization.
- Polarization can be recovered using polarization generator before the sample.
- Liquid crystals' voltages are scanned to produce linear polarization after the sample.



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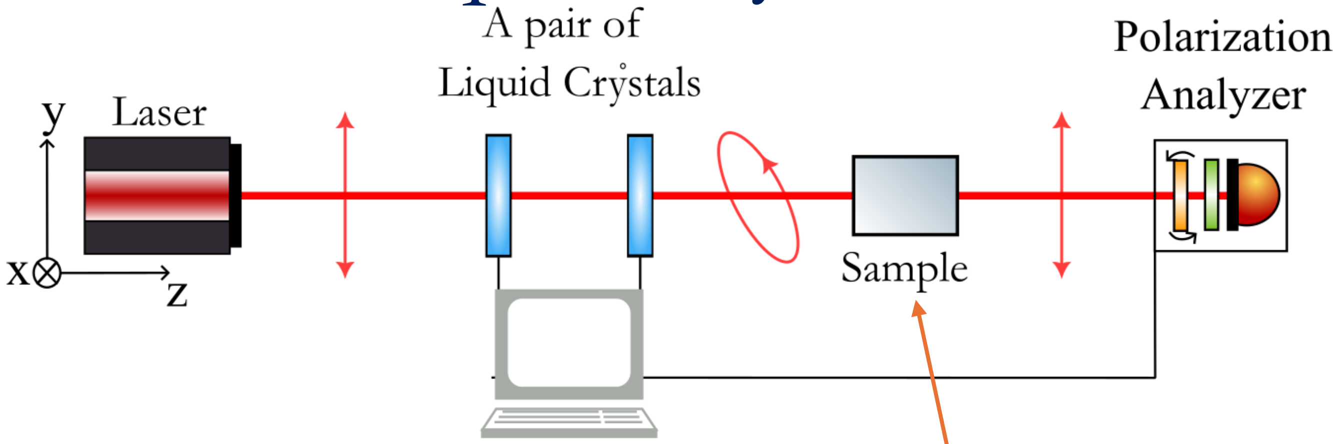
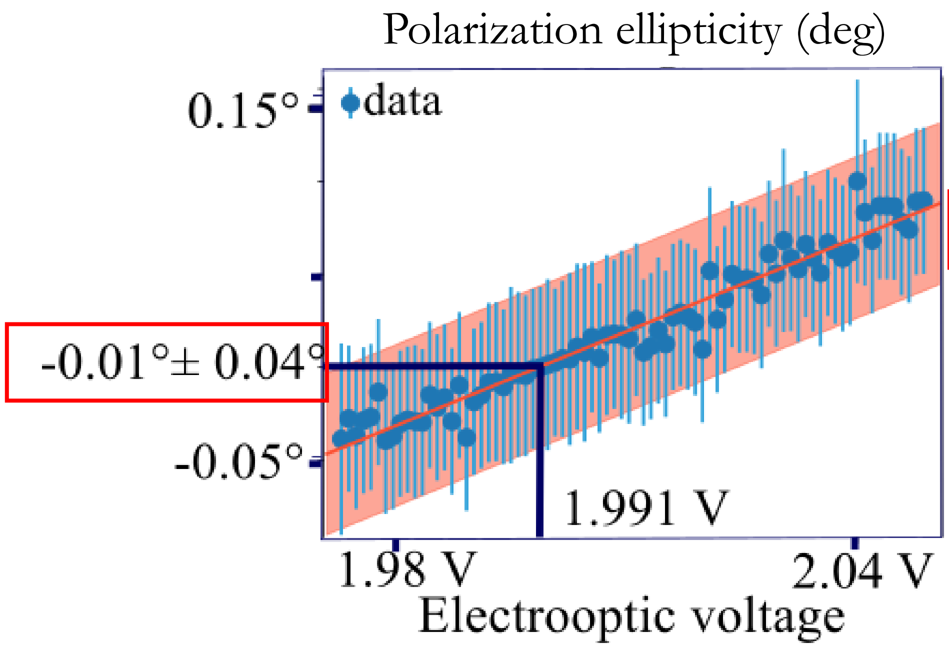
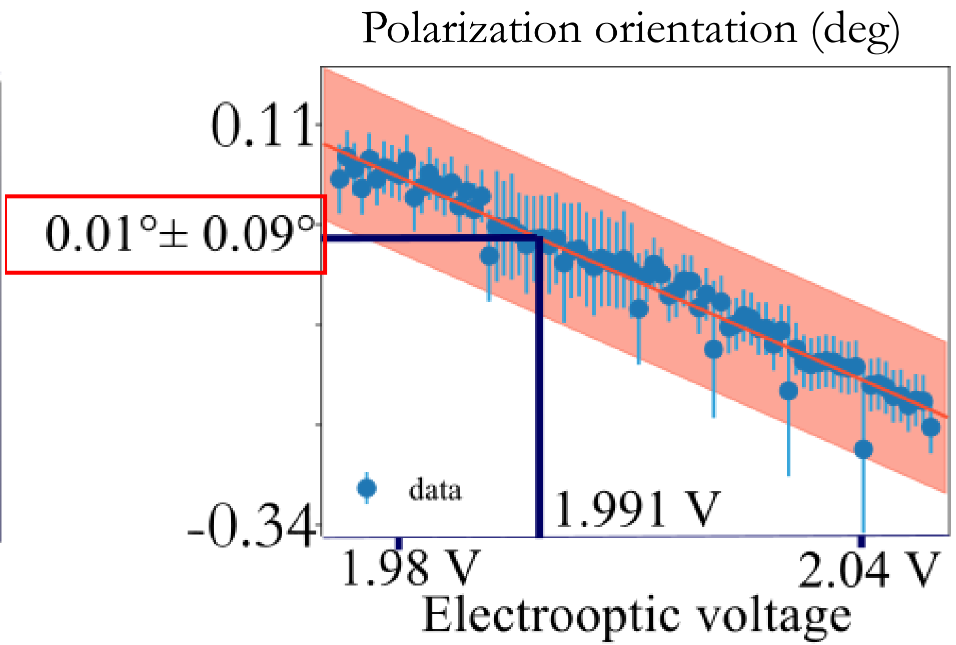
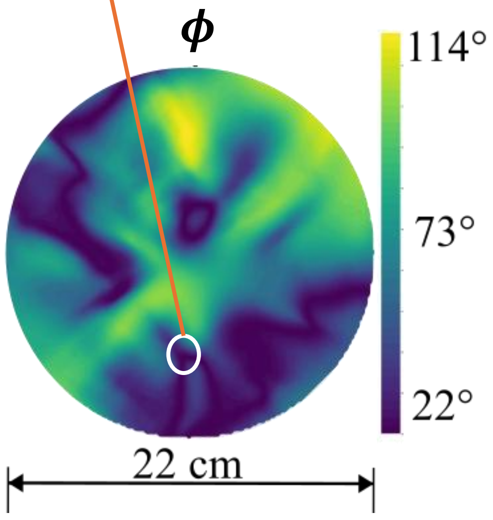






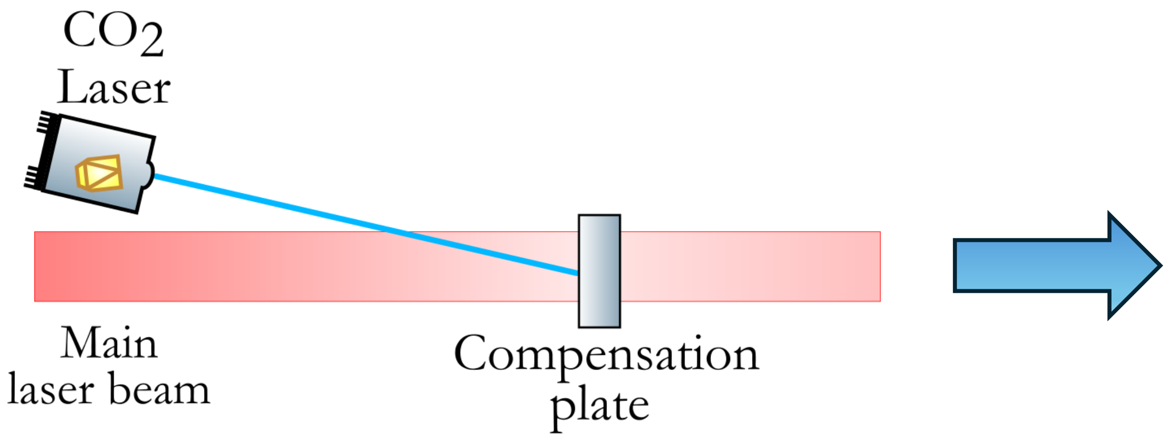


'Birefringence compensation method of test-mass substrates for gravitational wave detectors with arbitrary polarization states.' *Optics Letters, 2024.*

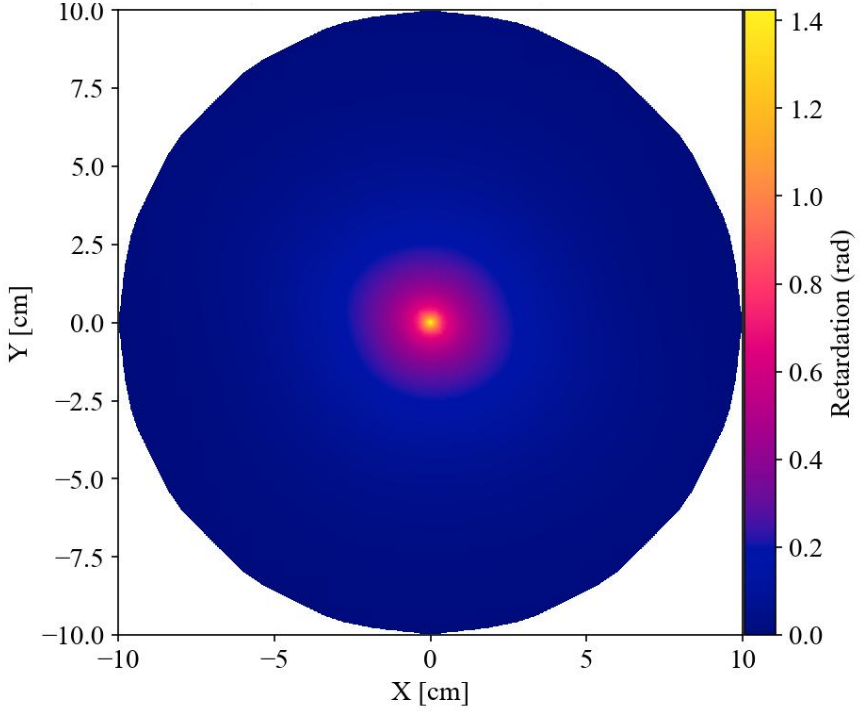
2D Birefringence compensation with Temperature Actuator

- Heat a material → main laser beam experiences birefringence due to
  - Thermorefractive effect (change in refractive index)
  - Thermoelastic effect (change in thickness)
  - Photoelastic effect (Stress induced)

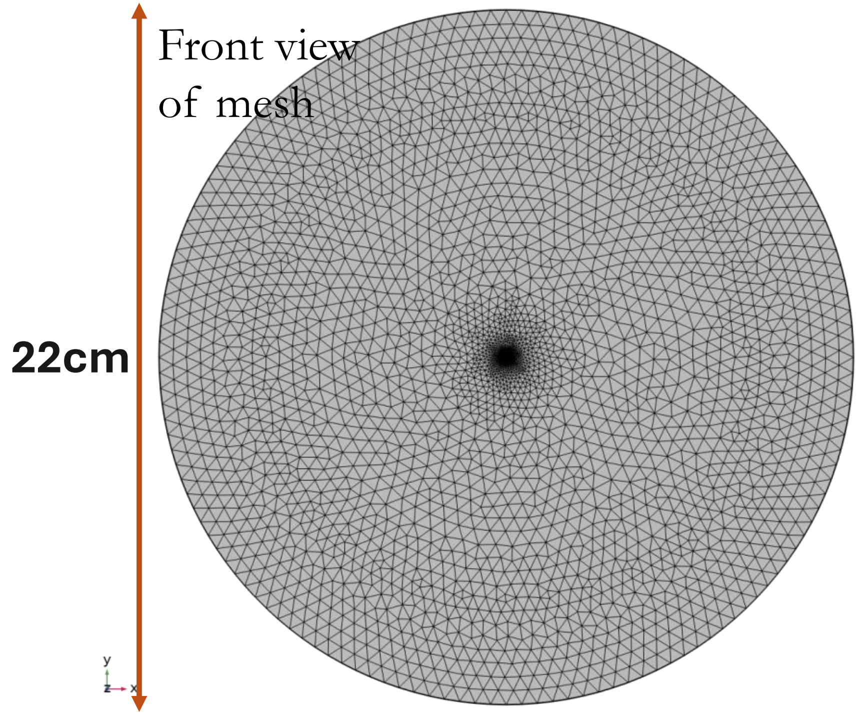
- Optimal material:
  - Can tolerate high laser power,
  - Low loss
  - Can offer large actuation on retardation with CO_2 laser.

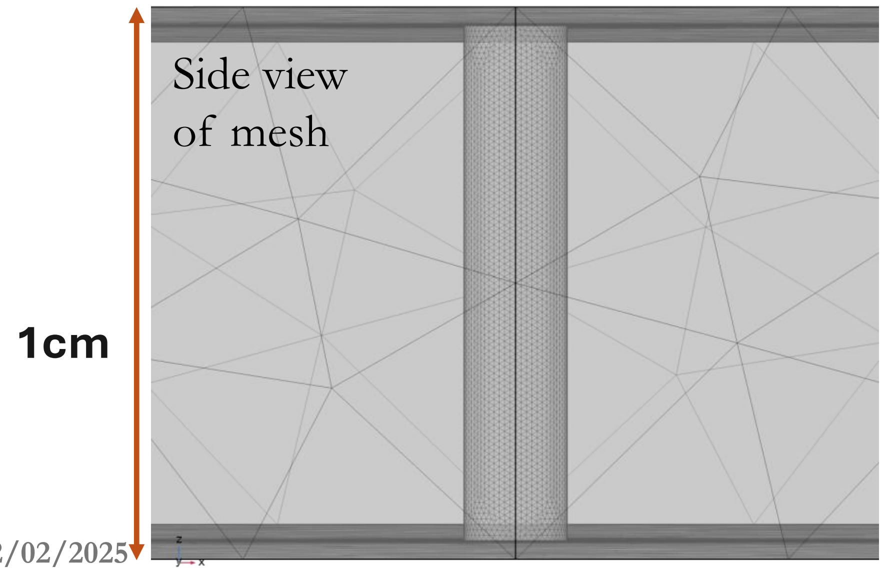


Main laser beam experience change in phase at the center



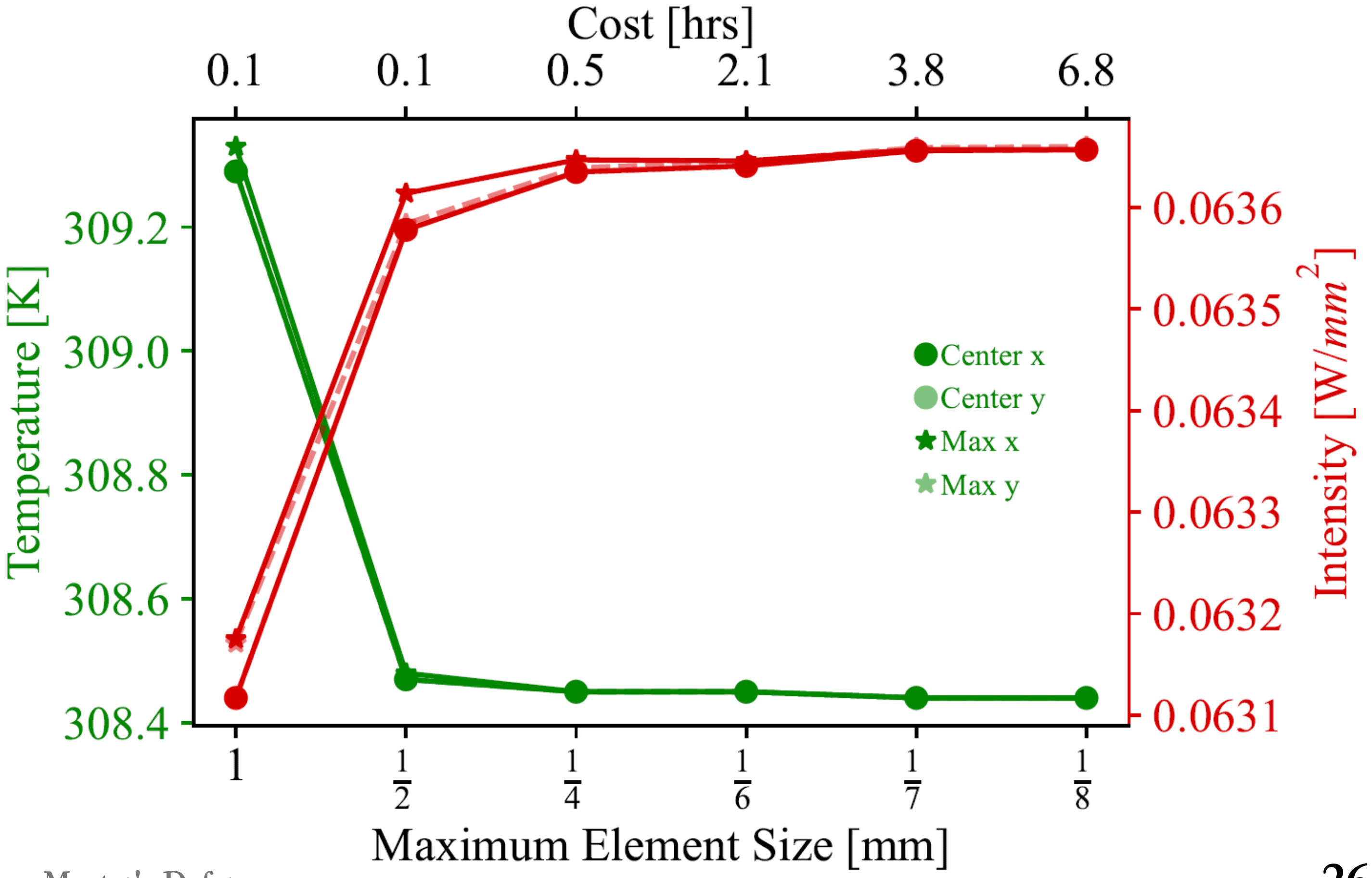
Finite Element Modeling to find optimal material





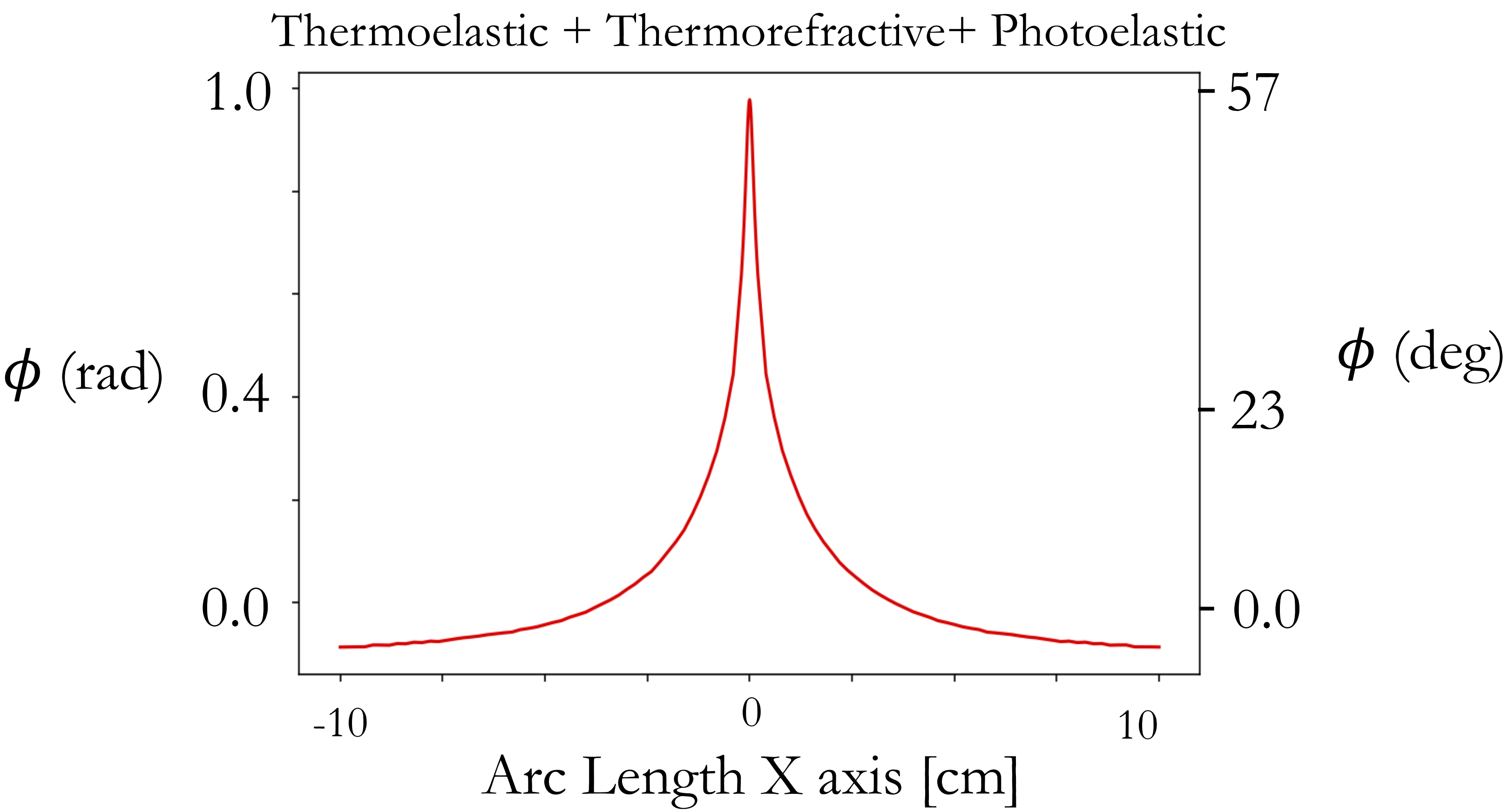
- Mesh optimized to have best prediction of temperature & intensity, on the front surface and thickness

- Optimization shown on front surface [calcite with 0.1W/mm^2 CO_2 laser]



Actuator response with 0.1W/mm^2 CO_2 laser

- Compared response of 7 crystals
- α-Barium Borate can generate 1 rad with 0.1 W/mm^2 .
- α-Barium Borate exhibits 5000 ppm/cm loss and damage threshold of 1GW/mm^2 for main laser.



Part 3: Summary

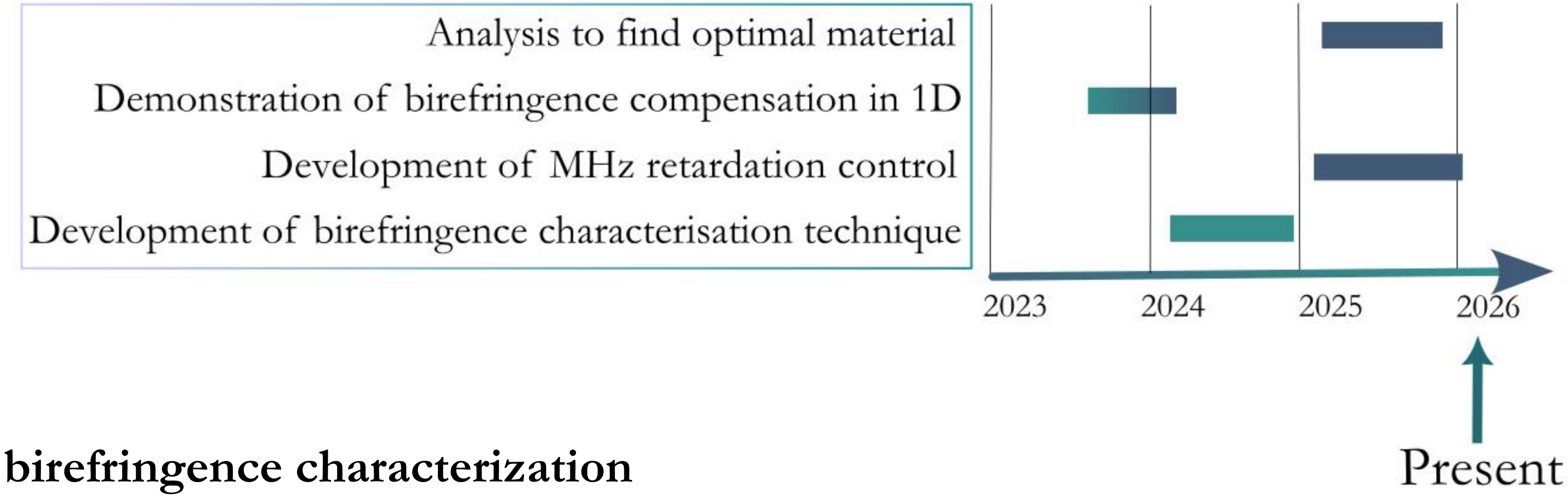
Demonstration of compensation in 1D → Analyzed several crystals to find the optimal one. → The material was purchased.

- Compensation demonstration in 1D
- Identifying material for compensation in detector in 2D

Future steps towards Compensation realization:

- Demonstration of non-uniform birefringence compensation
- Demonstration of non-uniform polarization generation
- Feasibility studies

Conclusion

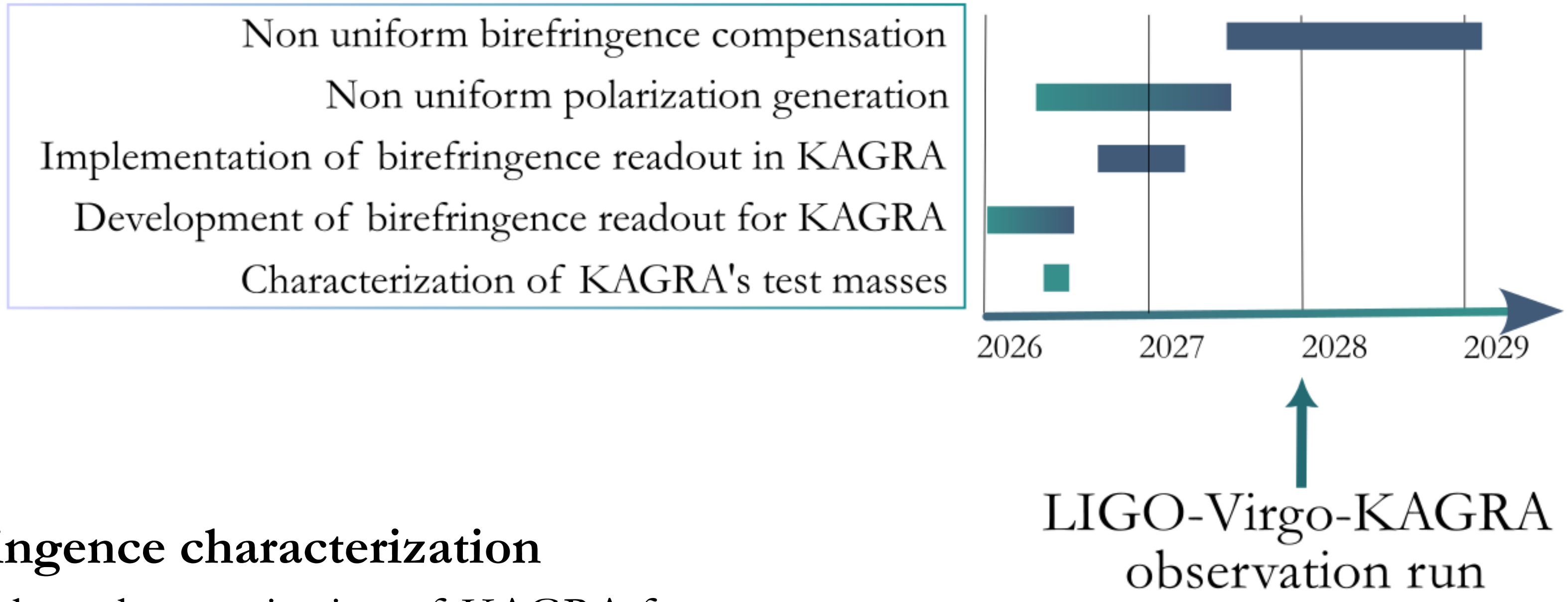


- **Part 1: Complete birefringence characterization**
  - Achieved development of characterization technique to get more information for transmissive and reflecting materials.
  - Two papers were published using this.

- **Part 2: Polarization control at MHz speed**
  - Achieved large range of retardation control at 15MHz using Pockels cell.

- **Part 3: Birefringence compensation**
  - Achieved 1D compensation using polarization generator. Additionally, found material for 2D compensation.
  - One paper was published using this.

Prospects



- **Part 1: Complete birefringence characterization**
  - Several applications such as characterization of KAGRA future test masses.
- **Part 2: Polarization control at MHz speed**
  - To develop birefringence readout for KAGRA and also measure birefringence fluctuations of materials.
- **Part 3: Birefringence compensation**
  - Demonstrate non-uniform birefringence compensation using the crystal.
- Help in utilizing potential of crystalline mirrors by addressing non-uniform birefringence.

Thanks for listening!