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Thermal conductivity measurements on sapphire as a thermally high efficient suspension material for 3rd generation gravitational wave detectors

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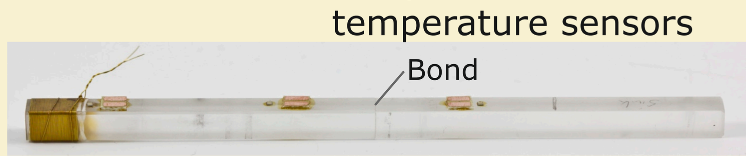
Motivation

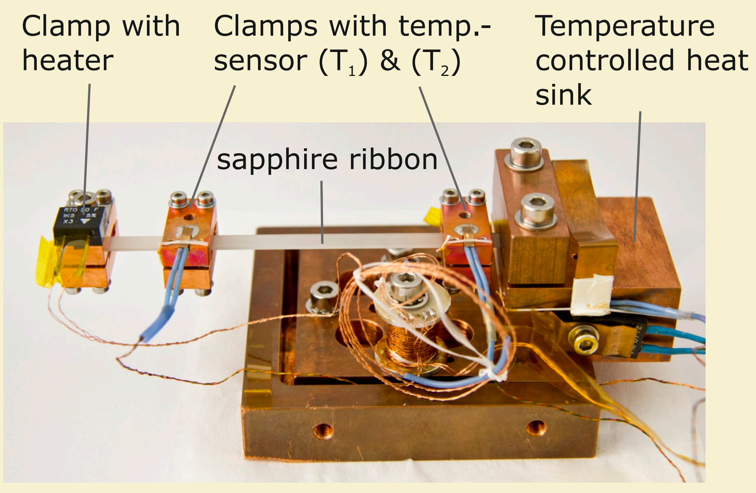
With the focus on its mechanical und thermal properties Sapphire is an appropriate suspension and optics material for 3rd generation gravitational wave detectors as KAGRA. In order to fulfil the desired thermal noise specifications not only low mechanical losses but also high thermal conductivity values of the optics and suspension parts are needed. Aiming at an optics operating temperature below 20 K an appropriate suspension design is of great significance allowing an effective heat extraction. As the shape of the suspension fibres restricts the feasibility of various surface machining techniques like grinding, lapping and polishing, we investigated the effect of different surface roughnesses on the achievable thermal conductivity values around the desired temperature range.
Beside surface effects, also different types of bonds to join suspension elements can limit the minimum operating temperature of the interferometer optics. Due to the impact of bonds on the overall thermal efficiency of the detector also the heat extraction through bond layers were part of our detailed investigations.

Experimental Setup

monolithic and non-monolithic prototype fibres with nail heads

HCB bonded sapphire sample with heater and temperature sensors

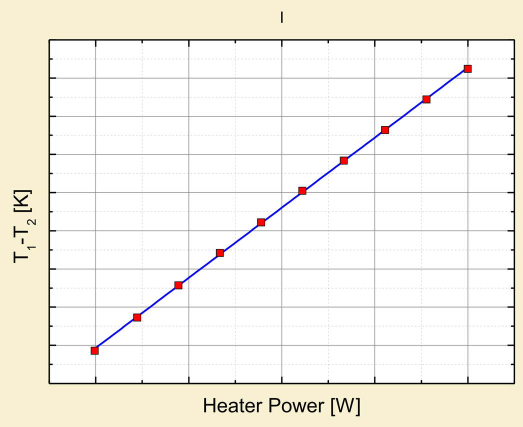




Assembled sample setup before mounting inside the cryostat

Measurement technique 1 - steady state:

#1 all temperature sensors in thermal equilibrium
#2 set a discret heater power and wait for thermal equilibrium of all sensors
#3 repeat #2 until a maximum desired temperature difference between T_1 and T_2 is reached
#4 plot T_1-T_2 vs. P_{Heater} + linear fit of the data



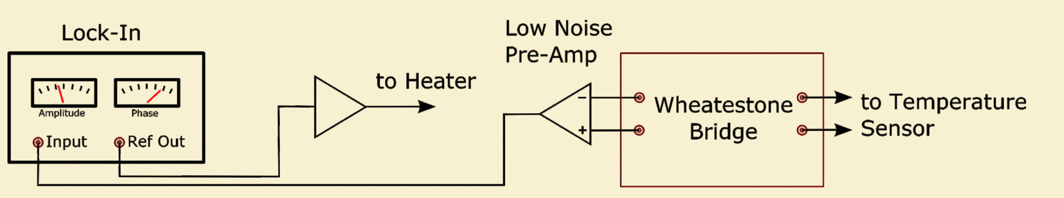
$$P = \frac{A}{L}\kappa\Delta T \quad \Rightarrow \quad \kappa = \frac{L}{A}\frac{dP}{dT}$$

P...electrical power
A...fibre cross section
ΔT..temperature difference
L...geometrical distance between temperature sensor T_1 & T_2
κ...thermal conductivity

Limits:
- high thermal conductivities resulting in small temperature differences between T_1 & T_2 being in the order of the sensor calibration accuracy
- low thermally resistive contact between sample and heat sink to avoid DC-heating

Measurement technique 2 - dynamic:

#1 all temperature sensors in thermal equilibrium
#2 drive heater with a harmonic current at a know frequency f_0
#3 measure phase shift Φ_1 between the heater voltage and the oszillating response of the temperature sensor T_1
#4 repeat #3 for sensor T_2
#5 calculate $\Delta\Phi_{exp} = \Phi_2 - \Phi_1$ as the phase lag between T_1 & T_2
#6 correlate $\Delta\Phi_{exp}$ with the thermal conductivity using FEA



Schematic of the excitation and read out setup to measure the phase lag between two temperature sensors

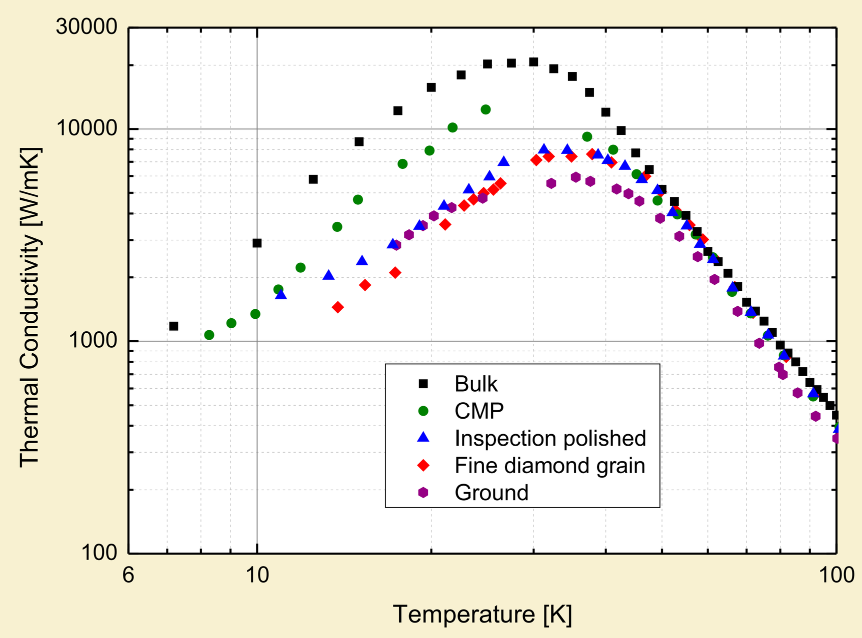
Limits:
- low thermal conductivities resulting in small temperature differences between T_1 & T_2 being in the order of the sensor calibration accuracy
- high thermally resistive contacts (sample -> heat sink, sample <-> T sensors, heater -> sample)

Current research focus on thermal conductivity:

- Investigation of the impact of different surface roughnesses (ground, lapped, inspection polished, chemo-mechanicaly polished)
- Comparison of κ for monolithic and non-monolithic fibres (possible influence of impurities below 30 K)
- Heat transition through material joints using different joining techniques between e.g. nail head and mirror (e.g. diffusion bonding, hydroxyd catalysis bonding, indium bonding)

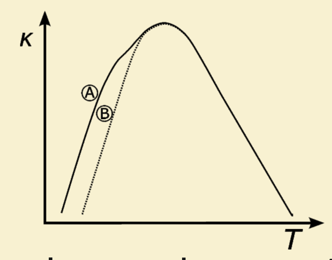
Experimental Results

- Effect of the Sample Surface



- sample geometry: 0.8 mm x 5 mm x 100 mm

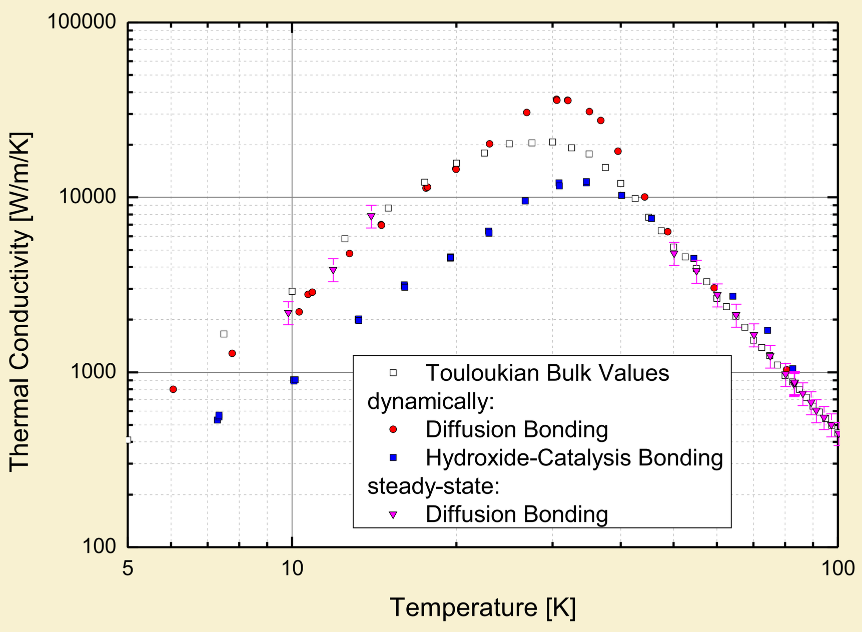
Scattering due to surface roughness:



sample roughness: A<B

Consclusion:
- relatively small effect of the surface roughness between 10 K and 30 K for roughnesses reaching from 20 nm to 3.3 µm
- significant improvements between 13 K and 30 K due to CMP polishing (but challenging on highly curved surfaces)

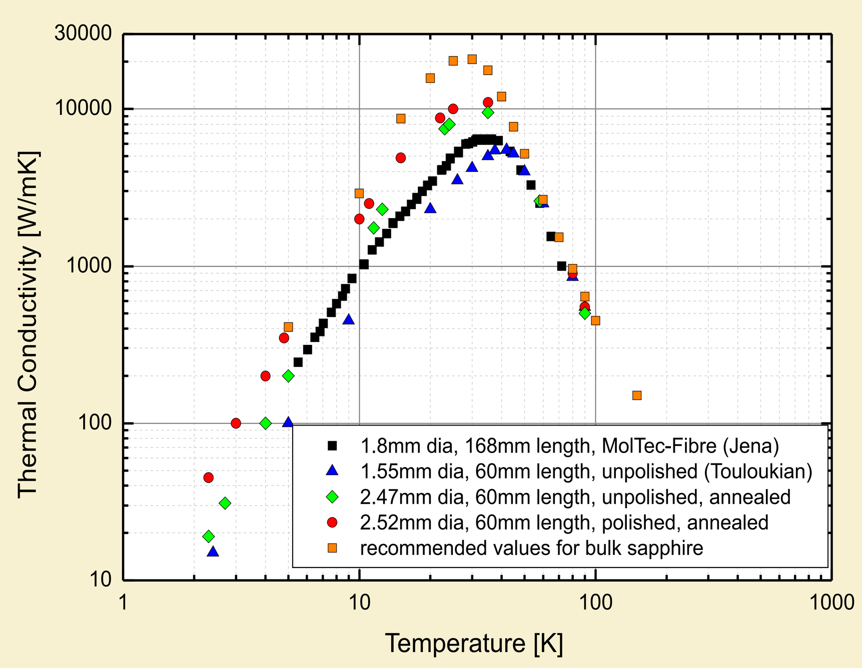
- Effect of Bonding



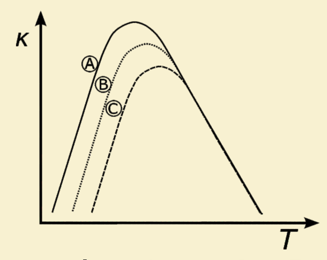
- sample geometry: 5 mm x 5 mm x 50 mm
- bonded on the 5mm x 5 mm surface which was polished to a flatness of λ/10
- confirmation of results using the steady-state and dynamic measurement method

Conclusion:
- no significant effect of the diffusion bond on the samples thermal conductivity
- preliminary measurements on a hydroxide-catalysis bonded sample reveal a possible reduction of the thermal conductivity ⇨ further studies are needed

- Prototype Fibre



Size effect:



sample size: A>B>C

Conclusion:
- the prototype fibres under investigation seem to be limited by their smallest geometric dimension
- most potential for heat extraction by increasing the fibre diameter due to mechanical feasibility (e.g. 2x fibre diameter results in ~ 8 times better heat extraction (factor of 2 from by the improvement of κ, factor 4 from cross section)

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