# Optical Characterisation of Nanofluidic Cavities for Experiments on Superfluids Under Confinement

William Cripps Dr. Lev Levitin

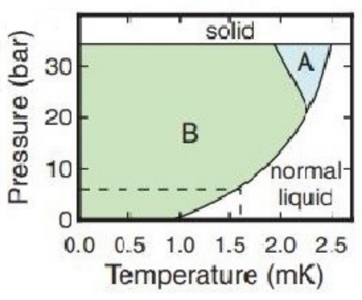
ROYAL HOLLOWAY UNIVERSITY OF LONDON

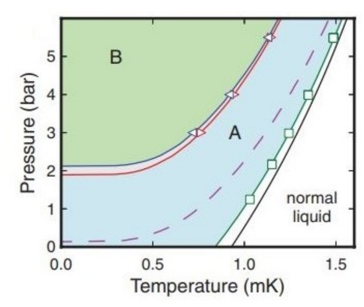
## Project Aim

**The aim of the project was to use the developed optical methods to fully characterise the depths of two nanofluidic cavities. The depths of both cavities were characterised at room temperature and one of them was also characterised at 80 K to investigate the possible thermal distortions that could arise.**

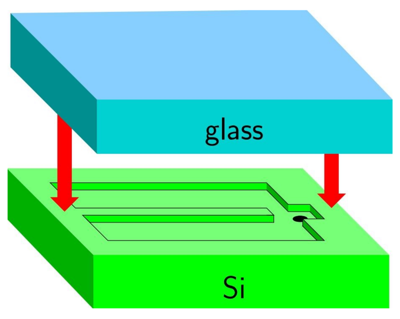
## Introduction

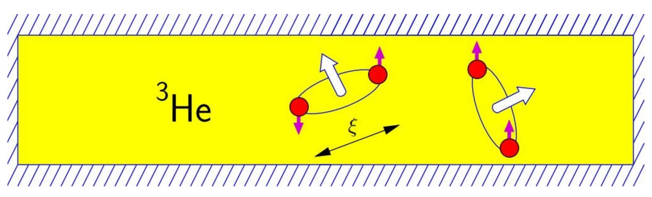
Fermionic liquids transition into a superfluid state through the formation of cooper pairs. The coherence length of these superfluids is much larger than that of conventional bosonic superfluids and is determined by the size of the cooper pairs. The properties of these superfluids can be changed by confining them in cavities where the depth is of the same order as the coherence length. In $^3$He there are two superfluid phases known as A and B which are shown in the phase diagrams on the right for bulk and confined helium. The bottom diagram shows how the confinement of the helium affects the phase boundary and allows the A phase to be accessed at low pressure.




The confinement is achieved through the use of nanofabricated cavities shown in the diagram on the bottom right. These are created by etching down into a silicon wafer and then bonding a glass wafer on top. The glass allows light to be used to measure the depth of the cavity but may create distortions in the cavity when it is cooled. This is because it has a different coefficient of thermal contraction at low temperature which could warp it or the silicon wafer.



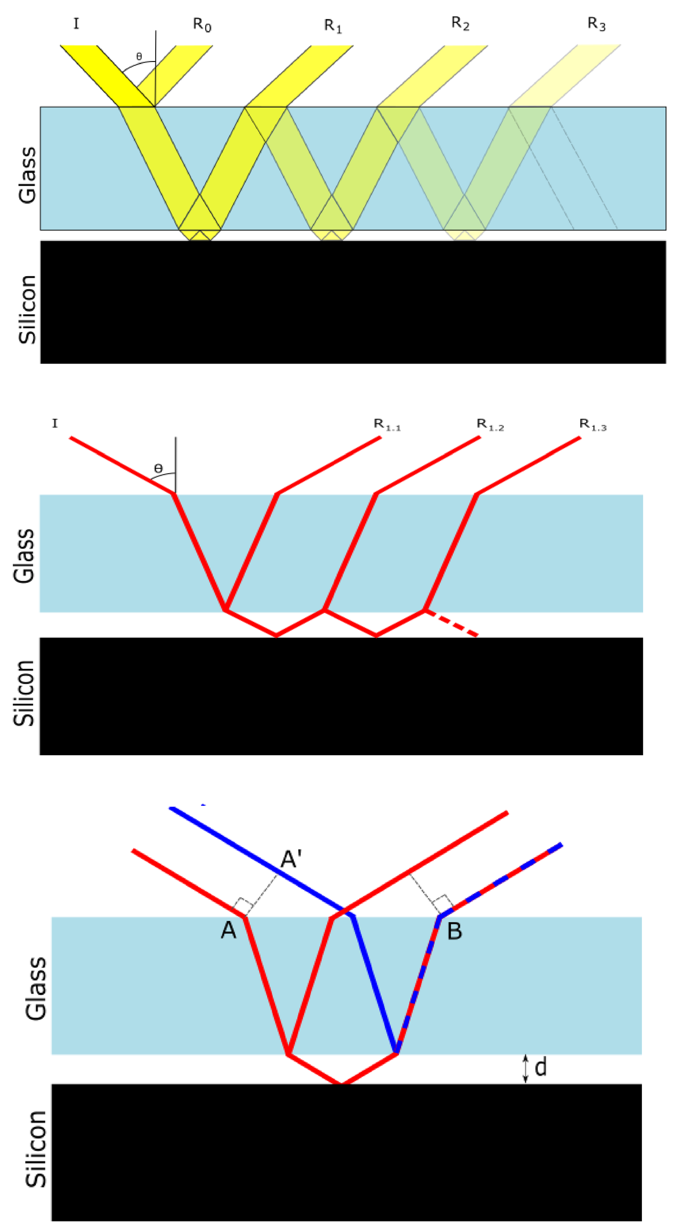




## Optical Characterisation

The reflection from a beam of light hitting the cell is made up of several parallel beams as there are different paths the light can take. The most important beam is $R_1$ as it interacts with the surfaces of the cavity and has the largest intensity. The different paths taken by light to form this beam are shown in the middle diagram. The phase of the light in $R_{1.2}$ will be shifted by π relative to $R_{1.1}$ as it is reflected at the air-silicon boundary. In the bottom diagram it is shown how the width of the incident beam leads to an overlap of these two components. There is optical path difference between the overlapping beams. This means that light with a wavelength that is an integer multiple of the optical path difference will be subject to destructive interference and their intensity in the reflected spectrum will be minimised. The minimised wavelengths can be used to determine the cavity using the equation

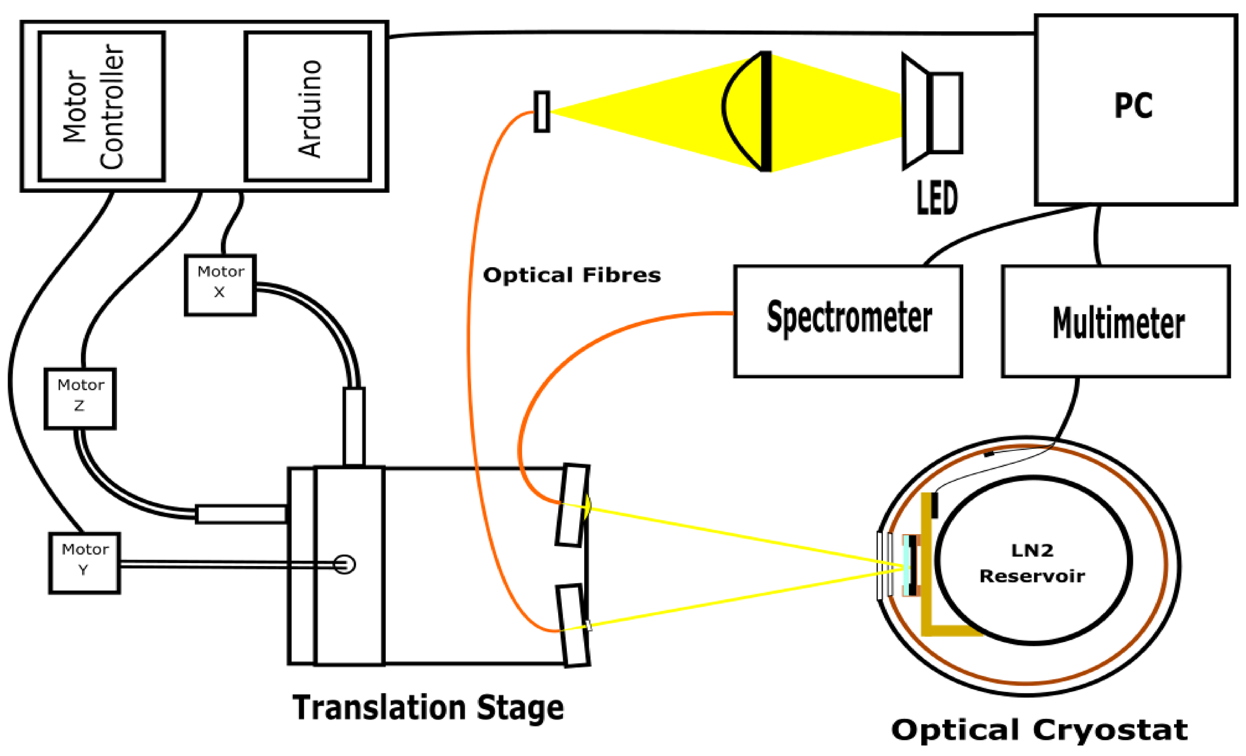
$$d = \frac{n\lambda_n^{min}}{2\cos\theta}$$

where $\lambda_n^{min}$ is the wavelength that is minimised because it is n times the path difference and θ is the angle of incidence of the beam of light.

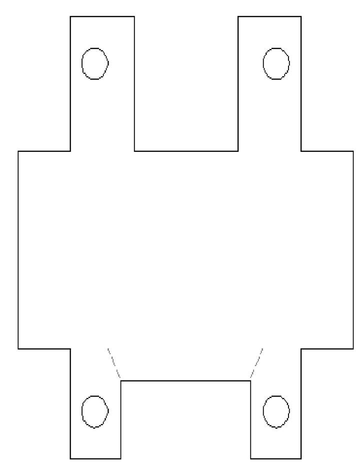


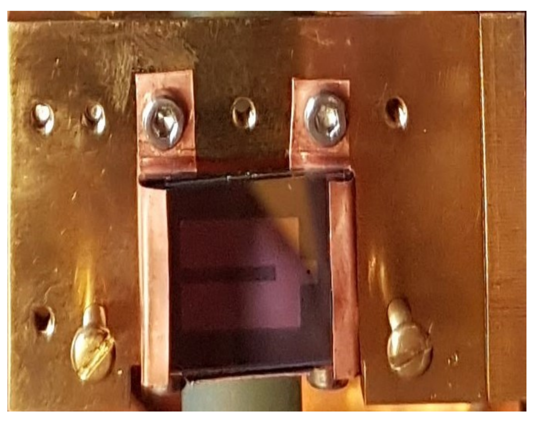

## Experimental Setup

To fully characterise the cavity there needs to be a depth measurement taken throughout the entire cavity. This was achieved by mounting some of the equipment on a motor controlled translation stage. The light source used was an LED lamp with a 'cold white' spectrum. The light was focussed into an optical fibre where it was carried to the translation stage, collimated and then sent to the cell. The reflection from the cell was then focused into a second optical fibre and input to the spectrometer for analysis. The movement of the translation stage was controlled by a python program that sent instructions to an Arduino that was connected to the motor controller. The distance moved in each step of a scan of the cavity was 0.25 mm as this was approximately the diameter of the collimated beam of light. The temperature of the set-up when cooled in the optical cryostat was inferred from measurements of the voltage across two standard signal diodes that were attached to the mounting bracket and the radiation shield.



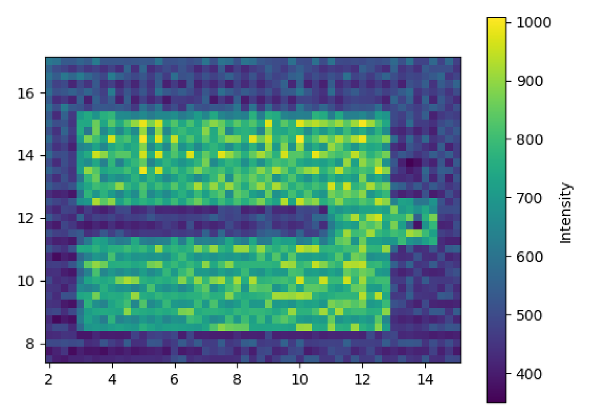

The cell was cooled by liquid nitrogen in an optical cryostat. However the cryostat used did not provide a suitable method for mounting the cell in view of the window. This meant that a bracket and cell holder had to be designed and fabricated so that the cavity could be characterised at low temperature. The main consideration for the design of the cell holder was for it to not constrict the movement of the cell during cooling. The final design was the template shown on the right that was used to cut a piece of copper foil. The foil was then annealed and bent into shape using a shaping platform that was also designed. The legs were folded so that the cell was suspended 2 mm above the bracket and the tabs were folded inward to hold the cell in place. The photograph on the right shows a cell in the completed cell holder.

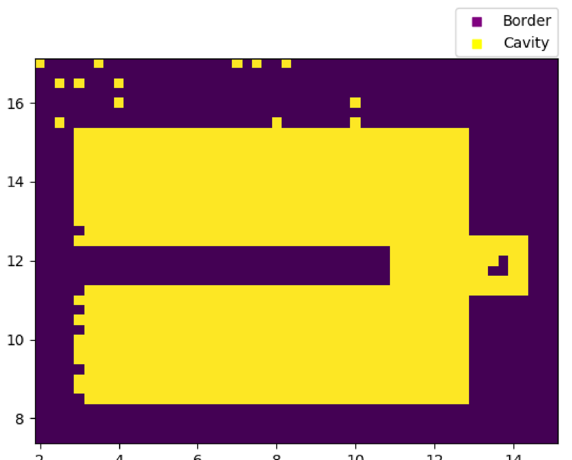




## Analysis and Results

First stage of data analysis was to plot a heatmap of the average reflected intensity at each point in a scan. This is shown in the top figure and clearly shows which points of the scan feature interactions with the cavity. Using this plot, the range of average intensities corresponding to measurements at the border and in the cavity were determined and used to classify points in the scan. The results of this classification are shown in the middle figure. The reflected intensity of all points classified as cavity was normalised using the average of all the border measurements and plotted. Then functions with minima were fitted to the data to find the wavelengths that were minimised due to interference. The results of this fit are shown below. For all points in the cavity minimised wavelengths corresponding to n=4 and n=5 were found. Both of these wavelengths were used to calculate the depth of the cavity.




The cavities in Cell N1 and Cell N2 were scanned at 300 K and the cavity in Cell N2 was also scanned at 80 K. The average depth calculated from the scan as well as the standard deviation of all the depths calculated are displayed in the table below. Here the subscript numbers denote the n value of the minimised wavelength used for the depth calculation and avg is the average of the two. The standard deviations show that the cavities are very uniform with the depth calculated for the majority of points being within 0.2% of the mean. This uniformity can be seen in the heatmaps of the depths shown below. When comparing the results for Cell N2 at different temperatures it was surprising to see that there was no observed change in the average depth. The lack of change was confirmed by calculation the standard deviation and plotting the heatmap of the difference in the depth. This means that the cells are suitable for confined superfluid experiments as the depth of the cavities remains the same and just as uniform under cooling.

| Cell | $D_4$ | $\sigma_4$ | $D_5$ | $\sigma_5$ | $D_{avg}$ | $\sigma_{avg}$ |
|---|---|---|---|---|---|---|
| $N1_{300K}$ | 1079±2 | 1.85 | 1082±2 | 2.20 | 1080±2 | 1.80 |
| $N2_{300K}$ | 1086±2 | 1.85 | 1088±2 | 2.05 | 1087±2 | 1.67 |
| $N2_{80K}$ | 1087±2 | 1.72 | 1089±2 | 1.87 | 1088±2 | 1.57 |
| $N2_{\Delta T}$ | 1±2 | 2.33 | 1±2 | 2.67 | 1±2 | 2.18 |