

Mach-Zendher interreferometer with phase shift

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1 Abstract

Mach-Zendher interferometer with phase shift used on diffusion of table salt and erosion of calcite in water. This interferometer has a higher resolution than the Michelson interferometer and gives a better picture of microfluidic devices. It also has more flexible components. In this report it was tested on table salt diffused in water and erosion of calcite with running water. The diffusion was a test to see if the equipment still worked and that all the pieces could cooperate, and the calcite were to give an estimate of the precision of the equipment. The erosion showed that the setup that was used did not have enough resolution to get the full effect of the Mach-Zendher interferometer.

2 Introduction

The Mach-Zendher interferometer was first proposed in 1891 by Ludwig Zendher [1] and later refined by Ludwig Mach [2]. In the later years it has been used for understanding the kinetics of dense fluid transport properties [3, 4] and diffusion measurements [5]. Exactly this interferometer were used by D. K. Dysthe in 1995 to measure interdiffusion in binary liquid mixtures, NaCl/water and 1-butanol/water. It was then found to have a precision of 0.6% for NaCl and 1.4% for 1-butanol [5].

We want to find out how accurate our setup is and what might be done with it to increase this accuracy. There is also the question of how well the phase unwrapping tools available can handle these high precision measurements. With this information the Mach-Zendher setup can be more permanently constructed and be used for future experiments.

3 Method

3.1 Mach-Zenhder setup

This setup for the Mach-Zendher interferometer with phase shifting consists of a laser (Melles Griot, 05-LHP-111), which is chosen for its long coherence length. If we had used white light the components would have to be placed with micrometer precision. Using a laser gives a coherence length of about a meter. Though it will create noise in the measurements which needs to be weighed in. The laser beam goes through a beam expander, which due to the

nature of lasers having a gaussian distribution of intensity, and us wanting a uniform distribution, we expand the laser and use only the middle of the beam. A beam splitter splits the laser beam in two, sending one to a piezo controlled mirror. The piezo is controlled by a computer sending signals to a Nidaq (National Instruments, NI USB-6211) which is connected to a high voltage DC OP amp (burleigh, PZ-70) converting a voltage in a range of -10 V to 10 V into 500 V to 1000 V. This gives high precision control of the movement of the mirror down to about the order of 10 nm, thus making it possible to move the phase of the light wave with great accuracy. From the piezo mirror it is sent through a sample cell which contains what we are measuring. Then it is sent to a beam collector and the interference pattern is picked up by a CCD camera (Imaging Source, DMK 21BUC03) which is connected to a computer who stores the data. The second beam travels without hinderance to the collector.

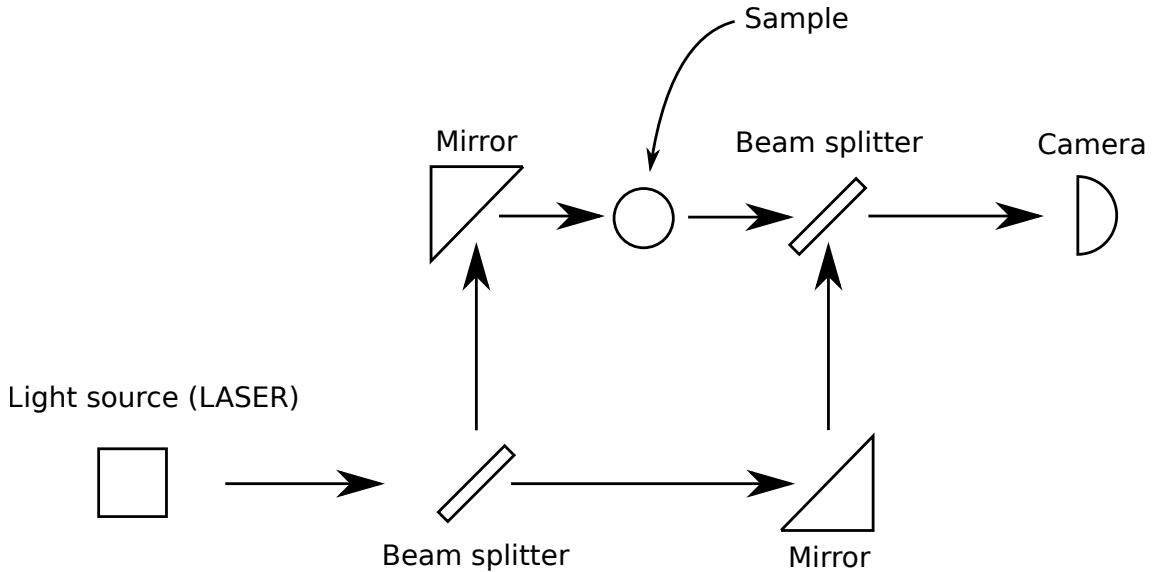


Figure 1: A sketch of the setup described above.

3.2 Unwrapping

To analyze the data coming from the camera we used a method called unwrapping. As we only get an intensity from the camera we have to translate this into something we can use to analyze the motion of the phase picture.

Most of this section is collected from the book Optical Measurement of Surface Topography chapter 8 [6]. The interference signal can be expressed as:

$$I(\phi) = I_{DC} + I_{AC} \cos[\theta + \phi] \quad (1)$$

where I_{DC} and I_{AC} are fixed coefficients and θ is the phase and ϕ is the phase shift in terms of the reference mirror displacement. This equation can then be expanded to

$$I(\phi) = I_{DC} + I_{AC}[\cos(\theta) \cos(\phi) - \sin(\theta) \sin(\phi)] \quad (2)$$

Fitting the sine and cosine waves to the interference signal gives the $\sin(\theta)$ and $\cos(\theta)$ terms. To get the wanted θ out of this equation it is possible to integrate over a full cycle of phase ϕ

$$N = - \int_{-\pi}^{\pi} I(\phi) \sin(\phi) d\phi \quad (3)$$

$$D = \int_{-\pi}^{\pi} I(\phi) \cos(\phi) d\phi \quad (4)$$

Then the phase θ can be extracted with

$$\tan(\theta) = N/D \quad (5)$$

The signal $I(\phi)$ is what we are measuring in the camera and thus by shifting ϕ with evenly placed discrete values $\Delta\phi = \pi/2$ the equation above becomes

$$N = I_0 + I_1 - I_2 + I_3 \quad (6)$$

$$D = -I_0 + I_1 + I_2 - I_3 \quad (7)$$

and we get

$$\tan(\theta) = \frac{I_0 - I_2}{-I_0 + 2I_1 - I_2} \quad (8)$$

This can be done for more intensity samples as well, and thus for 7, as we used, we get

$$\tan(\theta) = \frac{2I_1 - 2I_3}{-I_0 + 2I_2 - I_4} \quad (9)$$

By taking the arctan of this equation we are left with the shifted phase. But due to the nature of tan, the picture will only have a range of 2π and therefore have false drops. To correct these drops we used a 2 dimensional unwrapping algorithm in Matlab called Constantini phase unwrapping [7] which is based on an article written by M. Constantini [8]. This unwrapping of the phase gives a picture of how the phase θ is moving as ϕ is changed.

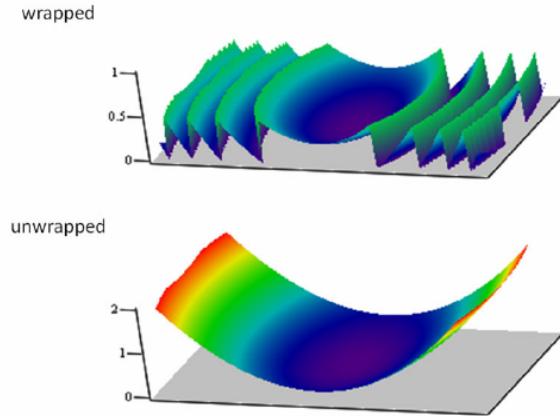


Figure 2: [6] An illustrative graph of a wrapped and unwrapped phase picture respectively with unit length on the x and y axis, z in radians.

3.3 Diffusion of table salt in water

The reason for this experiment was to test the equipment to see if every component could work together and also get an approximation of how well the accuracy is. We expected to see an inclination rising as the salt diffused into the water since the optical path length rises when the water and salt gets mixed. To be able to control the phase shift with the piezo we did a calibration to find which voltage represented one wavelength. By using the background it was measured to be a factor of 1.12 which we multiplied to the signal out to the Nidaq. Then we placed a rectangle sided vial with clear plastic in the middle in front of the beam.

The vial were filled with 2.16 g of water and a piece of 3 mg of salt was added to it, and a Matlab code took a picture about every 2 minutes depending on how long the unwrapping algorithm took. This went on overnight and we got around 300 measurements.

3.4 Calcit erosion by water

The goal of this experiment was to get an estimate of how accurate this setup can be, and find out what had to be changed to increase the precision. We want to see an erosion beginning in the start of the canal and have an exponential difference in optical path length along the canal as the erosion

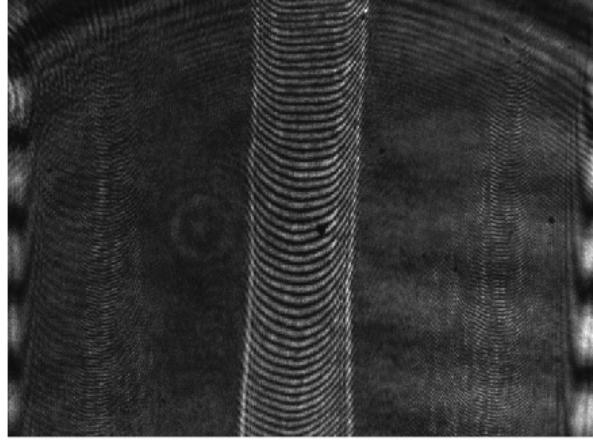
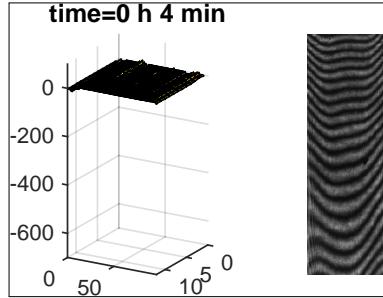


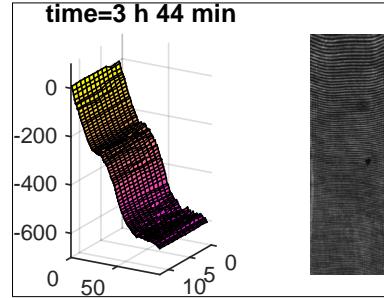
Figure 3: A vial with nothing in it. The black and white stripes are the interference of the beam because of the difference in optical path length compared to the unhindered beam. At the far sides there is a background interference pattern which arise from the camera not being completely aligned.

takes place. It is expected to be a steep inclination in the beginning of the unwrapping picture and as the experiment goes on, the inclination should spread to the entire picture.

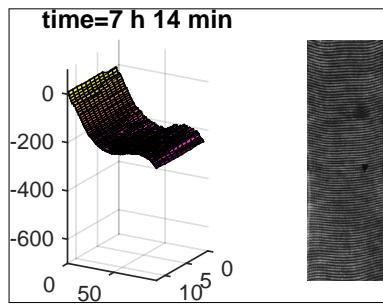
The water delivery system was a syringe put on an automated pump (kdScientific, LEGATO 180). We set the pump to 10 nl/s and started the same Matlab program as with the diffusion experiment only with about 5 minute spaces between the measurements and the experiment went on for about 24 hours. The second experiment was with the same parameters but with added salt peter acid to the water, 0.05 molare, to get a larger erosion rate. The unwrapping of the phase were done in the area from 5 pixels above to 5 pixels below the canal, and the canal before the erosion was about 2 pixels wide.



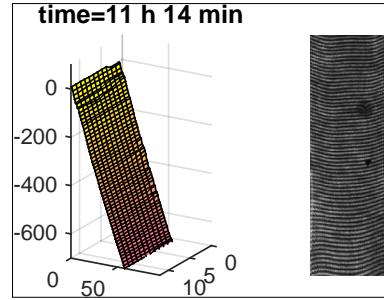
(a) The first image taken after starting the experiment. To the right is the unwrapped phase subtracted from the background giving it a zero value. On the z-axis the phase is plotted in radians and the x-y plane is in pixels. To the right is the image from the camera with both axes in pixels



(b) After almost 4 hours the salt has diffused into the solution and the phase has become a lot steeper. As seen on the camera the number of fringes has increased significantly. There are also some optical effects due to too much salt as one can see in both the phase and the camera.



(c) 7 hours in the phase is showing some warped behaviour due to the salt amount



(d) 11 hours into the experiment the solution has quiet down and shows a steep inclination compared to the background which is expected since the optical path length is higher in salt water then in pure water

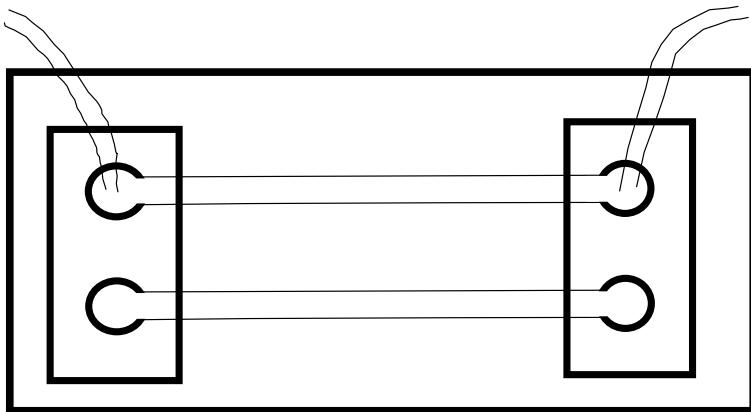
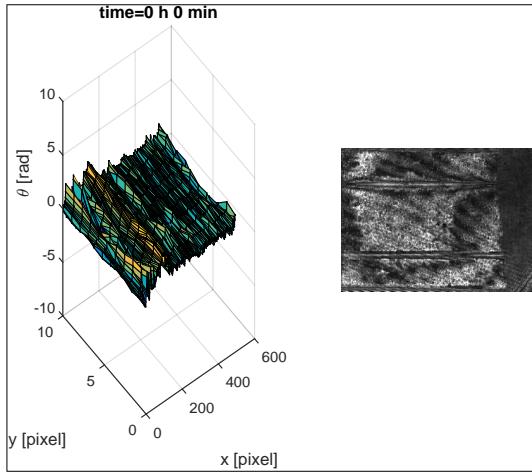


Figure 5: It was made of a calcit sample by taking a plexi glass surface, bore four holes in it and two other plexi cubes. Then using a special sticker with glue on it to fasten the calcit to the plexi surface and creating two canals, with a width of about $300 \mu\text{m}$, between the glass and the calcit. Two plastic tubes are threaded down on each side of a canal through the plexi cubes so it can deliver a water stream through the canals.

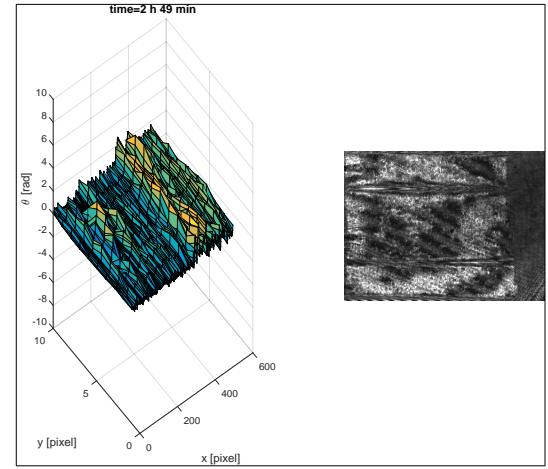
4 Result

4.1 Test system

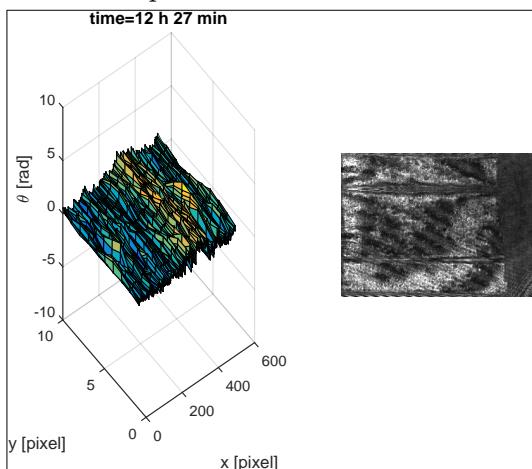
The diffusion of table salt in water gave the expected results from a diffusion experiment. As seen in Figure 4a, Figure 4b, Figure 4c and Figure 4d the unwrapping picture shows a clear inclination which means that the optical path length has been increased and the difference between a phase shift of the background to the next measurement has increased. The offset behaviour is due to too much salt being used and gave off some optical disturbance. From Figure 4a to Figure 4d the phase picture has behaved as expected. The precision seem to be adequate in that the phase unwrapping picks up on the changes in optical path length, the piezo control moves the phase at increments small enough, and the calibration of $1.12 \cdot V$ is giving a correct phase shift.



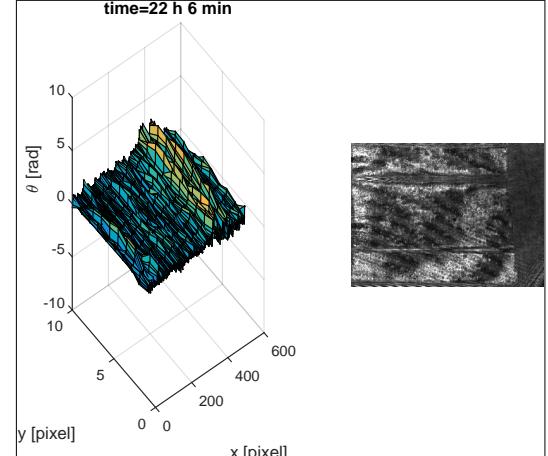
(a) First measurement where there is just noise as expected in the unwrapped phase picture and there is no erosion in the canal. We used the top canal.



(b) After 3 hours there are very distinct changes in the optical path length in the measurement at the beginning of the canal.



(c) Half way through the experiment with a clear change in the optical path length in the measurement.



(d) The image has not changed much and the erosion has virtually stopped.

4.2 Calcit erosion

4.2.1 By water

There were no change in the phase picture and no visible erosion in the raw camera feed. A possible reason for this was the water pressure, it may have been too low. If we had more time and could wait a day or two more, there should have been som change.

4.2.2 By water with salt peter acid

With the added salt peter acid and same rate of flow, 10 nl/s, the erosion started after 1-2 hours, and became visible on the raw feed from the camera. There were no distinct features in the phase picture, as seen in Figure 6a, Figure 6b, Figure 6c and Figure 6d. Though there is noe data to be collected from these pictures they give information about what the next step should be.

5 Conclusion

The diffusion experiment gave a pointer to that this setup can be used at high precision measurements down to the order of 100 nm. And the calcit test showed that the are limitations to the camera and the unwrapping algorithm used. Since the canals only became 2 pixel wide the unwrapping did not give any meaningful results. Beacuse this is a Mach-Zendher interferomter the different components are highly felxible in their positions and thus could be set up in a way so that the canals in the calcit sample took more room on the camera chip. The way forth would be to get the components closer together by using a breadboard so each component can be moved to each specific experiment, use a higher resolution camera to get more pixels per size of sample we are looking at

6 Acknowledgment

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