Temperature Dependence of Refractive Indices of Liquids

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Abstract

The refractive index of a fluid changes ever so slightly with temperature. This can be measured with Michelson's interferometer. I examine the change in refractive index of various liquids using a slightly modified setup of Michelson's interferometer. Here the temperature dependence of refractive index of water and chloroform is examined.

1 Introduction

Velocity of light is very high for our day-to-day activities to be affected by changes in it. We do know that light slows down in material media such as water.

$$n = \frac{c}{v_m}$$

where v_m is the velocity of light in the medium, c is the speed of light in vacuum. n is the refractive index of the liquid. The speed of light in a medium and in turn, the refractive index depend on the its temperature. To make precise, Michelson's interferometer is used. The refractive index can be measured with great precision using it.

The fringe pattern is observed, the number of fringes which collapse can be used to calculate the change in refractive index of the media.

2 Theory

2.1 Michelson's Interferometer

Michelson's interferometer is an optical setup which consists of interference of two optical fields, both derived form a single source. The setup includes 2 mirrors (M1 and M2), a beam splitter (BS), a light source (L), a diverging lens (DL) and a screen (S). The beam from the source is divided at the beam splitter such that the two fields travel orthogonally and come back after reflections from mirror to eventually interfere at the screen.

Light along the two paths, pick up phase difference as a result of any difference in the optical distance [1] it traverses.

[1] optical distance is defined 2.2

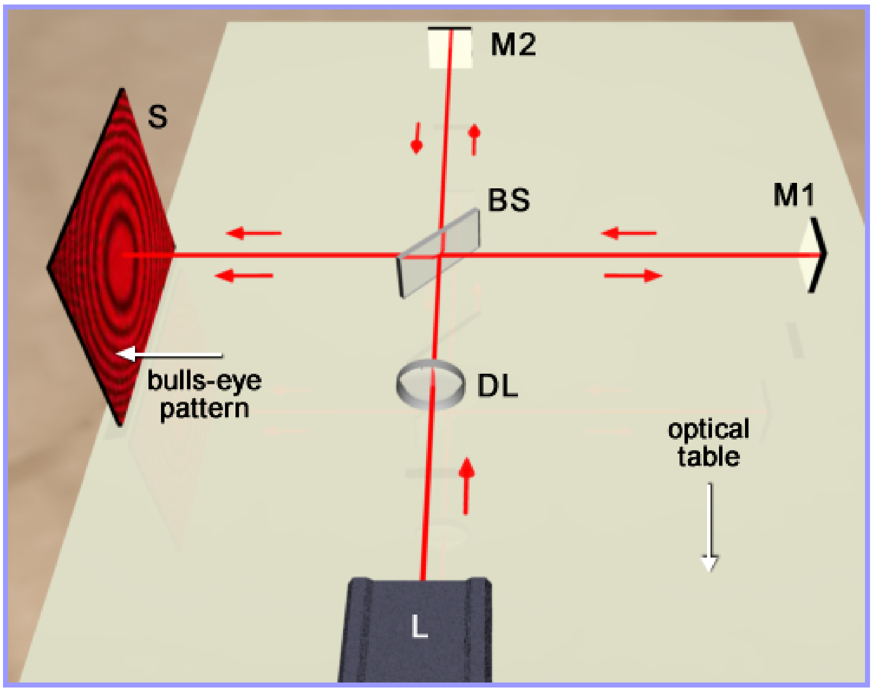

Figure 1: Standard Michelson's Interferometer

2.2 Optical Distance

In vacuum, the light wave picks up a phase 2π for each λ distance it travels. In any other medium, the frequency of the light remains the same but the speed reduces by a factor of n, the refractive index. According to the relation

$$\nu_0 = \frac{c}{\lambda_0}$$

where ν_0 is the frequency of the wave, λ_0 is the wavelength in vacuum and c is speed of light in vacuum. Now, writing the same equation in a medium,

$$\nu = \frac{v_s}{\lambda} = \frac{c}{n\lambda}$$

where the symbols are corresponding quantities in a medium with n being the refractive index of the medium. Note that, the frequency is same in all media, therefore,

$$\nu_0 = \nu$$
$$\frac{c}{\lambda_0} = \frac{c}{n\lambda}$$
$$\lambda = \frac{\lambda_0}{n}$$

λ is the distance a wave travels while its phase changes by 2π. If λ decreases by a factor of n, it means the wave will have to travel a distance smaller by a factor of n for its phase to change by 2π.

Equivalently, for a phase difference of θ the wave will have to travel a distance n times greater in vacuum than in the medium with refractive index n.

We define optical distance as the distance a wave would have to cover to undergo the same phase change as it has in a medium. And we just found out that this distance in vacuum would be n times the distance in a medium.

$$OP = n \times GP$$

OD is Optical Distance and GP is the Geometric Distance or the actual distance traveled.

3 Experiment

3.1 Experimental setup

The experimental setup is a slightly altered form of Michelson's interferometer. In addition to the standard Michelson Interferometer setup as shown in Fig 1, a $10cm$ long container is placed along the arm BS-M2 of the interferometer. The container is transparent from the sides as a result, light can propagate through it, get reflected from the mirror M2 and come back to the Beam Splitter.

3.2 Making the two path lengths exactly equal

The geometric distance of the two mirrors from the beam splitter is to be adjusted such that previously visible circular fringes on the screen collapse and uniform bright light appears on the screen. This will happen when the optical distance the two light waves have traveled is the same.

NOTE: The light wave undergoes a π phase shift on reflection. But as the beam from along both the arms undergoes two reflections each, the phase difference between the two is only because of the difference in the optical distance traversed.

Now, adding the liquid to the column would change the optical path along one arm and the resultant phase difference would again give us the circular fringes like before. Now, the mirror M2 can be moved so as to again get the same optical distance along the two arms.

Note that, changing the distance of the mirror by x units results in change of $2x$ [2] units as the light has to go back and forth the added distance.

3.3 Measuring change in refractive index

The liquid in the container is heated up and then left to cool down while the temperature is continuously noted. Along with the temperature, the number of fringes collapsing while the temperature is in some particular range is also observed.

[2] here, it is true only if the refractive index of the air/atmosphere around the setup is 1. Though this is not accurate as the refractive index of air is slightly greater than 1, the entire calculation is done using this only. And thus, the results obtained are not really the absolute values of the refractive index but are relative to the refractive index of the surrounding air

For each change of λ in the optical path difference, 1 fringe will collapse at the screen. Let the number of fringes collapsed be N and the wavelength of the laser used is $\lambda = 632nm$.

Also, for a change of refractive index Δn, the optical path difference changes by ΔnL. L is the geometric path covered. Note that, the light goes through the liquid twice, hence $L = 2 * l$ where $l = 10cm$.

Equating the two ways we deduced the change in optical path difference,

$$\Delta n * 2 * l = \Delta N * \lambda$$

$$\Delta n = \Delta N \frac{\lambda}{2l}$$

Where ΔN is the number of fringes collapsed.

4 Results and Interpretation

4.1 Water

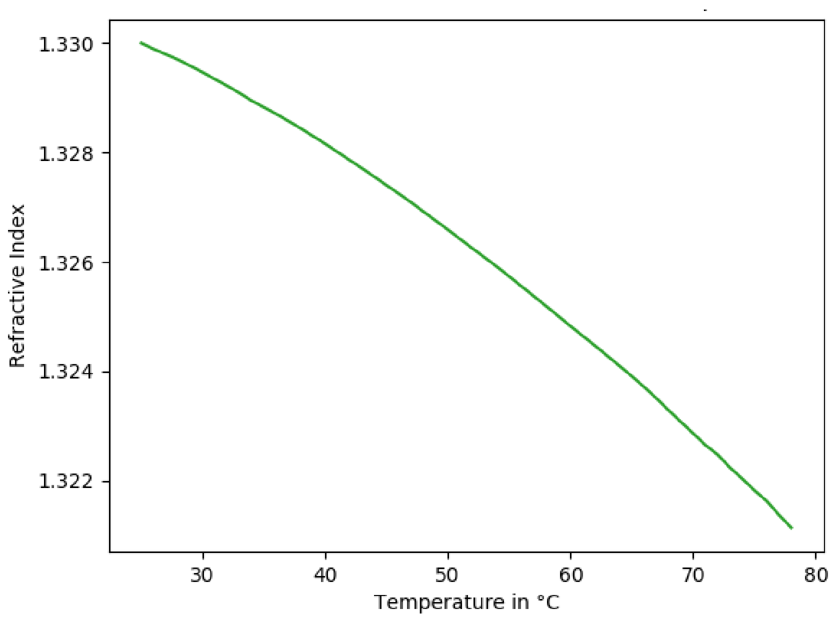

Figure 2: Variation of Refractive Index of Water with Temperature

The above graph in Fig 2 shows the reduction in refractive index of water with increasing temperature.

Note that as stated before, this is the refractive index relative to the refractive index of the surrounding air. Also, for this, the refractive index at 25 ° Celsius is assumed to be 1.33. Thus, what is calculated is the change in refractive index and then the change is added algebraically to the preceding value to get the value of refractive index at the higher temperature. Thus, if the value of refractive index at 25 ° Celsius were something other than 1.33, the graph shown in Fig 2 would simply move up or down a bit.

4.2 Chloroform

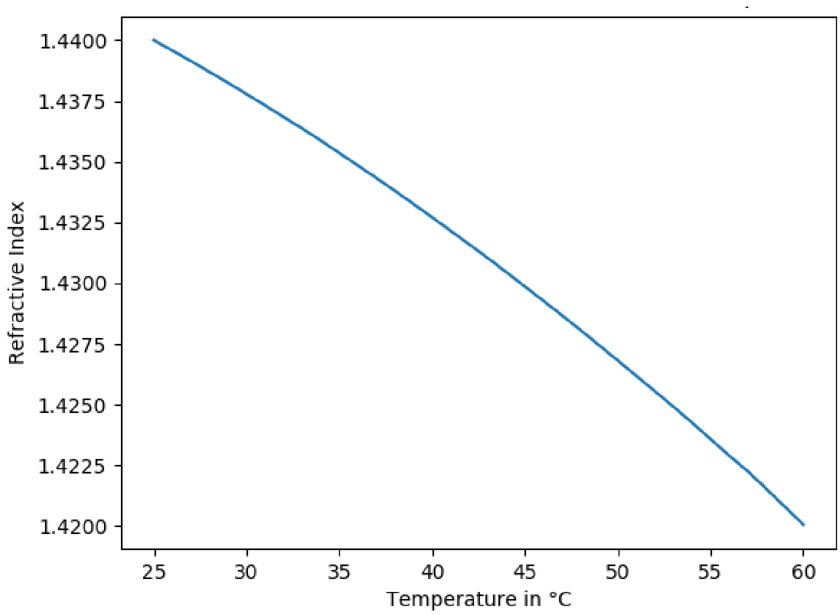

Figure 3: Variation of Refractive Index of Chloroform with Temperature

The above graph in Fig 3 shows the reduction in refractive index of chloroform with increasing temperature.

Just as it was for Water, this is the refractive index relative to the refractive index of the surrounding air. For chloroform, the refractive index at 25 ° Celsius is assumed to be 1.44. Thus, what is calculated is the change in refractive index and then the change is added algebraically to the preceding value to get the value of refractive index at the higher temperature. Thus, if the value of refractive index at 25 ° Celsius were something other than 1.44, the graph shown in Fig 3 would simply move up or down a bit.

5 Discussion and Improvements

- For neither of the liquids was the refractive index at 25 ° Celsius measured. And thus we have just stated the difference. We can measure the refractive index relative to air at 25 ° Celsius as well. What we need to do is once the empty container is set up, math the exact optical distance. Then, fill the container with the liquid at 25 ° Celsius and then move one of the two mirrors two again have the light travel the same optical distance along both the arms. Record the distance the mirror has to be moved. This can be used to calculate refractive index of liquid at 25 ° Celsius.

  The introduction of liquid in the path increases the optical distance by $(n-1) * 2l$ and thus, this has to be compensated by moving the other mirror away a distance d, which would introduce a path difference of $2d$.

These two are equal when it again has the same optical distance. Thus,

$$(n-1)*2l = 2d$$

$$n = \frac{d}{l} + 1$$

- The entire change in optical distance is attributed to the change in refractive index of the liquid. The change in refractive index of the container walls through which light passes is ignored. This is mainly because light travels a very small distance through it, but if one wishes greater accuracy, one can heat up the empty container and do the same analysis as done here to get the corresponding data for it. This then could be used to get more analysis for Water.

- If one wishes to find the absolute refractive index and not the one relative to the surrounding air, one will need to have a vacuum chamber along one arm of the Standard Michelson's Interferometer (Fig : 1). This way, one can find the absolute value of n_{air} by:

  $$n_{air} * l_{air} = 1 * l_{vacuum}$$

  Then, we can multiply n_{air} to the values we calculated above to get the absolute refractive index of liquids at different temperature.