# Accurate wavelength measurement with Pohl interferometer through post detection processing

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# Construction of an inexpensive molecular iodine spectrometer using a self-developed Pohl wavemeter around 670 nm wavelength

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**Abstract**

We describe the construction of an inexpensive iodine spectrometer with a homemade iodine vapour cell and a self-developed wavemeter based on the Pohl interferometer, around the 670 nm wavelength. This can be easily realized in an undergraduate teaching laboratory to demonstrate the use of a diode laser interferometer using a Pohl interferometer and measurement of the wavelength using image processing techniques. A visible alternative to the infrared diode lasers, the 670 nm diode laser used here gives undergraduate students a chance to perform comprehensive though illustrative atomic physics experiments including the Zeeman effect, the Hanle effect, and the magneto-optic rotation effect with a little tweaking in the present spectrometer. The advantage of the spectrometer is its ease of construction with readily available optics, electronics, evacuation and glass-blowing facilities, and easy analysis algorithm to evaluate the wavelength. The self-developed algorithm of raster scanning and circular averaging gives the researcher insight into the basics of image processing techniques. Resolution approaching 0.5 nm can be easily achieved using such a simple setup.

Keywords: Pohl wavemeter, wavelength, iodine, spectrometer

## 1. Introduction

With more than 100 000 ro-vibrational lines in the visible and near infrared (IR) region [1], diatomic iodine presents a wealth of reference lines for various spectroscopic studies, making it an integral part of most atomic spectroscopy experiments. A large nuclear quadrupole moment and long lifetime of upper states in iodine result in easily resolvable, though narrow,

transitions [2, 3]. Thus it has been possible to use it for defining the meter [4], laser stabilization of many systems [5] and other important metrological applications. Another aspect of iodine spectroscopy is the availability of standard atlases, wherein the frequencies can be looked up [6] or can be predicted by available programs like IodineSpec5 [7].

All these facts make iodine a suitable molecular species to be used for experimenting at the undergraduate level. It gives budding researchers a flavour of atomic physics experiments covering simple absorption/fluorescence spectroscopy to more interesting ones involving the Zeeman effect [8], the Hanle effect [9] and magneto-optic rotation (MOR) [10] to name a few. As a visible laser is used for the present experiment at 670 nm, this makes the study easier in terms of detection requirements, visibly as well as electronically. Such introduction of iodine as an atomic species in undergraduate labs was not done earlier due to the non-availability of a cheaper and simpler vapour source and the use of inexpensive diode lasers.

Here we present the construction of an inexpensive iodine spectrometer which comprises an easy-to-design vapour cell along with a diode laser at 670 nm and a Pohl wave meter used for measuring the wavelength. The instrument presented here not only provides a tool to understand basic spectroscopy, but also gives a sample of diode laser usage and performing interferometry with it using a simple image processing algorithm in MATLAB and the Pohl interferometer.

The present work is divided into five sections. We first introduce our preparation of the iodine vapour cell describing the nitty gritty of the design parameters involved. Next are details describing the self-developed Pohl wavemeter and wavelength measurement using the same. This is followed by the iodine spectroscopy around the 670 nm laser, wherein we access the transition at 671 nm. The 671 nm transition is the hyperfine components of the R (78)4-6 line of $I_2$ [1]. We then describe the wavelength measurement of the iodine spectrometer using the Pohl wavemeter. This is then followed by results and analysis, and sources of error. The final section discusses possible up-gradation of the wavemeter design and tweaking of the iodine spectrometer to study various atomic physics effects. We finally describe incorporating the present work in our ongoing Li laser cooling experiment.

## 2. Iodine vapour cell preparation

An iodine vapour cell was constructed using the following steps. First and foremost, all the optical components/glasswares were thoroughly cleaned, initially with soap and water and then acid and methanol. A tube of BK7 glass, with a diameter of 25 mm and length 70 mm, was taken and its ends were fused with two optical flats, also of BK7 glass with a regularly available $\lambda/4$ flatness. Two short glass stems were fused on to the sides of this tube diametrically opposite to each other. One of the two stems was then filled with pure iodine and sealed from the outside. The other stem was coupled to a vacuum pump and evacuated to a regular rotary vacuum $\sim 10^{-3}$ Torr ($1.33 \times 10^{-5}$ Pa). Care was taken to keep the iodine stem cool at this point so that iodine is not pumped out. After this, the vacuum stem was heated to soften and then sealed. When this cell is required to be used, the iodine stem is heated so that iodine sublimes and fills the cell. Because elemental iodine is toxic, care must be taken while handling the same. A glove box was used while handling the element during the above procedure. It is noted here that as an alternative to glass blowing and evacuation facilities, one can buy a commercially available vapour cell of iodine (for example, Thorlabs GC19100-I).

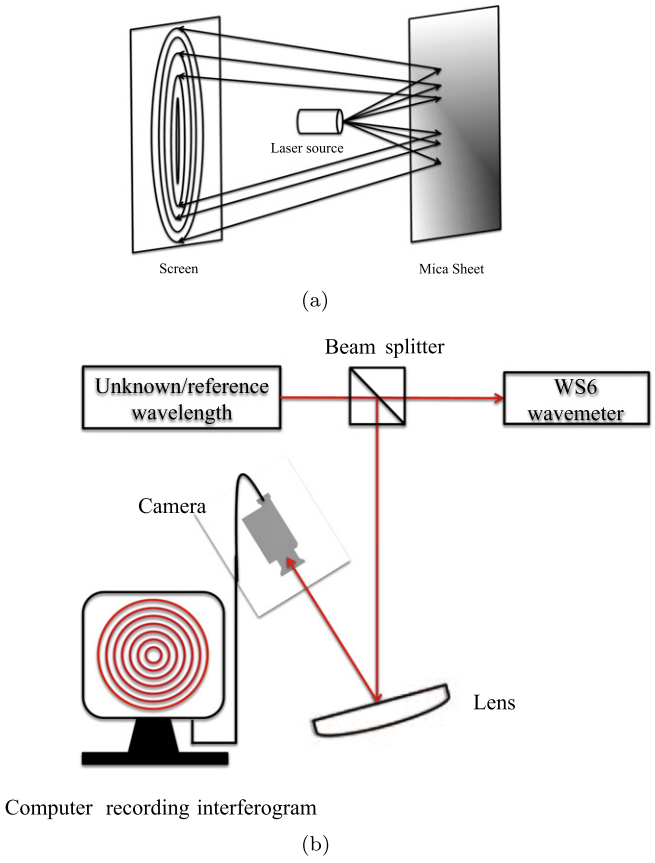


**Figure 1.** (a) Illustration of Pohl fringes with a mica sheet at near-normal incidence. (b) Experimental arrangement for Pohl interferogram measuring wavelength for unknown wavelength.

## 3. Pohl interferometer: principle and details of measurement

The Pohl configuration [11] provides a quick and simple, though efficient, way of measuring wavelength [12, 13]. This is shown in our previous work on some preliminary measurements of the wavelength of a diode laser with the Pohl interferometer [14]. Although a very simple interference device, it has been used for performing sensitive optical characterizations like phase measurement [15]. Its versatility has been proven in shop testing conditions as well as while measuring the parallelism of transparent surfaces [16, 17]. Unlike other interferometry devices [18], not needing very special optical components, it can very easily be incorporated in undergraduate laboratories as a wavelength measuring device.

The Pohl interferometer shown in figure 1(a) is an amplitude splitting interferometer. As shown, a point source, when reflected by front and back surfaces of a mica sheet, resembles a situation where two pseudo-sources separated by double the thickness of the sheet are emitting light and result in an interference pattern at a point on the screen. The full schematic showing the wavelength measurement using the Pohl wavemeter is in figure 1(b). A plano-convex lens of $f \sim 1000$ mm is taken for producing Pohl fringes. A DCU223M Thorlabs Digital Camera with 30 frames per second is used to capture the images. At the heart of the

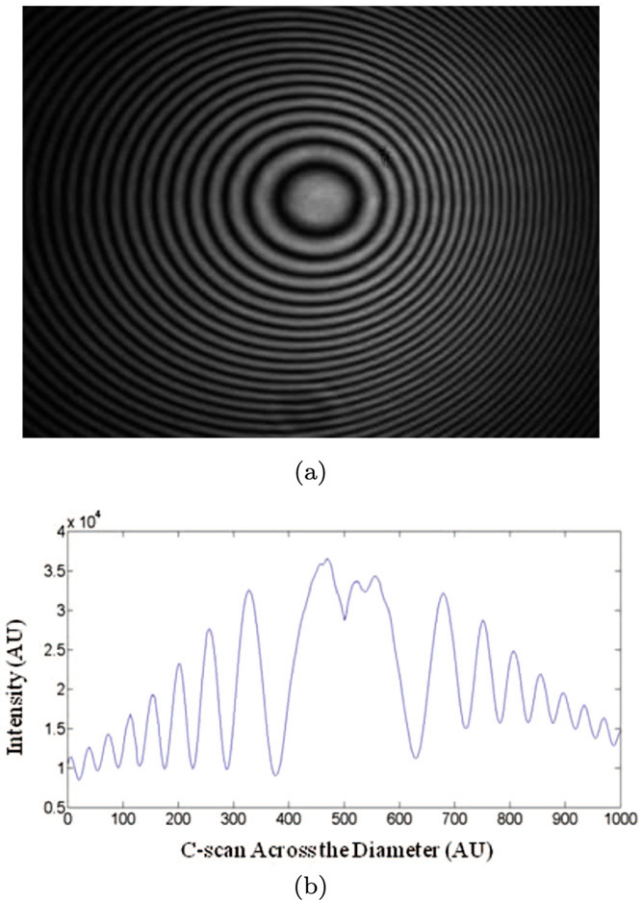


**Figure 2.** (a) An interferogram with a 670 nm laser. (b) A C-scan using the averaging algorithm.

wavemeter lies post-detection analysis of the interferogram. This involves a simple but efficient self-developed algorithm of raster scanning and then circular averaging. The raster scan is a commonplace technique for surface studies using atomic force microscopy in the field of soft condensed matter physics [19]. In the algorithm, we first choose a region of interest (ROI) as the first few fringes (say seven) going outward in the interferogram and its centroid $(x_c,y_c)$ is found. Then we take a radial point $(x_r,y_r)$ on the outermost fringe in the ROI. Joining $(x_c,y_c)$ and $(x_r,y_r)$, we then find the intensity profile along this radius, thus getting a measure of the radial variation of the intensity in the rings formed. The same procedure is followed to give similar data along the radius with different inclinations with respect to the first one. This is done by adding an extra variable $\theta$, an angle between the initial radius and the next one. This procedure is followed for $\theta$ going from $0 \rightarrow 360^{\text{deg}}$ for every 5-degree angle and all intensity variations are found. This is finally averaged to get a circularly averaged intensity profile. One such interferogram and intensity variation found experimentally is as shown in figure 2. The whole algorithm is realized using the MATLAB image processing package.

First the above procedure is followed with the He–Ne laser at 632 nm. Now by using the interferometer ring formula [20] and knowing the wavelength of the light creating the

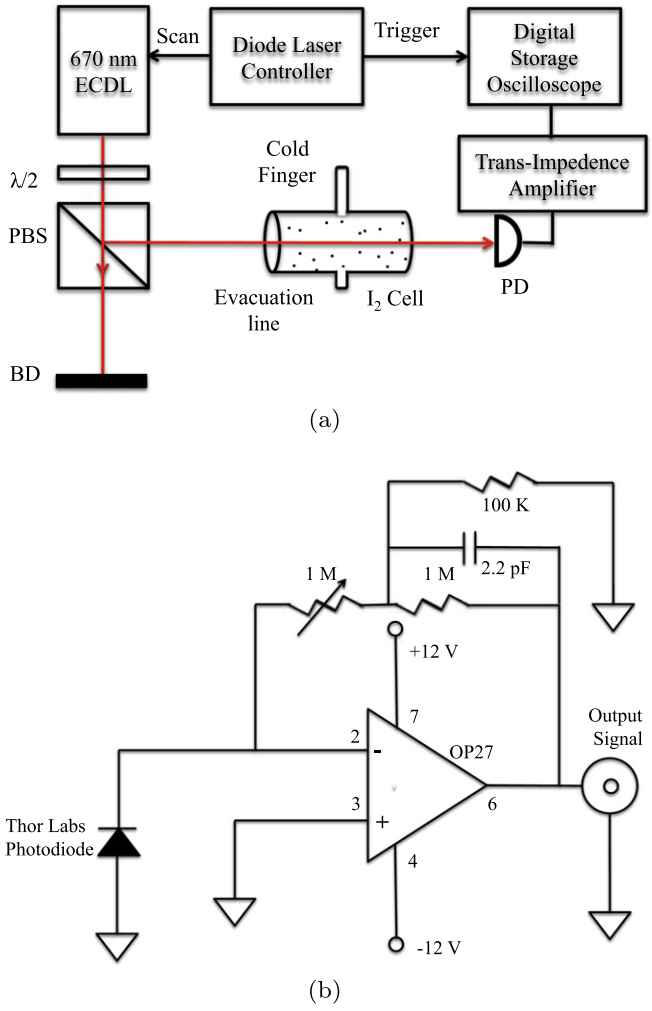


**Figure 3.** (a) Experimental arrangement for iodine spectroscopy; PBS: polarising beam splitter, BD: beam dump, PD: photo-diode, $\lambda/2$: half waveplate. (b) High-gain trans-impedence amplifier used for signal detection.

interferogram, we can measure the other constant, i.e. $k$ in the equation below

$$\lambda = k\frac{D_{m+p}^2 - D_m^2}{4p} \tag{1}$$

where $D_{m+p}$ and $D_m$ are the diameters of the $(m + p)$th and $m$th fringe in pixels while $k$ is only the calibration factor. A similar $k$ value is measured for the other He–Ne laser at 543 nm to take care of any dispersion effects. This $k$ value is then used for the measurement of the unknown wavelength for the diode laser. As an alternative to the 543 nm He–Ne, one can use a simple and inexpensive laser pointer at 532 nm, which is frequency-doubled output from a diode pumped solid state laser.

## 4. Iodine spectroscopy at 670 nm transition using the Pohl wavemeter

The laser used for the experiment is a 35 mW external cavity diode laser (ECDL) by Toptica Photonics centred at 670 nm with a tunability of ∼15 nm around the centre. This offers the opportunity to access various lines in the iodine molecule by varying the diode frequency utilizing the tunability of the laser. The experimental arrangement is shown in figure 3(a). As an alternative to the commercial ECDL, researchers can follow many self-developed designs of ECDL and related electronics, refer, for example, to [21].

The ECDL output is sent through the homemade iodine vapour cell described in the previous section. For tuning the diode laser, we needed to play with the grating angle initially using an adjustment screw behind the grating plate. This pushes the grating to change the incident angle of the laser beam on the grating. For finer adjustment of the frequency, a piezo drive going to the piezo stack behind the grating plate is played with in addition to the diode laser current. Once the diode is tuned to the right frequency, one can easily see the fluorescence with the naked eye. This can be made brighter by heating the cell a little using a heat gun to increase the iodine vapours in the cell. However, excessive heating is avoided so as not to coat the optical windows with violet vapours of the molecule. The cell is heated to about 150 °C using heating tapes tied around to get good enough vapours.

To get a good signal to noise ratio one needs to play with the power of the input beam by rotating the half-wave plate. The input power ($P_{\text{in}}$) has to be lowered to a level so that the relative absorption of the beam with respect to the $P_{\text{in}}$ becomes sufficient to get good enough absorption peak heights. Another thing to take care with is the mode hops of the laser. We find that the laser could be scanned by around 2 GHz without any mode hops problem. For recording the absorption spectra we have used a 1-nsec rise time photodiode (DET10A/M Si-biased detector from Thorlabs) available in our laboratory. Alternatively, an inexpensive photodiode BPW34 can also be used, which is sufficient to fulfil the demand of such an experiment. This is then connected to a trans-impedence amplifier built around an easily available low noise precision op-amp OP27 as shown in figure 3(b). It is to be noted in the design of the trans-impedence amplifier that a constant gain-bandwidth product would give a limit to the feedback resistor value being used. An unusually high-gain resistor might give a bandwidth that is out of our region of interest and the frequency response will go bad. To compensate for this we have used OP27, a wide bandwidth op-amp. In addition to this we used a feedback capacitor to reduce the gain for noise that is outside the bandwidth of the absorption signal [22]. Here it should be noted that for increasing the bandwidth of the detection system, an op amp faster than OP27 and a lower trans-impedence gain will help. Further, a second stage voltage amplifier can be added to get good signal at the oscilloscope.

A typical absorption signal for iodine from the current setup with the Thorlabs photodiode is as shown in figure 4. As seen, the laser is scanned by ∼1 GHz, which is well within the mode hop free region of the diode. The lines are identified as $a_1 - a_{15}$ hyperfine components of the R(78) 4-6 line of $^{127}I_2$ using IodineSpec5 [7]. The lines get broadened mainly due to the Doppler broadening at the temperature of 150 °C and pressure broadening due to high vapour density. At 150 °C the Doppler broadening comes to about ∼0.6 GHz using the following equation [23].

$$\delta\nu_D = 7.16 \times 10^{-7}\nu_0\sqrt{\frac{T}{M}} \tag{2}$$

where $T$ is the temperature in K and $M$ is the molar mass.

Heating the cell at 150 °C results in a vapour pressure of around ∼60 kPa using equation [24]

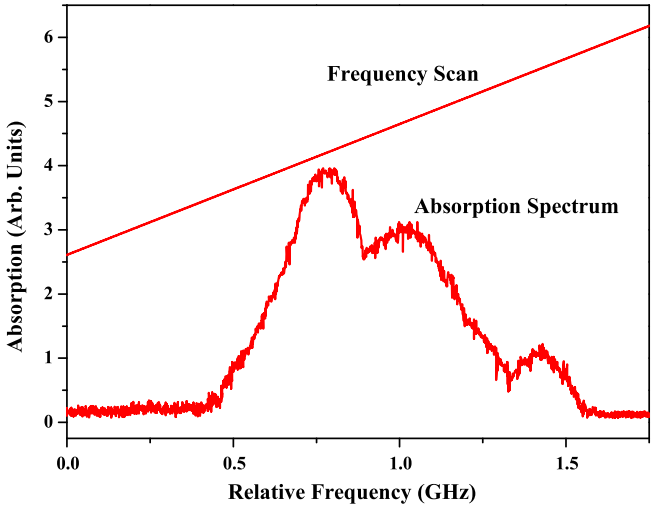


**Figure 4.** Absorption spectrum with laser scanning around 670 nm (the piezo scan is shown on top of it).

**Table 1.** Wavelength measurement using the Pohl wavemeter.

| Peak no. | WS-6 value | Pohl interferometer value | |
|---|---|---|---|
| | | With 1st and 5th ring | With 3rd and 7th ring |
| 1 | 670.9 | 670.8 | 671 |
| 2 | 670.9 | 670.6 | 670.9 |
| 3 | 670.9 | 671 | 670.8 |

$$\log(P) = \frac{-3512.830}{T} - 2.013\log(T) + 18.37971 \tag{3}$$

where $T$ is the temperature of the cell in K and $P$ is the resulting vapour pressure in Pa. To our knowledge we could find a previous work on similar lines on iodine, measuring the pressure broadening coefficient ($B_P$) in [25]. The referred work measures $B_P$ for the 675 nm transition in the $I_2$ molecule at 292 K, 348 K and 388 K in various buffer gases. However, compared to our work, the conditions used there are very different. Just to reiterate, we use a vapour cell that does not have a buffer gas, the cell is at a much higher temperature of 423 K and finally we measure the spectrum for the transition at 670 nm. Thus an estimated pressure broadening of ~2 GHz (using $B_P$ from [25] with 60 kPa vapour pressure used for our work), becomes much larger compared to our experimental result, wherein the spectrum shows us a pressure broadening of the order of ~0.5 GHz maximum, shown in figure 4. This gives us a rough estimate of the upper limit on $B_P \sim 1$ MHz/Torr for the transition and the experimental conditions we use. This we say is the maximum limit because Doppler's broadening is also of the same order.

## 5. Results, analysis and sources of error

Measurement results are summarized in table 1. We measured the wavelength of all three peaks resolved by the spectrometer. As the peaks are just ∼100 MHz away from each other, it is not in our resolution limit to resolve the same using the Pohl interferometer measurement, and hence each peak measurement shows the same wavelength. Each point is a result of 10 successive data sets taken to avoid any error in finding the diameter of the interference ring. As a consistency check we have measured the wavelength using different pairs of rings (see table 1). We have chosen 1st and 5th and 3rd and 7th rings, as the visibility of the rings will diminish as we go outward from the centre. This is due to the fact that the rings are being formed by multiple front and back surface reflections. This results in the intensity difference between the two reflections becoming more and more prominent as we go radially outward. This goes on until the time fringe contrast goes very low and there is uniform illumination with no more fringes seen on the screen. We have further compared the measurement with a commercial wavelength meter the WS6 Angstrom wavemeter [26], which is quoted to have a relative accuracy of $10^{-6}$. Our values come within the resolution we claim here.

The lower pixel resolution of the charge-couple device (CCD) used (pixel size $\rightarrow 4.65\,\mu\text{m} \times 4.65\mu\text{m}$) becomes the main source of error. Replacement of the same with a higher resolution CCD camera is to be taken in the next version of the instrument to reduce this error. Exact measurement of $D_m$ in equation (1) gives another possible source of error. This is tried to be reduced by taking data multiple times (10 times in the experiment) and making an average. To avoid any error coming due to the visibility of the fringes, a different set of interference rings for wavelength measurement are used (see table 1). Dispersion error can be due to the difference between the wavelength of calibration lasers and the actually measured wavelength. The instability of the gas laser used, due to fluctuation in the output, can be another source of error. However, all these errors come within the resolution we claimed here, i.e., 0.5 nm [27, 28].

## 6. Conclusion

In conclusion we can say that we have presented a construction of an iodine spectrometer. A simple method for making an iodine vapour cell was presented. This can very easily be repeated in a university workshop. Transition R(78) 4-6 is then accessed in $^{127}I_2$ around 670 nm. We then measured the transition wavelength using an in-house, simple, portable and accurate wavemeter, using a self-developed image processing technique and Pohl configuration as a simple interferometer. We can further refine the accuracy of the method using a fibre-coupled beam so as to get a refined wavefront and hence a clearer and sharper interferogram. We further plan to have a high-resolution complementary metal oxide semiconductor camera to be used for the detection part to enhance the image quality. Finally we are planning to automate the whole measurement process using a lab view code with a graphical user interface as well as making a module for wavemeter measurement. With a little tweaking, the iodine spectrometer designed here can be used to perform atomic physics experiments, including the Zeeman effect, the Hanle effect and MOR. This can be easily achieved by having a simple wire-wound solenoid around the cell to obtain the required magnetic field. Alternatively we can have Helmholtz configuration coils, regularly used in laser cooling experiments, to achieve a uniform magnetic field for such experiments. As a next step to our iodine experiment, we would like to incorporate the iodine spectrometer with our ongoing lithium laser cooling experiment. As the 671 nm iodine transition is just 3 GHz

away from the $D_2$ cooling line in lithium [1, 29], we can get a reference for the cooling line by measuring the beat frequency of the two lasers with a fast photodiode.

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