SELECTIVE EXPERIMENTS IN PHYSICS

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THE FABRY-PEROT INTERFEROMETER

OBJECT: To calibrate a Fabry-Perot interferometer and to use the calibration for measuring unknown wavelengths and the difference in wavelength between the two D lines of sodium.

METHOD: A Fabry-Perot interferometer is adjusted to yield interference fringes and the resulting changes in the fringe system are observed when the separation between the reflecting plates is changed. The instrument is calibrated with light of known wavelength, and then is used to measure wavelengths of other "unknown" light sources.

THEORY: Interference fringes are produced in a Fabry-Perot interferometer by the multiple reflection of light in the air film between two plane parallel plates of glass that are lightly silvered. A broad source of light, such as a frosted glass plate illuminated from the rear, is required for producing Fabry-Perot fringes. The source is viewed with the aid of light transmitted through the two plates, as shown in Fig. 1. Concentric circular fringes appear in the field of view when the plates are positioned accurately parallel. When the distance between the plates is increased, the circles expand and new fringes appear at the center. Conversely, the circles contract in size and disappear at the center as the distance between the plates is decreased.

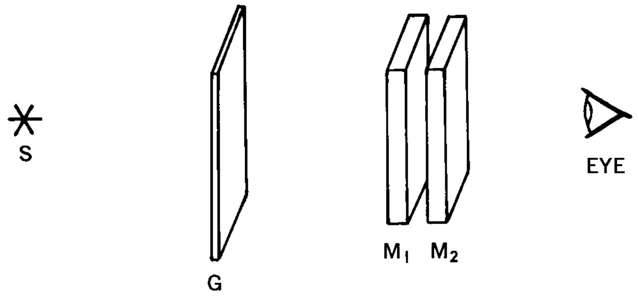

Fig. 1. Optical system for the Fabry-Perot interferometer: S, light source; G, frosted glass plate; M_1 and M_2, lightly silvered mirrors, with silvered surfaces facing each other.

In the M-4 interferometer shown in Fig. 2 one of the mirrors is mounted on a movable plate that is supported on well-machined tracks or "ways." The other mirror is mounted on the main frame of the instrument and is provided with adjusting screws for bringing the two mirrors into parallelism. In this instrument, the movable plate rests directly on the ways and is held securely against them by means of a lock screw that passes through a slot in the plate. Slow motion is provided by means of a micrometer screw, that projects from the base of the instrument, and is accomplished through an intermediate set of levers, one of which is connected to the lock screw. When the lock screw is loosened, the movable plate can be moved by hand to any desired position.

The nature of the interference pattern produced by a Fabry-Perot interferometer can be visualized by referring to Fig. 3. A ray of light such as the one originating from point P on an extended source is broken up by multiple reflection into a series of parallel rays. Interference occurs

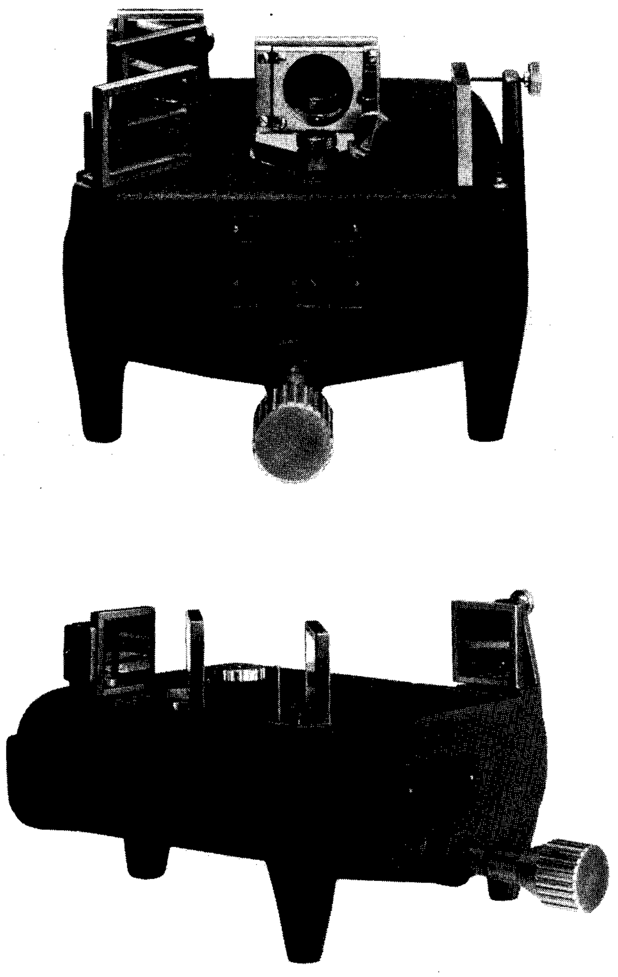

Fig. 2. The Atomic Laboratories M-4 interferometers, with Fabry-Perot attachment (top) and Michaelson optics (bottom). One of the Fabry-Perot plates is mounted on the main frame of the instrument and the other one on the movable carriage.

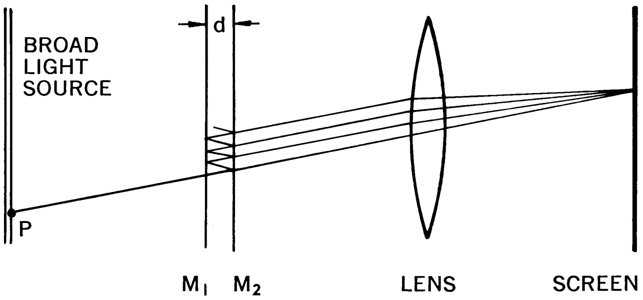

Fig. 3. The equivalent optical system of a Fabry-Perot interferometer. A ray of light from point P on an extended source is multiply reflected by the partially reflecting mirrors M_1 and M_2. Circular fringes are produced on the screen when the resulting rays are brought back together by means of a lens.

when the transmitted rays are brought together—either by the eye of an observer or by the objective lens of a telescope. The rays interfere constructively or destructively depending on the difference in path travelled by adjacent rays. This difference is $2d \cos \phi$, where d is the separation between the plates and ϕ is the angle the particular ray makes with the normal to the plates. If the mirrors are accurately parallel the interference pattern consists of concentric circular fringes, with bright fringes visible in those directions for which the path difference, $2d \cos \phi$, is an integral number of whole wavelengths—the condition for fringes of equal inclination. This condition is the same as that for fringes produced by the Michelson interferometer. However, because of the multiple reflections, there are more than two interfering rays in the Fabry-Perot interferometer and hence Fabry-Perot fringes are sharper than Michelson fringes, as shown by the photographs of Fig. 4.

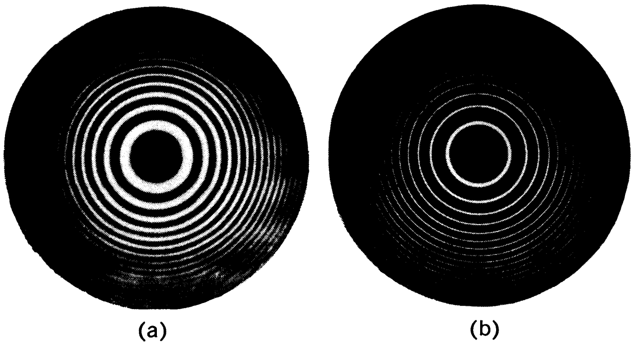
(a) (b)

Fig. 4. Comparison of sharpness of fringes produced with (a) the Michelson interferometer and (b) the Fabry-Perot interferometer with surfaces of reflectance 0.8. From Fundamentals of Optics, *by F. A. Jenkins and H. E. White. Copyright 1957. McGraw-Hill Book Company. Used by permission.*

If the two mirrors in Fig. 3 are within a small fraction of a millimeter of each other, very few fringes will be visible in the field of view, as is clear from the following. The path difference for a pair of adjacent rays is equivalent to $\frac{2d \cos \phi}{\lambda}$ wavelengths, where λ is the wavelength of the light. At normal incidence this difference is $2d/\lambda$ wavelengths. Therefore, within a field of view that extends out to angle ϕ, $\frac{2d}{\lambda}(1 - \cos \phi)$ fringes will be visible, and this number is directly proportional to d. Furthermore, as the distance between the mirrors is changed, $2d \cos \phi$ must remain constant for a particular fringe. Thus, as the mirrors are moved apart, $\cos \phi$ must decrease; the fringes move outward and new fringes appear at the center. Conversely, fringes move inwards and disappear at the center as the distance between the two mirrors is decreased.

In general, as one of the mirrors is moved a distance Δd, the wavelength λ of the light can be determined from the equation

$$2\,\Delta d = n\lambda,$$

where n is the number of fringes that either appear or disappear at the center (or that pass a point near the center). Thus, if one counts fringes for a measured motion of the mirror, the wavelength of the light can be calculated. Conversely, the mechanism for moving the mirror can be calibrated in terms of known wavelength.

APPARATUS: Fabry-Perot interferometer, sodium arc, low pressure mercury arc with green filter, low power telescope (magnification in the range of one to six).

Caution: *The components of an interferometer are delicate and can easily be damaged; they must be handled with care. Under no circumstances should the mirror surfaces be touched or the adjustments be forced.*

PROCEDURE: The interferometer should be mounted on a platform that is as free of vibration as possible and at a height that is convenient for viewing. Bring the Fabry-Perot plates to within a fraction of a millimeter of each other and adjust them by eye to approximate parallelism. Mount a monochromatic source of light in the position S shown in Fig. 1. If the source is a mercury arc, it should be a low-pressure arc for most distinct fringes, and it should be provided with a filter that passes the 5461 A green line (e.g., a Wratten No. 77 or 77A filter, or a thin film filter of appropriate thickness). A frosted glass plate (G in Fig. 1) should be mounted between the source and the interferometer to serve as an extended source of nearly uniform brightness.

To simplify bringing the Fabry-Perot plates into parallelism so that fringes do appear, a black card with a pin hole in it should be placed between the frosted glass plate and the interferometer. Two images of the pinhole can then normally be seen and, by manipulation of the adjusting screws, the two images can be accurately superposed. When the card is removed fringes should appear. If they do not, slight adjustment of the screws should bring them into view, or it may be necessary to repeat the process with the black card and pin hole. Once fringes have been obtained, further small adjustments should be made to center the fringe system in the field of view. When properly adjusted, the fringes will appear to be at infinity and, as one moves his head from side to side, the fringe system will move across the field of view and remain the same size.

Fringes can be viewed either with the naked eye or with a low-power telescope fitted with crosshairs in the eyepiece. The magnifying power of the telescope may be unity or slightly greater. The crosshairs provide a convenient reference system for counting fringes that pass by a given point in the field of view when the distance between the mirrors is being changed. If a telescope is not used, two pins can be mounted in line between the interferometer and the eye to insure that the line of sight remains constant when fringes are being counted.

After having learned how to obtain circular fringes at will, one should become acquainted with the behavior of the fringe system as mirror M_1 is moved. In particular, observe how the direction of motion of the fringes is related to the change in separation between the two mirrors.

I. Calibration of the Interferometer. Mount the low power telescope in viewing position and direct it a little to one side of the center of the circular pattern. It is possible to count the fringes that pass the crosshairs somewhat more reliably with the telescope in this position than to keep track of the fringes that either appear or disappear at the center of the pattern as the distance between the mirrors is changed. Obtain several values of the change in reading of the micrometer screw that causes, say, 100 fringes to move past the crosshairs. To obtain a number of readings expeditiously, take readings of the micrometer screw at every tenth fringe for 190 fringes, and treat the data as follows. Calculate the difference between the readings for the zeroth and the 100th fringes, the 10th and the 110th, etc., on up to the 90th and the 190th fringes. From the average of these data and the known wavelength of the light used, calculate the change in separation between the mirrors for each revolution of the micrometer screw, using the equation $n\lambda = 2d$.

The motion of the base that supports the movable mirror can also be measured directly by using a micrometer microscope together with a scale accurately graduated, for example, to tenths of a millimeter. The scale is attached to the movable base and the microscope is mounted to one side in such a position that the scale can be read conveniently. The microscope should be clamped firmly to the main frame of the interferometer or otherwise secured so that it will not move relative to the instrument while readings are being taken. With the assistance of a second person, the number of fringes that pass the field of view can then be counted while the movable mirror is moved through successive one-tenth millimeter steps.

II. Determination of the Difference between the Wavelengths of the Sodium D lines. The yellow line of sodium ordinarily seen in an instrument of low resolving power consists of two lines of wavelengths λ_1 and λ_2, separated by only a few Angstrom units. Thus, when a sodium arc is used with the Fabry-Perot interferometer, each line produces a separate fringe system. When the two Fabry-Perot plates are almost touching, so that $2d$ is almost zero, the two sets of fringes fall on top of each other and the fringes appear sharp and extra bright. As the plates are separated, one set of fringes moves outward somewhat more rapidly than the other, and when the distance between the mirrors is such that

$$2d_1 = n_1\lambda_1 = (n_1 + \tfrac{1}{2})\,\lambda_2 \qquad (1)$$

the two fringe systems will be exactly interlaced—the fringes of one set will lie midway between those of the other set. If the distance between the mirrors is continuously increased, the fringes can again be made to overlap and then to separate until

$$2d_2 = n_2\lambda_2 = (n_2 + \tfrac{1}{2})\,\lambda_2 \qquad (2)$$

at which time the two systems are again exactly interlaced. By determining the distance between adjacent settings where the two systems are exactly interlaced, you can calculate the difference between the two wavelengths. From Eqs. 1 and 2,

$$\lambda_1 - \lambda_2 = \frac{\lambda_1\,\lambda_2}{2\,(d_2 - d_1)},$$

Or, the difference between the wavelengths is given by

$$\Delta\lambda = \frac{\lambda^2}{2d} \qquad (3)$$

where λ is the geometric mean of the two wavelengths and d is the distance between adjacent settings for which the two fringe systems are exactly interlaced.

1. Wavelength Measurement: Adjust the interferometer to give distinct fringes when a sodium arc is used as the source of light. Obtain a series of micrometer readings for every 10th fringe that passes the crosshairs for 190 fringes. If you make your measurements over a range where the two sets of fringes are resolved one from the other, you must be sure to count only those fringes that belong to one set—count alternate fringes only. Also, observe which set of fringes you are measuring. If it is the set that moves out more rapidly than the other set, you are measuring the D line of shorter wavelength. If the measurements are made over a range where the two sets of fringes overlap, your readings will give the average wavelength of the D lines. Note that if there is any play or backlash in the micrometer system, successive sets of readings must all be approached from the same direction. Treat your data as outlined earlier, and use the calibration obtained in Part I for calculating the wavelength.

2. Difference in Wavelength between the Sodium D Lines: Obtain as many settings as the range of the micrometer screw will permit of the positions where the two sets of fringes in sodium light are most accurately interlaced. Determine the average distance d between these settings and calculate the difference in wavelength between the two lines of sodium, using Eq. 3.

The micrometer screw mechanism for moving the movable mirror in each of the Atomic Laboratories instruments shown in Fig. 2 has a limited range and thus one can obtain only two settings of the positions where the two fringe systems are interlaced. Since it is difficult to estimate the position where one set of lines is exactly midway between those of the other set, several readings for each setting should be obtained and approaches should be made from each direction. The accuracy of the final average can be improved by taking pairs of readings of the setting when one set of lines is judged to be just barely to one side of center and then when barely on the opposite side.

Since the ways on the Atomic Laboratories instruments permit considerably more motion than can be produced by the micrometer screws, additional settings can be obtained if the base on which the movable mirror is mounted is moved by hand. A micrometer microscope together with a finely divided scale are used as described in Part I. The scale is read each time the fringe systems overlap and also when they are interlaced, and each set of data is treated as described earlier for a similar set in Part I. If, say, 19 readings for each set are obtained, one can calculate the difference between the zeroth and the tenth readings, the first and the eleventh, and so on. From the final average, d can be determined and $\Delta\lambda$ calculated.

QUESTIONS: 1. Estimate the probable error in your calibration of the Fabry-Perot interferometer from the variation amongst the individual readings for 100 fringes obtained in Part I. Use this information together with the estimated uncertainty in the readings in Part II to determine the approximate probable error for your wavelength measurements of sodium light.

2. When only two rays of light interfere with each other, as in the Michelson interferometer, the fringes that are produced are broad—brightness gradually fades into darkness on each side of a fringe. When a large number of rays interfere with each other, as in the Fabry-Perot interferometer, the fringes are much narrower (see Fig. 4). Explain what the number of rays has to do with this.

3. Prove that adjacent rays in Fig. 3 will interfere with each other constructively if $2d \cos \phi = n\lambda$.

4. Calculate the number of fringes that must pass a point in the field of view for one of the D lines of sodium when the Fabry-Perot plate separation is changed from one position where the two sets of fringes are interlaced to the next position.

5. Derive Eq. 3 from Eqs. 1 and 2.

6. Explain why the fringes associated with the sodium D line of shorter wavelength move out more rapidly than those for the line of longer wavelength when the separation between the Fabry-Perot plates is increased.