PSE-605
Photonics Lab Techniques
Semester II: 2019-2020

Centre for Lasers and Photonics
IIT Kanpur
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## SCHEDULE OF EXPERIMENTS

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### First Round

- **Week 1**: 8-9 Jan.
- **Week 2**: 15-16 Jan
- **Week 3**: 22-23 Jan
- **Week 4**: 29-30 Jan
- **Week 5**: 5-6 Feb
- **Week 6**: 12-13 Feb

### Second Round

- **Week 1**: 26-27 Feb
- **Week 2**: 4-5 Mar
- **Week 3**: 18-19 Mar
- **Week 4**: 25-26 Mar
- **Week 5**: 1-4 Apr
- **Week 6**: 8-9 Apr

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REPORT PREPARATION GUIDELINES

REPORT WRITING

All experiments require a formal laboratory report. The report should be written in such a way that anyone could duplicate the performed experiment and obtain same results, i.e., the reports should be simple and clearly written. **Reports are due seven days after the date of experiment.** The report should communicate several ideas to the reader:

1. The report should be neatly done. The experimenter is in effect trying to convince the reader that the experiment was performed in a straightforward manner with great care and with full attention to detail. A poorly written report might instead lead the reader to think that just as little care went into performing the experiment.
2. The report should be well organized. The reader should be able to easily follow each step discussed in the text.
3. The report should contain accurate results. This will require checking and rechecking the calculations until accuracy can be guaranteed.
4. The report should be free of spelling and grammatical errors.

FORMAT OF REPORTS

**Title Page**—The title page should show the title and number of the experiment, the date the experiment was performed, experimenter's name and experimenter's partners' names (if any).

**Table of Contents**—Each page of the report must be numbered for this section.

**Objective**—The objective is a clear concise statement explaining the purpose of the experiment. This is one of the most important parts of the laboratory report because everything included in the report must somehow relate to the stated objective. The objective can be as short as one sentence, and is usually written in the past tense.

**Results**—The results section should contain a formal analysis of the data with tables, graphs, etc. Any presentation of data, which serves the purpose of clearly showing the outcome of the experiment, is sufficient.

**Discussion and Conclusion**—This section should give an interpretation of the results explaining how the objective of the experiment was accomplished. If any analytical/empirical expression is to be verified, calculate the % error and account for the sources. Discuss this experiment with respect to its faults as well as its strong points. Suggest extensions of the experiment and improvements. Also recommend any changes necessary to better accomplish the objective. Each experiment contains a number of questions. These are to be answered or discussed in the **Discussion and Conclusions** section.
Appendix
(1) Original data sheet (signed by the TA in charge of that experiment)
(2) Sample calculation, showing the adopted data analysis procedure.
(3) Calibration curves of instrument, which was used in the performance of the experiment. Include manufacturer of the instrument, model and serial numbers. The instructor will usually supply calibration curves.
(4) Bibliography listing all references used.

Graphs
In many instances, it is necessary to compose a plot in order to graphically present the results. Graphs must be drawn neatly following a specific format. There are many computer programs that have graphing capabilities. Nevertheless an acceptably drawn graph has several features of note.

Features of note
- Border is drawn about the entire graph.
- Axis labels defined with symbols and units.
- Grid drawn using major axis divisions.
- Each line is identified using a legend.
- Data points are identified with a symbol
- The line representing the theoretical results has no data points represented.
- Nothing is drawn freehand.
- Title is descriptive.

QUESTIONS TO ASK?

The experimental procedure suggested in the manual should not be followed blindly. The students should always ask questions. Remember that we conduct experiments to verify the theoretical observation or to generate empirical data.
CLEANLINESS AND SAFETY

Cleanliness

There are “housekeeping” rules that the user of the laboratory should be aware of and abide by. Equipment in the lab are delicate and it is important that the equipment stay clean. If no one cleaned up his or her working area after performing an experiment, the lab would not be a comfortable or safe place to work in. No student appreciates walking up to and working with a piece of equipment that another student or group of students has left in a mess. Consequently, students are required to clean up their area at the conclusion of the performance of an experiment. Wipe the table top on which the equipment are mounted and place the equipment and other accessories in order. The lab should always be as clean or cleaner than it was when you entered. Cleaning the lab is your responsibility as a user of the equipment. This is an act of courtesy that students who follow you will appreciate, and that you will appreciate when you work with the equipment.

Safety:

Do not disturb the fellow students. Everyone is suggested to talk to the TA ONLY in case of any doubt. Every effort has been made to create a positive, clean, safety conscious atmosphere. Students are encouraged to handle equipment safely and to be aware of, and avoid being victims of, hazardous situations.

Note: There is a penalty (10% per day) for late submission of reports.
Essentials of Data Analysis

This chapter tries to give you a working knowledge of data analysis which would be essential in all experiments that you do. Specifically, the following topics are covered:

- Error Analysis
- Graphical Analysis
- Significant Figures

ERROR ANALYSIS

To err is human; to evaluate and analyze the error is scientific

1. Introduction:

Every measured physical quantity has an uncertainty or error associated with it. An experiment, in general, involves

(i) direct measurement of various quantities (primary measurements) and
(ii) calculation of the physical quantity of interest which is a function of the measured quantities. An uncertainty or error in the final result arises because of the errors in the primary measurements (assuming that there is no approximation involved in the calculation).

For example, the result of a recent experiment to determine the velocity of light (Phys. Rev. Lett. 29, 1346(1972) was given as

\[ C = (299,792,456.2 \pm 1.1) \text{ m/sec} \]

The error in the value of C arises from the errors in primary measurements viz., frequency and wavelength.

Error analysis, therefore, consists of (i) estimating the errors in all primary measurements, and (ii) propagating the error at each step of the calculation. This analysis serves two purposes. First, the error in the final result is an indication of the precision of the measurement and, therefore, an important part of the result. Second, the analysis also tells us which primary measurement is causing more error than others and thus indicates the direction for further improvement of the experiment.
For example, in measuring ‘g’ with a simple pendulum, if the error analysis reveals that the errors in ‘g’ caused by measurements of l (length of the pendulum) and T (time period) are 0.5 cm/sec$^2$ and 3.5 cm/sec$^2$ respectively, then we know that there is no point in trying to devise a more accurate measurement of l. Rather, we should try to reduce the uncertainty in T by counting a larger number of periods or using a better device to measure time. Thus, error analysis prior to the experiment is an important aspect of planning the experiment.

Nomenclature of Errors:
(i)  Discrepancy denotes the difference between two measured values of the same quantity.
(ii) Systematic errors occur in every measurement in the same way – often in the same direction and of the same magnitude – for example, length measurement with a faulty scale. These errors can, in principle, be eliminated or corrected for by proper analysis and calibration.
(iii) Random errors cause the result of a measurement to deviate in either direction from its true value. We shall confine our attention to these errors and discuss them under two heads: estimated and statistical errors.
(iv) A measurement which has small random errors has high precision. A measurement which has small random errors as well as systematic errors has high accuracy.

2. Estimated Errors
   (a) Estimating a primary error
   An estimated error is an estimate of the maximum extent to which a measured quantity might deviate from its true value. For a primary measurement, the estimated error is often taken to be the least count of the measuring instrument. For example, if the length of a string is to be measured with a meter rod, the limiting factor is the accuracy in the least count, i.e., 0.1 cm. A note of caution is needed here.

   What matters really is the effective least count and not the nominal least count. For example, in measuring electric current with an ammeter, if the smallest division corresponds to 0.1 amp., but the marks are far enough apart so that you can easily make out a quarter of a division, then the effective least count will be 0.025 amp. On the other hand, if you are reading a Vernier scale where three successive marks on the Vernier scale (say 27th, 28th, 29th) look equally well in coincidence with the main scale, the effective least count is 3 times the nominal one. The estimated error is, in general, to be related to the limiting factor in the accuracy. This limiting factor need not always be the least count. Take another example. In a null-point electrical measurement, suppose the deflection in the galvanometer seems to remain zero for all values of resistance R from 351 Ω to 360 Ω. In that case, the uncertainty in R is 10 Ω, even though the least count of the resistance box may be less. Therefore, make a judicious estimate of the least count.
(b) Propagation of estimated errors

How to calculate the error associated with $f$, which is a function of measured quantities $a$, $b$ and $c$? Let

$$f = f(a, b, c) \quad (1)$$

From differential calculus (Taylor’s series in the 1$^{\text{st}}$ order)

$$df = \frac{\partial f}{\partial a} \, da + \frac{\partial f}{\partial b} \, db + \frac{\partial f}{\partial c} \, dc. \quad (2)$$

Eq. (2) relates the differential increment in $f$ resulting from differential increments in $a$, $b$, $c$. Thus if our errors in $a$, $b$, $c$ (denoted as $\delta a$, $\delta b$, $\delta c$) are small compared to $a$, $b$, $c$, respectively, then we may say

$$\delta f = \left| \frac{\partial f}{\partial a} \right| \delta a + \left| \frac{\partial f}{\partial b} \right| \delta b + \left| \frac{\partial f}{\partial c} \right| \delta c \quad (3)$$

Where the modulus signs have been put because errors in $a$, $b$, and $c$ are independent of each other and may be in the positive or negative direction. Therefore the maximum possible error will be obtained only by adding absolute values of all the independent contributions. (All the $\delta$'s are considered positive by definition). Special care has to be taken when all errors are not independent of each other. This will become clear in special case (V) below.

Some simple cases:

(i) For addition or subtraction, the absolute errors are added, e.g.

If $f = a + b - c$, then

$$\delta f = \delta a + \delta b + \delta c \quad (4)$$

(ii) For multiplication and division, the fractional (or percent) errors are added, e.g.,

If $f = ab/c$, then

$$\left| \frac{1}{f} \right| \delta f = \left| \frac{1}{a} \right| \delta a + \left| \frac{1}{b} \right| \delta b + \left| \frac{1}{c} \right| \delta c. \quad (5)$$
(iii) For raising to constant powers, including fractional powers, the fractional error is multiplied by the power, e.g.,

If \( f = a^{3.6} \), then

\[
\left| \frac{1}{f} \right| \delta f = \left| 3.6 \times \frac{1}{a} \right| \delta a. \tag{6}
\]

(iv) In mixed calculations, break up the calculation into simple parts, e.g.,

If \( f = a/b - c^{3/2} \), then

\[
\delta f = \delta \left( \frac{a}{b} \right) + \delta (c^{3/2})
\]

Since,

\[
|b/a| \delta (a/b) = \left| \frac{1}{a} \right| \delta a + \left| \frac{1}{b} \right| \delta b + \left| \frac{1}{c^2} \right| \delta \left(c^{3/2}\right) = \left| \frac{2}{ac} \right| \delta c \tag{7}
\]

So, \( \delta f = \left| \frac{1}{b} \right| \delta a + \left| \frac{a}{b^2} \right| \delta b + \left| \frac{3}{2c^{1/2}} \right| \delta c. \)

Note that the same result could have been derived directly by differentiation.

(v) Consider \( f = ab/c - a^2 \).

The relation for error, before putting the modulus signs, is

\[
\delta f = \left( \frac{b}{c} \right) \delta a + \left( \frac{a}{c} \right) \delta b - \left( \frac{ab}{c^2} \right) \delta c - 2a \delta a.
\]

Note that the \( \delta a \) factors in the first and fourth terms are not independent errors. Therefore, we must not add the absolute values of these two terms indiscriminately. The correct way to handle it is to collect the coefficients of each independent errors before putting modulus signs, i.e.,

\[
\delta f = \left| \frac{b}{c} - 2a \right| \delta a + \left| \frac{a}{c} \right| \delta b + \left| \frac{ab}{c^2} \right| \delta c. \tag{8}
\]

(3). Statistical Errors

(a) Statistical distribution and standard deviation: Statistical errors arise when making measurements on random processes, e.g. counting particles emitted by a radioactive source. Suppose we have a source giving off 10 particles/sec. on the average. In order to evaluate this
count rate experimentally, we count the number of particles for 2 seconds. Shall we get 20 counts? Not necessarily. In fact, we may get any number between zero and infinity. Therefore, in a measurement on a random process, one cannot specify a maximum possible error. A good measure of uncertainty in such a case is the standard deviation \((s.d.)\) which specifies the range within which the result of any measurement is “most likely” to be.

The exact definition of “most likely” depends on the distribution governing the random events. For all random processes whose probability of occurrence is small and constant. Poisson distribution is applicable, i.e.,

\[
P_n = \frac{m^n}{n!} e^{-m} \tag{9}\]

Where, \(P_n\) is the probability that you will observe a particular count \(n\) when the expectation value is \(m\).

It can be shown that if an infinite number of measurements are made, (i) their average would be \(m\) and (ii) their standard deviation \((s.d.)\) would be \(\sqrt{m}\), for this distribution. Also if \(m\) is not too small then 68\% or nearly two-thirds of the measurements would yield numbers within one s.d. in the range \(m \pm \sqrt{m}\).

In radioactive decay and other nuclear processes, the Poisson distribution is generally valid. This means that we have a way of making certain conclusions without making an infinite number of measurements. Thus, if we measure the number of counts only once, for 100 sec, and the number is say 1608, then (i) our result for average count rate is 16.08/sec, and (ii) the standard deviation is \(\sqrt{1608} = 40.1\) counts which correspond to 0.401/sec. So our result for the count rate is \((16.08 \pm 0.40 /\text{sec}^{-1})\). The meaning of this statement must be remembered. The actual count rate need not necessarily lie within this range, but there is 68\% probability that it lies in that range.

The experimental definition of \(s . d.\) for \(k\) measurements of a quantity \(x\) is

\[
\sigma_x = \sqrt{\frac{\sum_{n=1}^{k} (\delta x_n^2)}{k} - 1.} \tag{10}\]
Where $\delta_n^x$ is the deviation of measurement $x_n$ from the mean. However since we know distribution, we can ascribe the s.d. even to a single measurement.

(b) **Propagation of statistical errors:** For a function $f$ of independent measurements $a, b, c$, the statistical error $\sigma_f$ is

$$\sigma_f = \sqrt{\left(\frac{\partial f}{\partial a} \sigma_a\right)^2 + \left(\frac{\partial f}{\partial b} \sigma_b\right)^2 + \left(\frac{\partial f}{\partial c} \sigma_c\right)^2}$$  \hspace{1cm} (11)

A few simple cases are discussed below.

(i) For addition or subtraction, the squares of errors are added e.g.

If $f = a + b - c$

Then,

$$\sigma_f^2 = \sigma_a^2 + \sigma_b^2 + \sigma_c^2$$  \hspace{1cm} (12)

(ii) For multiplication or division, the squares of fractional errors are added, e.g.

If $f = ab/c$, then

$$\left(\frac{\sigma_f}{f}\right)^2 = \left(\frac{\sigma_a}{a}\right)^2 + \left(\frac{\sigma_b}{b}\right)^2 + \left(\frac{\sigma_c}{c}\right)^2$$  \hspace{1cm} (13)

(iii) If a measurement is repeated $n$ times, the error in the mean is a factor $\sqrt{n}$ less than the error in a single measurement. i.e.,

$$\sigma_f^- = \frac{\sigma_f}{\sqrt{n}}$$  \hspace{1cm} (14)

Note that Eqs. (11-14) apply to any statistical quantities $a, b$ etc. i.e., primary measurements as well as computed quantities whereas

$$\sigma_m = \sqrt{m}$$  \hspace{1cm} (15)

Applies only to a directly measured number. Say, number of $\alpha$- particle counts but not to computed quantities like count rate.
4. Miscellaneous

i) Repeated measurements: Suppose a quantity \( f \), whether statistical in nature or otherwise is measured \( n \) times. The best estimate for the actual value of \( f \) is the average \( f \) of all measurements. It can be shown that this is the value with respect to which the sum of squares of all deviations is a minimum. Further, if errors are assumed to be randomly distributed, the error in the mean value is given by

\[
\delta_f = \frac{\delta f}{\sqrt{n}}.
\]

Where \( \delta_f \) is the error in one measurement. Hence one way of minimizing random errors is to repeat the measurement many times.

ii) Combination of statistical and estimated errors: In cases where some of the primary measurements have statistical errors and others have estimated errors, the error in the final result is indicated as a s.d. and is calculated by treating all errors as statistical.

iii) Errors in graphical analysis: The usual way of indicating errors in quantities plotted on graph paper is to draw error bars. The curve should then be drawn so as to pass through all or most of the bars.

Here is a simple method of obtaining the best fit for a straight line on a graph. Having plotted all the points \((x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\), plot also the centroid \((\bar{x}, \bar{y})\).

Then consider all straight lines through the centroid (use a transparent ruler) and visually judge which one will represent the best mean.
Having drawn the best line, estimate the error in slope as follows. Rotate the ruler about the centroid until its edge passes through the cluster of points at the ‘top right’ and the ‘bottom left’. This new line gives one extreme possibility; let the difference between the slopes of this and the best line be $\Delta m_1$. Similarly determine $\Delta m_2$ corresponding to the other extreme. The error in the slope may be taken as

$$\Delta m = \frac{\Delta m_1 + \Delta m_2}{2} \frac{1}{\sqrt{n}}$$

Where $n$ is the number of points. The factor $\sqrt{n}$ comes because evaluating the slope from the graph is essentially an averaging process.

It should be noted that if the scale of the graph is not large enough, the least count of the graph may itself become a limiting factor in the accuracy of the result. Therefore, it is desirable to select the scale so that the least count of the graph paper is much smaller than the experimental error.

**iv) Significant Figures:** A statement of result such as $f = 123.4678 \pm 1.2331$ cm contains many superfluous digits. Firstly, the digits 678 in quantity $f$ do not mean anything because they represent something much smaller than the uncertainty $\delta f$. Secondly, $\delta f$ is an *approximate* estimate for error and should not need more than one significant figure. An acceptable expression would be $123.4 \pm 0.2$ cm.

No physical measurement is exact. For example, consider a meter scale, which has a least count of 1 mm used for measuring the length of a pencil. The reading, if we keep one end at the origin of the scale, might lie between say 8.5 cm and 8.6 cm. One might estimate the length as 8.52 cm, the final digit (2) being an estimate of a part of a millimeter division on the scale. Perhaps the estimate of final digit could have been 3 or 1 instead of 2. In any case, we
find that the length expressed as 8.52 tells us that the length lies between 8.53 and 8.51 – the measurement has 3 significant figures. A significant figure is reasonably trustworthy. The number of significant figures does not depend upon the decimal point. The length could have been written as .0852 m or as 85.2 mm which mean exactly the same thing. Whenever we make a measurement, our reading should indicate the number of significant figures. Suppose we want to measure the area of a square whose sides are 8.52 cm with the final digit indicating the precision or accuracy of the measurement. In this case, the number has 3 significant figures. Then to what precision or accuracy do we know the area? We know

\[ A = l^2 \quad (\Delta l \text{ is the possible error in } l = 0.01 \text{ cm}) \]

\[ \Delta A = 2l \Delta l = 2 \times 8.52 \times 0.01 = 17.04 \times 0.01 \approx 0.17 \text{ cm}^2 \]

Hence the area is known to an accuracy of 0.2 cm² which means

\[ A = (8.52)^2 \text{ cm}^2 = 72.6 \text{ cm}^2 \text{ (keeping only the first digit after the decimal point)} \]

In addition and subtraction carry the operation only as far as the first column of doubtful figure,

(1) Addition of two lengths.

\[ \ell_1 = 2.54 \text{ cm} \quad \text{(known to 3 significant figures)} \]

\[ \ell_2 = 10.29 \text{ cm} \quad \text{(known to 4 significant figures)} \]

\[ \ell_1 + \ell_2 = \underline{12.83} \text{ cm} \]

The doubtful figure is underlined.

On the other hand if

\[ \ell_1 = 2.5 \]

\[ \ell_2 = 10.22 \]

\[ \ell_1 + \ell_2 = 12.72 = 12.7 \]

(2) Multiplication of two lengths:

If \( \ell_1 = 2.54 \text{ cm} \) and \( \ell_2 = 10.29 \text{ cm} \)

\[ \ell_1 \times \ell_2 = 2.54 \times 10.29 = 26.1366 = 26.1 \text{ cm}^2 \]
where we have rounded off keeping only the first doubtful figure. In this case the second doubtful figure being 3 does not change the first doubtful figure in rounding off.

For rounding off the insignificant figures (doubtful figures after the first doubtful figure) are dropped, but the first doubtful figure (or the last significant figure) is unchanged if the figure dropped is less than 5. It is increased by 1 if it is greater than 5. There are different practices for rounding off if the figure dropped is 5. You can take any of them. You can increase the digit by 1 in this case if you so like. Alternatively, you may keep the digits after 5 also, keeping 2 significant figures in the error bar.

Rules for Computation

1. In addition and subtraction take only the first column that contains the doubtful figure. Use the rule of rounding off mentioned earlier.

2. In multiplication and division, carry the result to the same number of significant figures that are in the factor with the least number of significant figures.

An Example

(1) Consider the measurement of acceleration due to gravity \((g)\) using the simple pendulum. We have,

\[
g = \frac{4\pi^2 l}{T^2}
\]

where \(l\) = length and \(T\) = time period of the pendulum. Suppose, \(l = 95.2\) cm and \(T = 1.95\) sec

\[
g = \frac{4\pi^2 l}{T^2} = 988.388\ \text{cm/sec}^2\ \text{(obtained by calculator)}
\]

However, not all figures are significant. To determine which figures are significant, we note

\[
\frac{\Delta g}{g} = \left(\frac{\Delta l}{l}\right) + 2\left(\frac{\Delta T}{T}\right)
\]

\[
= \frac{0.1}{95.2} + 2\left(\frac{0.01}{1.95}\right) \approx 0.01
\]

which shows that the number of significant figures in this case is only 2. Indeed, \(\approx 0.01 \approx 990\) cm/sec\(^2\) which means that the second digit is uncertain and we should write the answer as \(g = 990\) cm/sec\(^2\).

Note that \(\Delta l\) and \(\Delta T\) are not necessarily the least counts of the scale and the clock repeatedly used to measure the quantities. Depending on the circumstances they may be larger or even smaller than the least count. If the pendulum’s ends cannot be defined (located) precisely \(\Delta l\) could be
limited by this rather than least count of the scale used. Similarly T can read far more accurately than the clock’s least count by taking reading’s for the time taken for more than one oscillation.

v) Instructions

1. Calculate the estimated/ statistical error for final result. In any graph you plot, show error bars. (If the errors are too small to show up on the graph, then write them somewhere on the graph).
2. If the same quantity has been measured/ calculated many times, you need not determine the error each time. Similarly one typical error bar on the graph will be enough.
3. In propagating errors, the contributions to the final error from various independent measurements must be show. For example if

\[ f = ab; \ \frac{\delta f}{|f|} = \frac{\delta a}{|a|} + \frac{\delta b}{|b|}, \ a = 10.0 \pm 0.1, b = 5.1 \pm 0.2. \]

Then,

\[ \delta f = 51.0 \left[ \frac{0.1}{10.0} + \frac{0.2}{5.1} \right] = 0.51 + 2.0 = 2.5 \]

Therefore, \( f = 51.0 \pm 2.5 \).

Here the penultimate step must not be skipped because it shows that the contribution to the error from \( \delta b \) is large.

4. Where the final result is a known quantity (for example, \( e/m \)), show the discrepancy of your result from the standard value. If this is greater than the estimated error, this is abnormal and requires explanation.

5. Where a quantity is determined many times, the standard deviation should be calculated from Eq.(10). Normally, the s.d. should not be more than the estimated error. Also the individual measurements should be distributed only on both sides of the standard value.

vi) Mean and Standard Deviation

If we make a measurement \( x_1 \) of a quantity \( x \), we expect our observation to be close to the quantity but not exact. If we make another measurement we expect a difference in the observed value due to random errors. As we make more and more measurements we expect them to be
distributed around the correct value, assuming that we can neglect or correct for systematic errors. If we make a very large number of measurements we can determine how the data points are distributed in the so-called parent distribution. In any practical case, one makes a finite number of measurements and one tries to describe the parent distribution as best as possible.

Consider N measurements of quantity x, yielding values \(x_1, x_2, \ldots, x_N\). One defines

\[
\text{Mean } \bar{x} = \lim_{N \to \infty} \left[ \left( \frac{1}{N} \sum_{i=1}^{N} x_i \right) \right]
\]

(1)

Which is equivalent to the centroid or average value of the quantity x.

Deviations: The deviation \(d_i\) of any measurement \(x_i\) from the mean \(\bar{x}\) of the parent distribution is defined as

\[
d_i = x_i - \bar{x}.
\]

(2)

Note that if the \(\bar{x}\) is the true value of the quantity being measured, \(d_i\) is also the true error in \(x_i\).

The arithmetic average of the deviations for an infinite number of observations must vanish, by definition of \(\bar{x}\) (Eq (1)).

\[
\lim_{N \to \infty} \left[ \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x}) \right] = \lim_{N \to \infty} \left[ \frac{1}{N} \sum_{i=1}^{N} x_i \right] - \bar{x} = 0
\]

(3)

There are several indices one can use to indicate the spread (dispersion) of the measurements about the central value, i.e., the mean value. The dispersion is a measure of precision. One can define average deviation \(d\) as the average of the magnitudes of the deviations (absolute values of the deviations).

\[
d = \lim_{N \to \infty} \left[ \frac{1}{N} \sum_{i=1}^{N} |x_i - \bar{x}| \right]
\]

This can be used as a measure of the dispersion of the expected observation about the mean. However, a more appropriate measure of the dispersion is found in the parameter called standard deviation \(\sigma\), defined as
\[
\sigma^2 = \lim_{N \to \infty} \left[ \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2 \right] = \lim_{N \to \infty} \left( \frac{1}{N} \sum (x_i)^2 - (\bar{x})^2 \right)
\]

(4)

\(\sigma^2\) is known as VARIANCE and STANDARD DEVIATION \(\sigma\) is the square root of the variance. In other words it is the root mean square (rms) of deviations. That is

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{N} d_i^2}{N}}
\]

(5)

The expression derived from a statistical analysis is

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{N} d_i^2}{(N - 1)}}
\]

(6)

Where, the denominator is \(N-1\) instead of \(N\). In practice the distinction between these formulae is unimportant. According to the general theory of statistics the reliability of a result depends upon the Number of measurements and in general, improves with the square root of the number.

**Significance:** The mean \(\bar{x}\), is a parameter which characterizes the information we are seeking when we perform an experiment. The mean is, of course, not the only parameter which is used to characterize a distribution, but it is the most popular one and also the best when an experiment is performed under near ideal conditions\[^1\]. It can be proved that if we use the average (mean) of the measured values for calculating the deviations, the sum of the square of the deviations is a minimum. The standard deviation is simply related to this minimum value of the square of the deviations and is used for specifying error quantitatively.

The standard deviation characterizes the uncertainties associated with our experimental attempts to determine the “true” value- mean value (defined by Eq.(1) for all practical purposes. \(\sigma\), for a given finite number of observations is the uncertainty in determining the mean of the parent distribution. Thus it is an appropriate measure of the uncertainty in the observations.

\[^1\text{In place of mean, one can characterize a distribution by the median (the middle value) which is a robust measure of central tendency. Median would give a better estimate than the mean if the data set is}\]
contaminated by too much noise and contains outlier points. Mean gives all the data points equal weight and hence can be easily affected by an outlier while the median would automatically reject an outlier. The appropriate width to use with the median is the mean deviation which is the average absolute deviation calculated from the median. One can show that the average absolute deviation is a minimum if it is calculated about the median.

**(vii) Method of Least Squares**

Our data consist of pairs of measurements \((x_i, y_i)\) of an independent variable \(x\) and a dependent variable \(y\). We wish to fit the data to an equation of the form

\[
y = a + bx
\]  

(1)

By determining the values of the coefficients \(a\) and \(b\) such that the discrepancy is minimized between the values of our measurements \(y_i\) and the corresponding values \(y = f(x_i)\) given by Eq. (1). We cannot determine the coefficients exactly with only a finite number of observations, but we do want to extract from these data the most probable estimates for the coefficients.

The problem is to establish criteria for minimizing the discrepancy and optimizing the estimates of the coefficients. For any arbitrary values of \(a\) and \(b\), we can calculate the deviations \(\delta y_i\) between each of the observed values \(y_i\) and the corresponding calculated values

\[
\delta y_i = y_i - a - bx_i
\]  

(2)

If the coefficients are well chosen, these deviations should be relatively small. The sum of these deviations is not a good measure of how well we have approximated the data with our calculated straight line because large positive deviations can be balanced by large negative ones to yield a small sum even when the fit is bad. We might however consider summing up the absolute values of the deviations, but this leads to difficulties in obtaining an analytical solution. We consider instead the sum of the squares of deviations. There is no unique correct method for optimizing the coefficients which is valid for all cases. There exists, however, a method which can be fairly well justified, which is simple and straightforward, which is well established experimentally as being appropriate, and which is accepted by convention. This is the method of least squares which we will explain using the method of maximum likelihood.
**Method of maximum likelihood:** Our data consist of a sample of observations extracted from a parent distribution which determines the probability of making any particular observation. Let us define parent coefficients $a_0$ and $b_0$ such that the actual relationship between $y$ and $x$ given by

$$y(x) = a_0 + b_0 x$$  \hspace{1cm} (3)

For any given value of $x = x_i$, we can calculate the probability $P_i$ for making the observed measurement $y_i$ assuming a Gaussian distribution with a standard deviation $\sigma_i$ for the observations about the actual value $y(x_i)$

$$P_i = \frac{1}{\sigma_i \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{y_i - y(x_i)}{\sigma_i} \right)^2 \right]$$

The probability for making the observed set of measurements of the $N$ values of $y_i$ is the product of these probabilities

$$P(a_0, b_0) = \prod P_i = \prod \left[ \frac{1}{\sigma_i \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{y_i - y(x_i)}{\sigma_i} \right)^2 \right] \right] \hspace{1cm} (4)$$

Where the product $\Pi$ is taken for $i$ ranging from 1 to $N$.

Similarly, for any estimated values of the coefficients $a$ and $b$, we can calculate the probability that we should make the observed set of measurements

$$P(a, b) = \prod \left( \frac{1}{\sigma_i \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\delta y_i}{\sigma_i} \right)^2 \right] \right) \hspace{1cm} (5)$$

The method of maximum likelihood consists of making the assumption that the observed set of measurements is more likely to have come from the actual parent distribution of Eq. (3) than from any other similar distribution with different coefficients and, therefore, the probability of Eq. (4) is the maximum probability attainable with Eq. (5) The best estimates for $a$ and $b$ are therefore those values which maximize the probability of Eq.(5).

The first term of Eq. (5) is a constant, independent of the values of $a$ or $b$. thus, maximizing the probability $P(a, b)$ is equivalent to minimizing the sum in the exponential. We define the quantity $x^2$ to be this sum

$$x^2 = \sum \left( \frac{\delta y_i}{\sigma_i} \right)^2 = \sum \left[ \frac{1}{\sigma_i^2} (y_i - a - bx_i)^2 \right] \hspace{1cm} (6)$$
Where $\sum$ always implies $\sum_{i=1}^{N}$ and consider this to be the appropriate measure of the goodness of fit.

Our method for finding the optimum fit to the data will be to minimize this weighted sum of squares of deviations and, hence, to find the fit which produces the smallest sum of squares or the least-squares fit.

**Minimizing $x^2$:** In order to find the values of the coefficients $a$ and $b$ which yield the minimum value for $x^2$, we use the method of differential calculus for minimizing the function with respect to more than one coefficient. The minimum value of the function $x^2$ of Eq.(6) is one which yields a value of zero for both of the partial derivatives with respect to each of the coefficients.

\[
\frac{\partial}{\partial a} x^2 = \frac{\partial}{\partial a} \left[ \frac{1}{\sigma_i^2} (y_i - a - bx_i)^2 \right] = -\frac{2}{\sigma^2} \sum \left( y_i - a - bx_i \right) = 0
\]

\[
\frac{\partial}{\partial b} x^2 = -\frac{2}{\sigma^2} \sum \{ x_i (y_i - a - bx_i) \} = 0
\]

Where we have for the present considered all of standard deviation equal, $\sigma_i = \sigma$. in other words, errors in $y$’s are assumed to be same for all values of $x$.

These equations can be rearranged to yield a pair of simultaneous equations

\[
\sum y_i = aN + b \sum x_i \\
\sum x_i y_i = a \sum x_i + b \sum x_i^2
\]

Where we have substituted Na for $\sum_{i=1}^{N} a$ since the sum runs from $i = 1$ to $N$.

We wish to solve Eqs.(8) for the coefficients $a$ and $b$. This will give us the values of the coefficients for which $x^2$, the sum of squares of the deviations of the data points from the calculated fit, is a minimum. The solutions are:

\[
a = \frac{1}{\Delta} (\sum x_i^2 \sum y_i - \sum x_i \sum x_i y_i) \\
b = \frac{1}{\Delta} (N \sum x_i y_i - \sum x_i y_i)
\]

(9)
\[ \Delta = N \sum x_i^2 - (\sum x_i)^2 \]

**Errors in the coefficients a and b:** Now we enquire what errors should be assigned to a and b. In general the errors in y’s corresponding to different values of x will be different. To find standard deviation in ‘a’, say \( S_a \), we approach in the following way. The deviations in ‘a’ will get contributions from variations in individual \( y_i \)’s. The contributions of the deviation of a typical measured value \( \delta y_n \) to standard deviation \( S_a \) is found using Eq. 9 reproduced below

\[
a = \frac{\sum x_i^2 \sum y_n - \sum(x_n y_n)}{N \sum x_n^2 - (\sum x_n)^2}.
\]

By differentiating it partially with respect to \( y_i \) we get

\[
\frac{\partial a}{\partial y_i} \delta y_i = \frac{\sum x_i^2 - (\Sigma x_n) x_i}{N \sum x_n^2 - (\sum x_n)^2} \delta y_i.
\]

Since \( \delta y_i \) is assumed statistically independent of \( X_n \) we may replace \( \delta y_i \) by its average value

\[
\overline{\delta y_i} = \sigma_y = \sqrt{\frac{\sum (\delta y_i)^2}{N}}.
\]

Thus this contribution becomes

\[
\frac{\partial a}{\partial y_i} \delta y_i = \sigma_y \left[ \frac{\sum x_i^2 - (\Sigma x_n) x_i}{N \sum x_n^2 - (\sum x_n)^2} \right].
\]

The standard deviation \( S_a \) is found by squaring this expression, summing over all measured values of y (that is, summing the index j from 1 to N) and taking the square root of this sum. Also it should be realized that \( \Sigma x_i = \sum x_n \), and \( \Sigma x_j^2 = \sum x_n^2 \). The result of this calculation is

\[
S_a = \sigma_y \sqrt{\frac{\sum x_n^2}{N \sum x_n^2 - (\sum x_n)^2}}.
\]

In a similar manner, the standard deviation of the intercept \( S_b \) can be found and

\[
S_b = \sigma_y \sqrt{\frac{N}{N \sum x_n^2 - (\sum x_n)^2}}.
\]
References:

EXPERIMENT NO-1

Title: Beam parameter of He-Ne Laser

Objective: To calculate beam parameters of He-Ne laser using:

a) Knife Edge
b) Intensity profile measurement

Equipment Required: He-Ne Laser, Pin hole Photo-detector (PD), Chopper, Chopper controller, Knife edge, Mounts, Posts & holders for different instruments, Lock in amplifier, Iris, Digital multimeter, Biasing circuit of PD, and BNC cables.

Theory:

The field distribution of a TEM$_{00}$ mode (fundamental mode of a common He-Ne laser) is Gaussian and is given by the following equation:

$$E(x, y, z) = A \frac{\omega_0}{\omega(z)} e^{-i(kx - \phi)} e^{-\frac{k(x^2+y^2)}{2R(z)}} e^{-\frac{(x^2+y^2)}{\omega(z)^2}}$$

where

$$w(z) = w_0 \sqrt{\left(1 + \frac{z^2}{z_0^2}\right)}$$

$$R(z) = z + \frac{z_0^2}{z}$$

$$\phi = \tan^{-1}(\frac{z}{z_0})$$

$$z_0 = \frac{\pi \omega_0^2}{\lambda} \& A \text{ is a constant}.$$}

The field distribution equation can be divided into two profiles to give the complete picture in the spatial domain. The longitudinal profile gives the information about how the field propagates in space while the transverse profile gives the power distribution in a plane perpendicular to the direction of propagation of the beam. In this experiment we measure both these profiles for a He-Ne Laser using various techniques.
**Longitudinal Profile:**

The longitudinal profile of the beam as it propagates is shown in figure 1.

![Figure 1: Schematic of Longitudinal profile](image)

The different parameters associated with the longitudinal profile are

\[ 2\omega_0 = \text{Beam spot diameter} \]

\[ 2\omega(z) = \text{Beam waist diameter} \]

\[ z_R = \text{Rayleigh Range} \]

\[ \lim_{z \to \infty} \frac{d\omega(z)}{dz} = \theta_0 = \frac{\lambda}{\pi\omega_0} = \text{Beam divergence angle} \]

**Transverse Profile:**

The intensity distribution as a function of Cartesian coordinates measured from the beam centre perpendicular to the direction of propagation is given by,

\[ I(x, y) = \frac{2P_0}{\pi\omega_0^2} e^{-\frac{2(x^2+y^2)}{\omega_0^2}} \]

Where, \( P_0 = \text{total power of the beam with beam spot radius} \omega_0 \)
The power $P$ transmitted past a knife edge blocking off all points for which $x \leq a$, 

$$P = \int_{-\infty}^{\infty} \int_{a}^{\infty} I(x, y) dx dy = \frac{P_0}{2} \text{erf} \left( \frac{a \sqrt{2}}{\omega_0} \right)$$

Where, \( \text{erf} c(x) = \frac{2}{\sqrt{\pi}} \int_{-\infty}^{x} e^{-t^2} dt \)  \& \( a = \text{depth of knife edge in the beam} \)

**Figure 2: Normalized Intensity vs Cartesian coordinates**

**Beam Divergence of the Laser:**

The beam width $\omega(z)$ of a Gaussian beam along $z$-direction is $\omega(z) = \omega_0 \sqrt{1 + \left( \frac{\lambda z}{\pi \omega_0^2} \right)^2}$, the gradient of the beam width is given by,

$$\theta(z) = \frac{d\omega(z)}{dz} = \left( \frac{\lambda}{\pi \omega_0} \right)^2 \frac{\frac{z}{\omega_0}}{\sqrt{1 + \left( \frac{\lambda z}{\pi \omega_0^2} \right)^2}}$$

Under the limits, $z \to \infty$, $\theta(z) = \theta(\infty) \to \theta_0$

$$\theta_0 = \frac{\lambda}{\pi \omega_0}$$

We can express $\omega(z)$ as
\[ \omega(z) = \omega_0^2 + \theta_0^2 z^2 \]

We can use three equations to determine the values of \( \omega_0 \) and \( \theta_0 \). Writing the above equation for \( z \), \( z+D \) and \( z+2D \) from a reference plane and solving them would give us

\[
\theta_0 = \frac{1}{\sqrt{2D}} \sqrt{\left( \frac{\omega_3^2}{2} - 2 \omega_2^2 + \omega_1^2 \right)}
\]

where \( \omega_1, \omega_2 \) and \( \omega_3 \) are beam spot radius at distance \( z, z+D \) and \( z+2D \) respectively.

**Experiment 1: Knife Edge Method**

Experimental Setup

![Diagram of experimental setup]

**Figure 3: Experimental setup for beam parameter measurements**

**Procedure:**

1. Arrange the instruments as shown in figure 3. Make sure that the laser and detector are on the same height and initially no part of the knife edge is obstructing the beam.
2. Adjust the photo-detector to maximize the intensity falling on it.
3. Check for power at three different points and observe the DMM reading as PD moves away.
4. If PD does not respond as expected, it is possible that PD could be in saturation. Then use filters to reduce the power and observe the DMM reading.
5. Observe the amount light incident on PD and reflected from it.
6. Manually insert the knife edge inside the beam, traversing across the beam.
7. After that, observe the scattering/diffraction due to knife edge by placing iris between the photo detector and knife edge.
8. Adjust iris such that scattered light is not incident on photo detector. Even though small part of light fall on detector, note the reading due to scattering.
9. Note the reading of the DMM (proportional to power) at each point while traversing from one side to the other (i.e. maximum value to minimum value of power).
10. Move the detector away or towards the laser by 40cm and repeat the steps 2-4. We need to take 3 readings at z, z+D and z+2D where D = 40cm and z is some arbitrary position.
11. In calculations, remove the minimum value due to scattered part from all the values of the measurement.

Experiment 2: Chopper Method

![Experiment 2: Chopper Method](image)

**Figure 4: Experimental setup for transverse profile measurements**

**Procedure:**
1. Arrange the instruments as shown in figure 4. Align the instruments that the laser and pin-hole detector is at the same height and the beam is passing properly through the chopper outer slots.
2. Turn on the chopper controller and slowly increase the frequency to 400 Hz. (Remember to bring the frequency back to 0Hz before turning off the chopper).
3. Adjust the photo detector to get the maximum intensity.
4. Adjust the sensitivity & time constant of the lock in amplifier so that it is not over loaded and the indicator is not overshooting the scale and also the fluctuation of reading is insignificant.
5. Thus the phase between the signal and reference given from the chopper are now the same.

6. Again maximize the output by adjusting the photodetector. Observe the voltage values of PD in lock in amplifier with and without biasing circuit. Use the biasing circuit to avoid the saturation and to keep in photo diode reverse biased.

7. Move the detector transversally away from the central maxima and note down the intensity at several points. More points may be required near the maxima.

8. Repeat the steps 3-7 after changing the distance between laser and detector by 30cm.

Sample results to be reported:

1. Spatial Intensity distribution of the laser beam
2. Beam spot size
3. Divergence angle
4. Comparison with manufacturer data

References for further study:

(3) http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.211.4430&rep=rep1&type=pdf
(4) http://web.physics.ucsb.edu/~phys128/experiments/laser/LaserFall06.pdf
(5) http://www.phys.unm.edu/msbahae/Optics%20Lab/HeNe%20Laser.pdf
Title: Diode Laser characteristics

Objective:

To measure:

i. V-I and L-I characteristics of the diode laser.
ii. Far-field pattern of the laser diode by recording the angular variance/dependence of the radiation; and its variation with distance and power level. This is to be done in two cases: a plane perpendicular and parallel to the junction plane.
iii. Spectrum of the diode laser.

Equipment Required: Diode laser (632 nm), Diode laser power supply, Lock in amplifier, Chopper, Chopper regulator, Si photodiode detector, Biasing circuit, Spectrum Analyzer (with spectrograph software), Multimeter, Fiber optic cable, Connecting cables etc., Rotational stage (position controller software), Desktop computer.

Theory:

A diode laser is electrically pumped semiconductor laser in which the active medium is formed by p-n junction of a semiconductor diode similar to that found in light emitting diode. In the active medium (region), carriers, electrons and holes are pumped into active region from n-region and p-region respectively where in the active region all the carriers are recombined and produces light. Thus, laser diodes are fabricated using direct band gap semiconductors. The active layer most often consists of quantum well which provide lower threshold current and higher efficiency.

Procedure: For V-I, L-I characteristics

1. Make the connections as per the figure 1(a) for each part for V-I and L-I characteristics.
2. Bring the photo detector as close as possible to the laser head ensuring that the O/P light from laser falls entirely on the area of the photodiode.
3. Make the connection and photodiode circuitry to measure photodiode current.
4. Adjust the potentiometer; increase the input voltage in proper steps. Here, potentiometer is the control parameter by changing the resistance; correspondingly the voltage drop across the resistance also changes.
5. Now increase the laser power in steps manner and note the laser current corresponding to each step size.
6. Get the responsivity of Si-photodiode at 673 nm and find the power corresponding to each photodiode current.

**Precaution:** The diode laser we will use for this experiment has an operating voltage of 2.6V, this must not be exceeded, or the diode will damage.

**For spectrum analysis**

1. Mount the fiber optic cable in front of the laser diode in such a way that all the light should fall on the fiber as shown in figure 1(b). Remove the protection cap of the fiber optic cable.

2. Load software ‘spectra suit’.

3. Adjust the potentiometer above the threshold and see the spectrum on Monitor.

4. Save the spectrum in a file Low power laser < 10mW
   High power laser > 10mW.

2. **Safety for unpacked diode lasers:**

   a. The laser is sensitive to the reverse bias breakdown due to the static electric charges when handling of the diodes. Therefore one needs to handle the diode only with grounded tweezers.
   b. The end facets are sensitive to dust and other contamination and so should be handled carefully.
   c. Sudden electrical spikes could damage the laser. Therefore, care should always be taken when increasing or decreasing power to diode. Never connect or disconnect cables to the diode without proper grounding.

**Experimental setup:**
iii. **Source of error:**

1. Diode laser output is temperature dependent. So temperature of diode laser leads to error.
2. Vibration of optical bench.
3. Least count of voltmeter.
4. Least count of photodetector.
5. Saturation of output (intensity) on photodetector
7. Least count of position controller.
8. Calculation errors.
Sample results to be reported:

1. V-I curve
2. L-I curve
3. Threshold power conversion efficiency
4. Differential efficiency of laser
5. Threshold current
6. Full width at half maximum value

References:
Experiment No. 3

Title: Electro-optic effect in a Lithium Niobate Crystal.

Objective:
1) To study the electro-Optic effect in a Lithium Niobate crystal.
2) To measure the half wave voltage.

Equipment Required:
He-Ne laser (632.8nm), Half-wave plate, Polarizer, Analyzer, Lithium Niobate crystal in a holder, Photo detector, Digital meter, DC power supply.

Theory:

Electro-optic effect: The change in refractive index induced in a crystal on the application of an electric field which effects the state of polarization of a light beam on propagation through the crystal is known as electro-optic effect. This effect is mainly observed in crystals of KDP (Potassium Dihydrogen Phosphate), ADP (Ammonium Dihydrogen Phosphate) and LN (Lithium Niobate). If the changes in the refractive index are proportional to the applied electric field such an effect is known as Pockets effect or the linear electro-optic effect. If the changes in refractive index are proportional to the square of applied electric field, the effect is known as Kerr effect or quadratic electro-optic effect. The electro-optic effect finds many applications in various devices such as directional couplers, optical switches, phase, amplitude and frequency modulators, Q-switching, mode locking etc.

Lithium niobate (LiNbO₃) crystal: It is a compound of lithium, niobium and oxygen. It has a trigonal crystal symmetry and negative uniaxial birefringence (when extraordinary index of refraction is less than ordinary index of refraction). It is a ferroelectric material suitable for many applications. Its versatility is made possible by the excellent electro-optic, non linear and piezoelectric properties of the intrinsic material. Applications that utilize the large electro-optic coefficients of lithium niobate are optical modulation and Q switching of infrared wavelengths. Because the crystal is nonhygroscopic and has a low half wave voltage, it is often the material of choice for Q switches in military applications. The crystal can be operated in a Q switch configuration with zero residual birefringence and with an electric field that is transverse to the direction of light propagation.
**Transverse electro-optic modulation:**

In this case, electric field is applied transversely between electrodes placed on the side faces of crystal as shown in fig (2).

In the absence of electric field, index ellipsoid equation in principle axis system is given by,

\[
\frac{x^2}{n_x^2} + \frac{y^2}{n_y^2} + \frac{z^2}{n_z^2} = 1
\]

Where, \(n_x\), \(n_y\) and \(n_z\) are principle refractive index of the medium.

LiNbO₃ is uniaxial crystal and hence index ellipsoid becomes,

\[
\frac{x^2}{n_0^2} + \frac{y^2}{n_e^2} = 1
\]

When electric field is applied along the Y-direction, index ellipsoid equation for LiNbO₃ crystal can be written as,
\[
x^2 \left\{ \frac{1}{n_0^2} - r_{22}E_y \right\} + y^2 \left\{ \frac{1}{n_0^2} + r_{22}E_y \right\} + z^2 \left\{ \frac{1}{n_e^2} + 2r_{51}E_y \right\} = 1
\]

Where \( r_{22} \) and \( r_{51} \) are the components of electro-optic tensor, and for LiNbO\(_3\) their values are:

\( r_{22} = 3.4 \text{ pm/V} \), \( r_{51} = 28 \text{ pm/V} \).

Change in refractive index of crystal when the electric field is applied along the Y-direction is becomes:

\[
\begin{align*}
n_x' &= n_0 + n_0^3r_{22}E_y \\
n_y' &= n_0 - n_0^3r_{22}E_y \\
n_z' &= n_e
\end{align*}
\]

For transversely operated electro-optic modulator phase shift (retardation) is given as,

\[
\Delta \Phi = \frac{2\pi L}{\lambda_0} (n_x - n_y) = \frac{2\pi Ln_0^3r_{22}V}{\lambda_0 d}
\]

The half wave voltage \( V_{1/2} \) of modulator is the voltage required to make it act as half wave plate i.e. \( \Delta \Phi = \pi \).

\[
V_{1/2} = \frac{\lambda_0 d}{2Ln_0^3r_{22}}
\]

Where,

\( \lambda_0 \): Laser Wavelength (632.8 nm),

\( d \): Distance between the electrodes (3mm).
L: Length of the crystal along the optic axis (25mm).

\( r_{22} \): Electro-optic coefficient (3.4pm/V)

\( n_o = 2.297 \) : \( n_e = 2.21 \)

Also, now \( \Delta \phi = \frac{\pi V}{V_{1/2}} \)

For the set up in figure 3, input (entering crystal) and output (leaving analyzer) fields are related as:

\[
\vec{E}_{out} = M_2 M_1 \vec{E}_{in}
\]

\( M_1 \) and \( M_2 \) are the transformation matrices corresponding to crystal and analyzer respectively.

For 45\(^\circ\) linearly polarized input light, the above equation becomes:

\[
\vec{E}_{out} = \begin{pmatrix} \cos^2\theta & \cos\theta \sin\theta \\ \cos\theta \sin\theta & \sin^2\theta \end{pmatrix} \begin{pmatrix} e^{\frac{i\Delta \phi}{2}} & 0 \\ 0 & e^{-\frac{i\Delta \phi}{2}} \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}
\]

Where \( \theta \) is the angle made by axis of analyzer.

Then in general for any \( \theta \), the output intensity varies as:

\[
I \propto \sin^2 \left[ \frac{\pi V}{2V_{1/2}} \right]
\]
Experimental setup:

![Diagram of electro-optic setup]

Figure 3. Set up for electro-optic

Procedure:

1. The experimental arrangement is shown in fig 3. The crystal is mounted in the holder and the two terminals across the crystal are connected to high voltage power supply. Laser beam is allowed to pass through the crystal.
2. The laser beam is aligned in such a way to get the 45° angle of polarization with respect to the crystal axis when the beam is propagating along z-direction using a half wave plate.
3. Now polarizer (with axis at 45°) is put after the half wave plate and wave plate is rotated slightly to make sure 45 degree polarized light has been obtained.
4. The beam is allowed to fall on the detector after passing through the analyzer placed after the crystal. The analyzer is rotated to obtain minimum output.
5. Now the voltage is applied and increased in steps of about 50 volts upto about 1300 volts.
6. For each applied voltage the detector output readings are taken on the meter.
7. A graph is plotted between the voltage and detector output, and is curve fitted into the following formula to obtain $V_{1/2}$, $V$ is the applied voltage.

$$I \propto \sin^2 \left( \frac{\pi V}{2V_{1/2}} \right)$$

8. Steps 5 to 7 are repeated on rotating the analyzer to obtain maximum output.
Precautions:

1. Do not look directly into the laser beam.
2. Take care while using the high voltage power supply.
3. The cable between the power supply and the LiNbO$_3$ crystal must not be unplugged.
4. Take care that the applied voltage value should not exceed 1600 V to avoid damage of the crystal.
5. After finishing the experiment, make the applied voltage down to zero before switch off of the HV power supply.
6. Multimeter connection must be done properly with the photo detector.

Sources of error:

1. After switching on the laser, wait for about 20 minutes so that output becomes stable, otherwise it will add an error to readings.

2. When changing the applied voltage, the multi-meter reading should be taken at 3 time intervals since there are fluctuations, and standard error can be obtained.

3. The value of half wave voltage is obtained after fitting the data on a particular curve. So the error from curve fitting should be included.

Sample results to be reported:

1. Half-wave voltage at cross and parallel polarization and comparison with specification.

References:

Experiment No. 4

Part-1

Title: Studies on polarization

Objective:
1. To check the polarisation of laser source
2. To verify Malus law
3. To characterize the functionality of HWP
4. Generate circular and elliptical polarized light using QWP

Equipment Required: He-Ne Laser (632.8nm), Linear polarizers, Half wave plate, Quarter wave plate, Photo diode, Biasing circuit and multi-meter.

Theory:
A plane wave is characterized by different states of polarizations, which may be any one of the following:
• Linearly polarized
• Circularly polarized
• Elliptically polarized
• Unpolarised
• Mixture of linearly polarized and unpolarised
• Mixture of circularly polarized and unpolarised
• Mixture of elliptically polarized and unpolarised light.

If we introduce a Polaroid in the path of the beam and rotate it about the direction of propagation, then one of the following three possibilities can occur:
1. If there is complete extinction at two positions of the polarizer, then the beam is linearly polarized.
2. If there is no variation of intensity, then the beam is unpolarised or circularly polarized or a mixture of unpolarised and circularly polarized light. We now put a quarter-wave plate on the path of the beam followed by the rotating Polaroid. If there is no variation of intensity, then the incident beam is unpolarised. If there is complete extinction at two positions, then the beam is circularly polarized (this is so because a quarter wave plate will transform a circularly polarized light into a linearly polarized light). If there is a variation of intensity (without complete extinction), then the beam is a mixture of unpolarised and circularly polarized light.
3. If there is a variation of intensity (without complete extinction), then the beam is elliptically polarized or a mixture of linearly polarized and unpolarised or a mixture of elliptically polarized and unpolarised light. We now put a quarter-wave plate in front of the Polaroid with its optic axis parallel to the pass axis of the Polaroid at the position of maximum
intensity. The elliptically Polarized light will transform to a linearly polarized light. Thus, if one obtains two positions of the Polaroid where complete extinction occurs, then the original beam is elliptically polarized. If complete extinction does not occur and the position of maximum intensity occurs at the same orientation as before, the beam is a mixture of unpolarised and linearly polarized light. Finally, if the position of maximum intensity occurs at a different orientation of the Polaroid, the beam is a mixture of elliptically polarized and unpolarised light.

• Malus Law:
  It states that the intensity of a beam of plane-polarized light after passing through a rotatable polarizer varies as the square of the cosine of the angle through which the polarizer is rotated from the position that gives maximum intensity.
  The Malus law expression which is given by,
  \[ I = I_0 \cos^2 \Theta \]
  where \( I_0 \) is the power before analyser or after polarizer.

Procedure:

I. Polarisation of laser source

1. See figure 1 for the details of the experimental arrangement. Turn on the laser source and wait for 5 minutes so that the laser gets stabilized.
2. Once the laser is stable place a polarizer and adjust the position of polarizer such that maximum light is passing through it.
3. And also check the light coming from polarizer is not passing through any rough surface and is clean.
4. Now rotate the pass axis of the polarizer and fix the position where maximum power is detected in photo detector.
5. Rotate the angle of polarizer in steps of 4° and note the output power of light
6. Next place a quarter-wave plate with its optic axis parallel to the pass axis of the polarizer.
7. Note the power reading from the photo diode at discrete angles of the polarizer (at same angle as the previous case).

Fig1: Experimental Setup for checking polarization of laser source
II. Verification of Malus law

1. See figure 2 for the details of the experimental arrangement. Set the position of analyser and the polarizer such that maximum light is passing through them and note the angles at which it is achieved.
2. After the output power is noted, calculate the loss occurring due the analyser.
3. Now start from the reference angle of the analyser, which would be starting point of readings.
4. Change the angle in the steps of 2° and note the change in output power accordingly.
5. Plot the output voltage variation with the angle of analyser and verify if the behaviour is following the Malus law expression which is given by, where \( P \) is the power before analyser or after polarizer.
6. Here it has to be noted that, in theory it is assumed that no loss exists in both polarizer and analyser, which is strictly not true.
7. Hence the maximum output power from the analyser is considered as for verification of Malus law.

![Fig2: Experimental setup for verification of Malus Law](image)

III. Characterisation of Half Wave Plate

1. See figure 3 for the details of the experimental arrangement. Now in the same setup used in the previous step, place a half wave plate between polarizer and analyser.
2. Theoretically a 90° shift has to be achieved, as HWP reverses the polarisation of light.
3. Now bring the angle of analyser to the same point where the maximum output was noted.
4. Adjust the knob of half wave plate or the optical axis of the HWP such that minimum amount of light is passing through the analyser.
5. Repeat the same procedure discussed in experiment-2 at exactly the same angles.
6. Ideally HWP should not cause any drop in the maximum power, but it is not possible practically.
7. Note the maximum value of output power and calculate the loss due to the HWP used in the setup.
8. Plot the results of experiment 2 and 3 in same plot and observe the shift in the power readings.
9. Theoretically the shift has to be 90°, note the practical value of this shift and comment on the result.

![Diagram of experimental setup](image)
IV. Generating Circular and Elliptical Polarisation

1. Align the components as drawn in the experiment setup (see figure 4)
2. By adjusting the position and the angle of rotation of polarizer and analyser their pass axis can be determined, but the optic axis of the quarter wave plate is unknown
3. In theory the optic axis of QWP must be parallel to the surface and the light incident must have polarisation for generating circularly polarised light
4. But in practise as the true angle is unknown, the angle of polarizer is fixed to its pass axis and the crystal is rotated.
5. Here the pass axis of the analyser is rotated with respect to polarizer, i.e. with no QWP minimal amount of light must pass through analyser.
6. Now place the QWP and rotate its optic axis.
7. At one angle at one angle say, light gets vanished at the detector.
8. If the crystal is rotated further, at one more angle say, approximately after, zero light is detected.
9. Average of these two angles gives the position of QWP where the optic axis is to the polarisation of light.
10. When the optic axis of QWP is fixed at this angle, circularly polarised light is generated at the output.
11. At any other arbitrary angle elliptical polarised light is generated except at two angles where linearly polarised light is generated.
12. In order to verify the polarisation of light, rotate the angle of analyser and note the light output power.
13. For circularly polarised light, intensity is same for any angle of rotation and for elliptical polarised light; intensity varies but does not go to zero.

**Fig 4: Experimental setup for generation of circular and elliptical polarizations**

**Sources of Error:**

**Observational error:** Due to visualization of polarizer at an angle can create error in setting the exact angle while rotating.
Sample results to be reported:
1. Verification of Malus Law
2. Comparison of polarization of laser with manufacturer data
3. Half-wave plate behaviour
4. Elliptically and circularly polarized beam profile
5. Loss due to QWP and HWP

REFERENCES:
Experiment No. 4

Part-2

Title: Simulation study of Polarization Experiment using Fred software

Objective:

1. To verify Malus’ law
2. To characterize the functionality of HWP
3. Generate Circular and Elliptical polarized light using QWP

1. Verification of Malus’ law

1. The details of the experimental arrangement are given in figure A.

2. Open the fred software. Open a blank FRED document (File>New>Fred Type, keystroke Ctrl+N or Toolbar button).

3. Create a new Subassembly by one of three methods:
   From the Main Menu, Create>New Subassembly
   Keystroke Ctrl+Alt+S
   Right-click on Geometry folder and select option Create New Subassembly
   Name this entry "malus law". The new Subassembly now appears in the Tree as shown in the Figure 1.
4. Create a plane by one of following methods, From the Main Menu, Create> New Element Primitive>Plane. Or, Right-click on either a Subassembly or the Geometry folder and select option Create New Element Primitive>Plane. Name the plane as “Polarizer”. And set the optical parameters as shown in the figure 2.
5. Now in similar fashion add another plane with same optical parameters as above and name it as “Analyzer”. Go to the position/orientation and Left-click anywhere inside the green highlighted entry Geometry.malus law and selects the down arrow to expose FRED's Entity Picker dialog. Select the surface of polarizer and hit the OK button. Geometry.malus law.Polarizer.Surface should now appear as the Starting Coordinate System of Analyzer. Right-click again and select Append to add shift operation to move Analyzer into position relative to Polarizer. Type in the 5 cm shift as the z-component shift and hit the Apply button to see the Analyzer move to its correct relative position. See figure 3.

6. Let us now add a source. We begin by adding a Simplified Source. This source type can be invoked by following methods:
From the Main Menu, Create>New Simplified Source
Keystroke Ctrl+Alt+I
Right-click on Optical Sources folder and select option <Create New Simplified Optical Source.
Select “Laser Beam(Gaussian 00 mode)” from the drop down menu in “Type”. Set the location/orientation by the method previously described in step iv and set it the way in the figure 4. Also make sure other source parameters are same as that in figure 4.

Figure 4.

7. Now let us add an image plane to do the analysis. Add a custom element by any of the following methods, From the Main Menu, Create>New Custom Element. Or, Keystroke Ctrl+Alt+E.
Name the custom element as “image”. Set the location/orientation by the method previously described in step iv and set it the way in the figure 5.

Next, add a Surface of type Plane to the Custom Element “image”. A Surface is added to the model by one of three methods:

From the Main Menu, Create>New Surface

Keystroke Ctrl+Alt+F

Right-click on Custom Element and select option <Create New Surface>

Now go the location/orientation tab and set the location/orientation by the method previously described in step iv and set it the way in the figure 6a.
Figure 6a.

Set the Aperture specifications as shown in figure 6b.

Figure 6b.
8. The Analysis Surface on the image plane provides a user-defined planar grid on which various calculations are made. An Analysis Surface is created by one of three methods:
From the Main Menu, Create > New Analysis Surface
Keystroke Ctrl+Alt+N
Right-click on Analysis Surface(s) folder and select option <Create New Analysis Surface>
Set all the parameters as in figure 7a. Also set the location/orientation by the method previously described in step iv and set it the way in the figure 7a.

![Figure 7a](image)

Figure 7a.
Now double click on the ‘Num 1’ of ‘Ray Selection’. And set the criterion and location as shown in figure 7b.

![Ray Selection Criterion](image)

Figure 7b.

9. Now we will create coatings for the polarizer and the analyzer. Create new coating by right click on the Coatings and select option ‘Create a New Coating’. And set all the parameters as shown in figure 8.

![Edit Coating](image)

Figure 8.

Now the polarizer coating would be ready. Similarly, create another coating naming analyzer with same parameter as that of polarizer coating.

10. Now we need to assign these created coatings to the geometry. Go to edit>edit/view multiple surfaces. Assign ‘polarizer’ coating to the polarizer, ‘analyzer’ coating to the
analyzer and ‘absorb’ coating to image plane. Also put ‘Raytrace Control’ as Transmit Specular’ for polarizer and analyzer and ‘halt’ for image surface. See figure 9.

11. Go to Objects-> Geometry-> Malus law-> double click on Analyzer. Now go to the location/orientation. Right click on the green area (Starting coordinate system) and append. Now choose in the ‘Action’ drop down menu-> Rotate about z-axis, See figure 10. Change the angle of analyzer in the steps of 9° and note the change in output irradiance/ intensity accordingly.

Figure 9.
12. We are now in position to trace our ray grid through the geometry. While there are numerous options for raytracing in FRED, we restrict ourselves at this stage to a basic raytrace initiated by one of three methods:

1. From the Main menu, Raytrace>Trace and Render

2. Keystroke Ctrl+Shift+F7

3. Raytrace Toolbar button

**Results to Report:**

Plot the output peak irradiance/ intensity variation with the angle of analyzer and verify if the behavior is following the Malus’ law.
2. Characterization of Half Wave Plate

i. The details of the experimental arrangement are shown in figure B. Now in the same setup used in the previous step, add a half wave plate geometry between polarizer and analyzer.

![Diagram of experimental setup](image)

Figure B.

ii. Before making the changes in the above fred script save it and save as the new script. Now change the name of Subassembly from malus law to HWP (for reference).

iii. Create a plane by one of following methods, From the Main Menu, Create>New Element Primitive>Plane. Or, Right-click on either a Subassembly or the Geometry folder and select option Create New Element Primitive>Plane. Name the plane as “HWplate”.

iv. Go to the position/orientation and Left-click anywhere inside the green highlighted entry Geometry.HWP and selects the down arrow to expose FRED's Entity Picker dialog. Select the surface of polarizer and hit the OK button.

v. Geometry.HWP.Polarizer.Surface should now appear as the Starting Coordinate System of HWplate. Right-click again and select Append to add shift operation to move HWplate into position relative to Polarizer. Type in the 2.5 (cm) shift as the z-component shift and hit the Apply button to see the HWplate move to its correct relative position.

vi. Create a coating in the same fashion as we did it for objective-I and name it HWplate. And put the parameters as shown in figure 1.
vii. Now we need to assign the created coatings to the geometry. Go to edit>edit/view multiple surfaces. Assign ‘HWplate’ coating to the HWplate. Also put ‘Raytrace Control’ as Transmit Specular’ for HWplate.

viii. Repeat the same procedure discussed in Objective-I at exactly the same angles of Analyzer.

ix. Plot the results of Objective 1 and 2 in same plot and observe the shift in the power readings.

**Results to report:**

Plot the intensity distribution for different analyzer angle and discuss the phase shift behavior.
3. Generating Circular and Elliptical Polarization

i. The details of the experimental arrangement are shown in figure C. Now in the same setup used in the previous objective, add a quarter wave plate geometry between polarizer and analyzer instead of half wave plate.

![Figure C](image)

ii. Here we need to keep the polarizer and analyzer in the cross position such that with no wave plate the output should be zero. So for this change the coating of analyzer. Go to Objective-> Coatings-> double click on Analyzer. Change the Type to Y Linear Polarizer as shown in figure 2.

![Figure 2](image)

iii. Before making the changes in the above fred script save it and save as the new script. Now change the name of Subassembly from HWP to QWP (for reference).
iv. Create a plane by one of following methods, From the Main Menu, Create>New Element Primitive>Plane. Or, Right-click on either a Subassembly or the Geometry folder and select option Create New Element Primitive>Plane. Name the plane as “QWPplate”.

v. Go to the position/orientation and Left-click anywhere inside the green highlighted entry Geometry. QWP and selects the down arrow to expose FRED’s Entity Picker dialog. Select the surface of polarizer and hit the OK button.

vi. Geometry.QWP.Polarizer.Surface should now appear as the Starting Coordinate System of QWPplate. Right-click again and select Append to add shift operation to move QWPplate into position relative to Polarizer. Type in the 2.5 (cm) shift as the z-component shift and hit the Apply button to see the QWPplate move to its correct relative position.

vii. Create a coating in the same fashion as we did it for objective-I and name it QWPplate. And put the parameters as shown in figure 3. Now the optic axis of QWP is 45˚ in reference to the optic axis of the polarizer.

![Figure 3.](image)

viii. Now the Output should be Circularly polarized light. To verify this rotate the angle of analyzer from 0 to 180 in the interval of 9 and plot the peak irradiance with the change of analyzer angles.
ix. At any other arbitrary angle elliptical polarized light is generated. For this go to Objects-> Geometry-> QWP-> double click on QWplate. Now go to the location/orientation. Right click on the green area (Starting coordinate system) and append. Now choose in the ‘Action’ drop down menu-> Rotate about z-axis, See figure 4. Change the angle of QWplate to 10.

![Figure 4.](image)

x. In order to verify the polarization of light, rotate the angle of analyzer and note the light output power.

xi. For circularly polarized light, intensity is same for any angle of rotation and for elliptical polarized light; intensity varies but does not go to zero.
Results to report:

Present the irradiance pattern of circular and elliptic polarization for different analyzer angles and discuss.
Experiment No. 5

Title: Mach-Zehnder Interferometry

Objective: Interferogram of a heated plate using Mach-Zehnder interferometer.

Equipment Required: He-Ne Laser, Beam-splitters with mount (2 nos.), Mirrors with mounts (2 nos.), Photo-detector, Heated Plate.

Warning: The interferometer beam splitters and mirrors have very sensitive surfaces. Please do not touch them. Check with your instructor before making any adjustments that require you to touch any of the glass surfaces.

Theory: This experiment involves the measurement of refractive index of air as a function of Zehnder interferometer. Set-up of the experiment is done as shown in fig.1. The temperature from a test cell placed in one of the optical arms of the Mach- laser beam is cleaned and collimated using spatial filter and collimating lens. The path length of both the arms is kept at same distance. To carry out the experiment, a heating element is placed in one of the arms of beam (test arm) and is covered with a perspex cell to avoid any disturbance from surrounding and to maintain the inside temperature of air. The optical path length of this arm will be given as,

\[
optical \ path \ length = m\lambda = nL
\]

(1)

Where, \( n \) is the refractive index, \( L \) is physical path length and \( m \) is an integer.

The refractive index for most gases is close to 1. For air and other ideal gases, the difference between the refractive index and 1 is proportional to the temperature difference of the gas. Thus, we define refractive index of air as

\[
n = 1 + \Delta n
\]

Where, \( \Delta n \) is due to change in temperature

\[
\Delta n = k \ast \Delta T
\]

(2)

Hence,

\[
n = 1 + k \ast \Delta T
\]
where, $k$ is proportionality constant. So, if we determine $k$, we can tell the refractive index at any value of $T$. Hence determining the value of $k$ is our main objective. From equation (1) and (2), we get,

$$k = \frac{\Delta m \lambda}{\Delta T L}$$

where $\Delta m$ is the number of fringes moved past the reference mark on the screen.

**Procedure:**

You need to setup/examine the setup of the interferometer on the bread board as shown in Fig. above. Following components are fixed on the base plate:

A He-Ne laser on an adjustable mount, objective lens(50X)with pinhole, mirror (M1) whose tilt is adjustable and can be translated with a screw, mirror (M2), beam splitters (BS1 and BS2) on tilt adjustable mounts. The Mirror M2 is fitted with a micrometre screw for precise translation of the mirror and measurement cell C which is removed at first.

1. Align the laser so that the beam is parallel with the top of the base. The beam should strike the centres of the mirrors.

2. Adjust objective lens with pinhole in path of laser such that maximum light passes through it without deviation of its original path.

3. Adjust the angle of the beam splitter BS1 as needed so that the reflected beam hits the fixed mirror M1 near its centre. Now the mirror M1 is adjusted so that the reflected beam hits BS2 at the centre.

4. There should now be two sets of bright patch on the screen; one set comes from the mirror M1 and the other from the mirror M2. Adjust the angle of the beam splitter BS2 and the mirror M2. Such that the two sets of patch overlap on BS2 and the beams run parallel to each other as they move away from BS2. This can be checked by moving the screen on the base plate.

5. Adjust the second arm beam such that it goes slight above and small part touching the temperature cell(which is introduced now to change the refractive index of air). This ensures the significant path difference due to temperature.

6. With photo detector observe the maximum and minimum value of fringes. If difference is less then adjust the spatial filter again such that significant contrast will come. Then set the photo detector pinhole at the maximum of fringe pattern.
7. It may require some skillful observations and adjustments to get fringes. This written procedure is only a guide line.

**Experimental Setup:**

![Mach-Zehnder Interferometry setup](image)

Figure 1 shows schematic of the Mach-Zehnder Interferometry setup.

**Precautions:** The interferometer beam splitters and mirrors have very sensitive surfaces. Please do not touch them. Check with your instructor before making any adjustments that require you to touch any of the glass surfaces.

**Sources of error:** Lack of alignment in any of the optical component used in the set-up will definitely lead to errors, so one should be very careful while doing alignment. Do not increase the temperature of the cell very rapidly because then there will be more fluctuations and as a consequence uneven shift in the fringe pattern.

**Sample results to be reported:**

1. Interferogram images at different temperature
2. Fringe shift relationship with temperature change and comparison with literature
3. Fringe visibility

**References:**


(2) K P Zetie et al, 2000, Phys. Educ. 35, 46
Experiment No. 6

Title: Acousto-Optic modulator

Objective:

1. To observe the diffraction pattern using acousto-optic modulator for two wavelengths
2. To measure the diffraction efficiencies corresponding to different RF powers.
3. To calculate diffraction angle with respect to the acoustic frequencies.

Equipment required: He-Ne Laser (632.8nm), Laser diode (960nm), Wave plate & lense setup, Polarizer, Reflecting mirrors, Acousto-optic modulator, Graph paper, IR Card, Photo detector, Multi-meter, RF power source.

Theory:

Acousto-optic effect: This effect deals with the interaction of light (optics) and sound (acoustics). It is also known as acousto-optic interaction or diffraction of light by acoustic waves, which was first predicted by Brillouin in 1921. This effect is based on the change in the refractive index of the medium due to presence of sound waves in that medium. Sound waves produce a refractive index grating in the material. These variations in refractive index, due to pressure fluctuations, may be detected optically by refraction, diffraction and interference effects. This effect is a special case of photo elastic effect (the strain changes the density of the crystal and distorts the bonds which lead to a change in the refractive index).

Acousto-optic modulator: 
The Acousto-Optic Modulator is based on the elasto-optic effect, in which a material strain causes a change in the refraction index of the material. When the strain is generated by an acoustic compression or rarefaction, an AOM is formed. Because the acoustic signal is sinusoidal, a moving refractive index grating is formed in the device. Like a permanent grating, the various wavelengths are spatially diffracted and separated from each other. With an output coupler placed at the appropriate diffraction order location, tunable filtering and switching can be achieved.

PRINCIPLE
The acousto-optic effect occurs when a light beam passes through a transparent material, such as glass, in which traveling acoustic waves are also present, as depicted in Fig. 1. Acoustic waves are generated in the glass by a piezoelectric transducer that is driven by a RF signal source. The spatially periodic density variations in the glass corresponding to compressions and rarefactions of the traveling acoustic wave are accompanied by corresponding changes in the index of refraction for propagation of light in the medium. For acoustic waves of sufficiently high power, most of the light incident on the Acousto-optic
modulator can be diffracted and therefore deflected from its incident direction.

**Figure 1**: Diffraction of light beam by travelling acoustic waves in acousto-optic modulator

For acoustic waves of frequency $f$ traveling at the speed of sound in a medium, $V_s$, the wavelength of the acoustic wave $\lambda$, and therefore the spacing between the planes of index of refraction variation, is given by the usual wave relation $V_s = \lambda f$.

A light beam passing through the acoustically driven medium will be diffracted at angles given by

$$\sin \theta = \frac{m \lambda}{2 \Lambda}$$

where $m = 0, \pm 1, \pm 2, \ldots$ is called the diffraction order.

From Fig. 1, the angle ($\alpha$) between a diffracted beam and the undiffracted beam is given by

$$\sin \left( \frac{\alpha}{2} \right) = \frac{m \lambda}{2 \Lambda}$$

$$\sin \left( \frac{\alpha}{2} \right) = \frac{m \lambda f}{2 V_s}$$
Light diffracted by an acoustic wave of a single frequency produces two distinct diffraction types: Raman-Nath diffraction and Bragg diffraction.

**Raman-Nath diffraction:** Here the diffraction occurs as if it was occurring from a line grating (See figure 3).

In this type of diffraction the acousto-optic interaction length is very small. It occurs at an arbitrary angle of incidence.
where $L$ is the interaction length, $\Lambda$ is acoustic wavelength and $\lambda$ is the wavelength of light.

**Bragg diffraction:** In this type of diffraction the interaction length is large, all diffraction orders are present and are weak, unless the optical and acoustic waves intersect at a particular angle (See figure 4). This angle is determined by constructive interference. When this condition is met only one diffraction order ($m = \pm 1$) becomes very strong and all other diffraction orders are suppressed. The condition for constructive interference is satisfied if:

$$\sin \theta_i = \sin \theta_d = \frac{\lambda}{2n\Lambda}$$

where incident angle $\theta_i$ is known as Bragg angle.

![Figure 4](image)

Figure 4: A schematic illustration of the principle of the Bragg diffraction.

For this type of diffraction, the following condition is met:

$$L \gg \frac{\lambda^2}{\Lambda}$$

**Diffraction efficiency:** It is the ratio of the $1^{\text{st}}$ order diffracted beam to the $0^{\text{th}}$ order diffracted beam and obtained by the following formula:

$$\eta_{DE} = \frac{I_1}{I_0} = \sin^2 \left[ \frac{\pi}{\lambda} \left( \frac{L}{2H} M_2 P_{RF} \right)^{1/2} \right] = \sin^2 \left( c \sqrt{P_{RF}} \right)$$

Where $L$ is the length, $H$ is the height, $P_{RF}$ is the acoustic power, $M_2$ is the material figure of merit with $C$ is a constant.
Working formulae:

OPTICAL TRANSMISSION = \frac{0th \ order \ power}{incident \ power}

Acoustic velocity = acoustic wavelength * rf frequency

Power = \frac{photo \ diode \ current}{responsivity}

Diffraction angle(2\theta) = \tan^{-1} \frac{distance \ between \ 1st \ & \ 0th \ order}{modulator \ & \ screen \ distance}

Experimental setup and Procedure:

1) He-Ne laser (632.8 nm)

1. Align the laser light and mirrors without any back reflections and angle mismatch.
2. Make sure that maximum linear polarized light is going inside AO modulator.
3. Set the RF power and frequency for AO modulator and observe diffraction pattern.
4. Take output photo diode voltage by properly adjusting height and rotation for maximum value
2. Diode laser (960 nm)

1. Set current and temperature for IR laser diode.

2. Make sure focus of lens on HWP and AO modulator.

3. Follow above steps and take data for different RF frequencies and for different powers.

**General Precautions:**

**Electrical Precaution:**

1. Do not force on the connectors

2. Never disconnect the connectors while power supply is ON

**Optical Precaution:**

a. Dust on optical windows can be responsible for irreversible damage on the coating. Use component in clean environment only.

b. Laser Power Density: Check the maximum value specified for the AO component, otherwise irreversible damage could occur.

c. Laser Polarization: The polarizer axis must be properly aligned with that of half wave plate, to ensure that maximum intensity comes out of the polarizer.


d. Optical Aperture: Make sure the laser beam diameter is lower than the given active aperture of AO component, typically beam diameter < 0.7 X Active aperture.

e. Incidence Angle: Make sure that position of AO component corresponds to the specified value of incidence angle in order to optimize the efficiency.

Sample results to be reported:

1. Diffraction angle variation w.r.t. RF frequency and power
2. Diffraction efficiency variation w.r.t. RF frequency and power
3. Optical efficiency variation

References:

EXPERIMENT 7

Title: Fresnel and Fraunhofer Diffraction

Motivation:

Diffraction is one of the most important and the most common manifestation of wave nature of light. Diffraction limits the performance of most of the high end telescopes, microscopes and other optical instruments. Therefore, for those who intend to study light, it is imperative to have an understanding of the behavior of light when it encounters a macroscopic obstacle.

Aim 1:

To measure intensity distribution along the axis of the circular aperture and compare it with the calculated distribution using the concept of Fresnel zones.

Equipment Used:

He-Ne laser (632.8 nm), Circular aperture, Si pinhole photodetector, Spatial filter, Lenses (focal length – 7.5 & 2.5 cm), Optical rail, Digital multi-meter, Travelling microscope.

Theoretical Background:

Fresnel diffraction for near field is an approximation of Kirchhoff-Fresnel diffraction theory. This analysis is based on scalar diffraction theory & can be useful to the propagation of waves in the near field. It is used to calculate the diffraction pattern formed by waves passing through a hole or around an object, when viewed from relatively close to the object. In this analysis the wave fronts are assumed to be parabolic in nature.

Fresnel diffraction occurs when either the distance from the source to the obstacle or the distance from the obstruction to the screen is comparable to the size of the obstruction. In case of Fresnel diffraction, the near-field diffraction pattern observed differs in size and shape, depending on the distance between the aperture and the projection. However, when you are at large distance from the aperture, you enter the Fraunhofer far field regime. So in the case of Fresnel diffraction either or both (the source and the screen) are at finite distances from the diffracting element.

The demarcation line between when to use the results of Fresnel or Fraunhofer theory, is a subjective one and depends on the size of the aperture and the wavelength. Quantitatively this demarcation can be expressed in terms of Fresnel number-

\[ F = \frac{a^2}{L\lambda} \]
Where, $a$ is the dimension of the diffracting element, $\lambda$ is the wavelength of light and $L$ is the minimum of distance between source to aperture and aperture to screen.

For Fresnel diffraction region $F \sim 1$, while for Fraunhofer region $F << 1$, additionally $F >> 1$ corresponds to the geometrical optics regime.

The intensity on the axis of a circular aperture of radius $r_0$ under the condition of Fresnel diffraction is given by (the corresponding geometry is given in Fig-1) –

$$I(P) = 4 * I_0(P) * \sin^2 \left( \frac{\pi}{2 * \lambda} \right) \left[ r_0^2 \left( \frac{1}{R_0'} + \frac{1}{R_0''} \right) \right]$$

Here, $I_0$ is the unobstructed intensity at the pint of observation (P).
$R_0'$ is the distance between circular aperture and collimating lens and $R_0''$ is the distance between circular aperture and point P. This expression may not be valid if $R_0'$ and $R_0''$ are too small.

![Figure 1: Geometry for Fresnel diffraction from a circular aperture.](image)

**Experimental Details:**

The experimental set up consists of microscope objective, circular aperture and lenses as shown in fig.2. The diffracted intensity is measured along the optic axis. The experimental setup is depicted in Fig-2.
**Procedure**

1. First of all, do the proper alignment of He-Ne laser mount so that laser beam has minimal drift in the lateral plane.
2. Put the spatial filter assembly in place and try to get a smoothed out but enlarged beam at the output.
3. Put the collimating lens in place and get a properly collimated beam which is well aligned to the optical bench.
4. Put the circular aperture and magnifying lens in place and observe the Fresnel diffraction pattern on screen. On changing the longitudinal distance, the pattern will change.
5. Now put the Si photodetector in place and start with a well-adjusted position of magnifying lens.
6. Before starting data collection once again make sure that all the optics is aligned properly so that the beam of the laser, having passed through the all the components, runs parallel to the optical bench.
7. Move the magnifying lens longitudinally in the steps of 1mm to get variation in the pattern at the detector and collect the readings.
8. Keep taking readings until you enter in the far field region.
9. From the collected data find the size of the diffracting aperture using the Fresnel diffraction theory.
10. Also measure the aperture size from travelling microscope.
11. Compare the two results and explain the error and plausible causes for it.

Figure 2: Experimental set up to study Fresnel diffraction from a circular aperture.
**Safety Precaution:**

The Helium Neon lasers used in this experiment is of low power but the narrow beam of light is still of high intensity. Consequently, never look directly into the unexpanded laser beam or at its reflection.

**Aim 2:**

To measure irradiance in the far field Fraunhofer zone in the transverse plane, for a slit and compare it with theoretical results.

**Equipment Used:**

He-Ne laser (632.8 nm), Circular aperture, Si pinhole photodetector, Spatial filter, Lenses (focal length – 7.5 & 2.5 cm), Optical rail, Digital multi-meter, Travelling microscope.

**Theoretical Background**

This analysis is also based on scalar diffraction theory. The Fraunhofer pattern is just a Fresnel Transform/pattern at large distances from the aperture. When the distance is increased, outgoing diffracted waves become planar and Fresnel transform reduces to a Fraunhofer pattern. In fact Fraunhofer diffraction pattern is nothing but the Fourier transform of the aperture function. Quantitatively this pattern is said to persist in the region for which $F<<1$, as previously defined. Depending on how well condition of $F<<1$ is satisfied, the lens may or may not be required in the experimental setup.

According to the Fraunhofer theory, for the circular aperture variation of normalized intensity should follow the equation –

$$I = I_0 \left[ \frac{\sin \beta}{\beta} \right]^2$$

$$\beta = \frac{2\pi}{\lambda} \cdot (a/2 \cdot \sin \theta)$$

Where, $a =$ width of the slit.
Procedure:

1. First of all, do the proper alignment of He-Ne laser mount so that laser beam has minimal drift in the lateral plane.
2. Put the spatial filter assembly in place and try to get a smoothed out but enlarged beam at the output.
3. Put the collimating lens in place and get a properly collimated beam which is well aligned to the optical bench.
4. Put the slit and lens in place and observe the Fraunhofer diffraction pattern on screen.
5. Now put the Si photodetector in place and before starting data collection once again make sure that all the optics is aligned properly so that the beam of the laser, having passed through the all the components, runs parallel to the optical bench.
6. Move the Si photodetector laterally in the steps of 0.1mm to record the intensity variation and collect the readings of photodetector output voltage.
7. Keep collecting the data until you cross at least two maxima and two minima.
8. From the collected data find the size of the diffracting aperture using Fraunhofer diffraction theory.
9. Also measure the size of diffracting aperture using a travelling microscope and compare the two results.
10. Record the diffraction pattern using camera.
Aim 3
To measure irradiance in the far field Fraunhofer zone in the transverse plane, for a circular aperture and compare it with theoretical results.

Equipment Used:
He-Ne laser (632.8 nm), Circular aperture, Si pinhole photodetector, Spatial filter, Lenses (focal length – 7.5 & 2.5 cm), Optical rail, Digital multi-meter, Travelling microscope.

Theoretical Background
According to the Fraunhofer theory, for the circular aperture variation of normalized intensity should follow the equation –

\[ I = I_0 \left[ \frac{J_1(v)}{v} \right]^2 \]

\[ v = \frac{2\pi}{\lambda} \cdot (r \cdot \sin \theta) \]

where, \( r \) = radius of the circular aperture & \( J_1 \) is the Bessel function of first kind.

Procedure:
1. First of all, do the proper alignment of He-Ne laser mount so that laser beam has minimal drift in the lateral plane
2. Put the spatial filter assembly in place and try to get a smoothed out but enlarged beam at the output.

3. Put the collimating lens in place and get a properly collimated beam which is well aligned to the optical bench.

4. Put the circular aperture and lens in place and observe the Fraunhofer diffraction pattern on screen.

5. Now put the Si photodetector in place and before starting data collection once again make sure that all the optics is aligned properly so that the beam of the laser, having passed through the all the components, runs parallel to the optical bench.

6. Move the Si photodetector laterally in the steps of 0.1mm to record the intensity variation and collect the readings of photodetector output voltage.

7. Keep collecting the data until you cross at least two maxima and two minima.

8. From the collected data find the size of the diffracting aperture using Fraunhofer diffraction theory.

9. Also measure the size of diffracting aperture using a travelling microscope and explain errors.

10. Record the diffraction pattern using camera.

Sample results to be reported:

1. Comparison with Fresnel diffraction theory

2. Comparison with Fraunhofer diffraction theory

3. Comparison of aperture diameter from microscopic and diffraction theory

4. Imaging of Fresnel and Fraunhofer diffraction pattern

References:

EXPERIMENT 8

Title: Nd:YAG laser and 2\textsuperscript{nd} harmonic generation

1 OBJECTIVE:
1) To align the Nd:YAG laser, observe the lasing wavelength (1064 nm) and hence to find the threshold pump power.
2) To produce second harmonics in the existing set up by using the given KTP Crystal, observe frequency doubled radiation (532 nm) and find the power conversion efficiency.

EQUIPMENTS REQUIRED:
Diode laser (808nm), Collimator, Focussing lens, Nd:YAG rod, KTP crystal, Mirror, Mounts, Filter plate, Spectrum analyser, Photodetector, Multi-meter and connecting wires.

THEORY:
Nd:YAG (neodymium-doped yttrium aluminium garnet; Nd:Y3Al5O12) is a crystal that is used as a lasing medium for solid-state lasers. The dopant, triply ionized neodymium, Nd (III), typically replaces a small fraction (1%) of the yttrium ions in the host crystal structure of the yttrium aluminium garnet (YAG), since the two ions are of similar size. It is the neodymium ion which provides the lasing activity in the crystal, in the same fashion as red chromium ion in ruby lasers. A neodymium YAG laser is pumped by a matched laser diode of high efficiency, resulting in a compact, high-efficiency and long-lifetime laser assembly. The wavelength of diode emission therefore matches an absorption band of the Nd-YAG crystal very well. It is possible to achieve efficiencies of 50-80\% in this manner. Output is in the near infrared range, but can be converted to the visible spectrum by an internal frequency doubler. A doubling crystal, which may be a KTP crystal, is placed at an optimum location in the laser cavity. Nd-YAG laser generates laser light commonly in the near-infrared region of the spectrum at 1064 nanometers (nm). It also emits laser light at several different wavelengths including 1440 nm, 1320 nm, 1120 nm, and 940 nm.
Typical neodymium doping concentrations are of the order of 1%. High doping concentrations can be advantageous e.g. because they reduce the pump absorption length, but too high concentrations lead to quenching of the upper-state lifetime e.g. via up-conversion processes. Also, the density of dissipated power can become too high in high-power lasers.

1) Experimental Procedure –
The Nd:YAG laser unit consists of the following components:

Module A Diode laser
Module B Collimator
Module C Focusing unit
Module D Laser mirror adjustment holder with Nd YAG rod
Module E Laser mirror adjustment holder
Module F Filter plate holder
Module G Photo detector
Module H Controller unit LDC01

The module A is positioned on the optical rail and clamped. The current control on the front panel of the control unit should be fully turned to the left. It can be seen that the diode laser beam is very divergent. The collimator is then placed in front of the diode laser module. The collimator has a focal length of 6 mm. The focus is located about 1-2 mm in front of the entry surface of the collimator. The light from the laser diode is almost parallel for a certain collimator position. Consequently the diode laser is Blocked Off and the focusing unit positioned on the rail. This unit contains a biconvex lens with a focal length of 60 mm. It is later used for focusing the diode laser beam into the YAG rod. It is practical to set up the focusing module at a distance of about 80-100mm from the collimator. The focus of the diode laser beam is produced at a distance of about 60mm from the main plane of the biconvex lens. The YAG rod should be positioned at this
point, so that the focus is located within the rod. The position of the focus can be found with a piece of white paper.

![Figure 2(a) Inserting the focusing unit](image)

![Figure 2(b) Inserting the YAG-rod](image)

**Procedure for lasing:**

1) Equipment is initially set as per the Figure 2 (a) and bring the photo detector nearer to the focusing unit (Module C) such that YAG rod(Module D) can also be inserted in the gap left between focusing unit and photo detector.
2) Now insert the YAG rod in between the focusing unit and photo detector such that the YAG rod is illuminated completely by the focus of focusing unit.
3) Insert the output coupler mirror(Module E).
4) Insert the 808 nm blocking 1064 nm pass filter (RG 1000 filter).
5) Now remove the photo detector, instead keep a mounted fiber optic cable and open software ‘SpectraSuite’.
6) Increase LD current slowly while observing spectrum on monitor and find the lasing wavelength.
7) Now place back the photo detector, vary the LD current (don’t go beyond 2 A) and note the corresponding output voltage.
8) Using the data provided (V-I values for laser diode), find the pump power corresponding to different values of LD current and finally plot output power of Nd:YAG laser as a function of the pump power. Find the threshold pump power.

**Second Harmonic Generation:**

![Figure 3 Set up for second harmonic generator using a KTP crystal.](image)

The second harmonic at 532 nm of the fundamental wave (1064 nm) is generated by means of a KTP crystal (Module K) (See figure 3)
1) Place the KTP crystal at a certain position in between Module D and the Module E.

2) Now switch on the laser diode. We can see a green coloured beam. Then put a filter to block 808nm and 1064 nm. If the beam is not observed then try changing the position of the KTP crystal and it must usually give a beam when placed at certain position.

3) Now remove photodetector and observe 532 nm using fiber optic cable and ‘SpectraSuite’.

4) Place the photodetector back and note the output voltage on varying the LD current

5) Plot the output power of the frequency doubled radiation as a function of pump power. And find threshold power.

6) Measure the 1064nm power to the KTP corresponding to one value of LD current and also measure the 532nm power corresponding to same LD current. Find the power conversion ratio.

Sample Results to report:

1. Threshold pump power of Nd-YAG laser and comparison with specification
2. Power conversion ratio of the KTP crystal

References:

Title: Diffraction grating characterization

Objective:

1. To find the ruling density (grooves/mm) of the given grating
2. To find the deviation as a function of wavelength for 1st order diffraction at different incident angle.
3. To find the Littrow condition and then the blazing angle.
4. To find the relative efficiency as a function of wavelength.

Equipment Required:
Grating, Laser source (457 nm, 532 nm, and 632.8 nm), Photo detector, Mirror etc.

Diffraction Grating: Diffraction grating is an optical component which consists of a polished surface, usually glass or metal, having a large number of very fine parallel grooves or slits and used to produce optical spectra by diffraction of reflected or transmitted light. When monochromatic light is incident on a grating surface, it is diffracted into discrete directions. We can picture each grating groove as being a very small, slit-shaped source of diffracted light. The light diffracted by each groove combines to form a diffracted wavefront. The usefulness of a grating depends on the fact that there exists a unique set of discrete angles along which, for a given spacing \( d \) between grooves, the diffracted light from each facet is in phase with the light diffracted from any other facet, so they combine constructively.

Diffraction by a grating can be visualized from the geometry in Fig: 1, which shows a light ray of wavelength \( \lambda \) incident at an angle \( \alpha \) and diffracted by a grating (of groove spacing \( d \), also called the *pitch*) along angles \( \beta_m \). These angles are measured from the grating normal, which is the dashed line perpendicular to the grating surface at its center. The sign convention for these angles depends on whether the light is diffracted on the same side or the opposite side of the grating as the incident light according to the fig: 2. The diagram shows a *reflection grating*, the angles \( \alpha > 0 \) and \( \beta_1 > 0 \) (since they are measured counterclockwise from the grating normal) while the angles \( \beta_0 < 0 \) and \( \beta_{-1} < 0 \) (since they are measured clockwise from the grating normal).

There are two types of diffraction gratings: ruled gratings and holographic gratings. Ruled gratings are created by etching a large number of parallel grooves onto the surface of a substrate, then coating it with a highly reflective material. Holographic gratings, on the other hand, are created by interfering two UV beams to create a sinusoidal index of refraction variation in a piece of optical glass. This process results in a much more uniform spectral response, but a much lower overall efficiency. While ruled gratings are the simplest and least expensive gratings to manufacture, they exhibit much more stray light. Gratings influence the optical resolution and the maximum efficiency for a specific wavelength range. The grating can be described in two parts: the groove density and the blaze angle.
The most fundamental grating equation is: \( \sin \alpha + \sin \beta = m \cdot n \cdot \lambda \)

Where \( \alpha \) – angle of incidence, \( \beta \) - Angle of diffraction, \( m \) - Diffraction order, \( n \) - Groove density, \( \lambda \) - Wavelength of light

**Ruling density of the grating:** The amount of dispersion is determined by the amount of grooves per mm ruled into the grating. This is commonly referred to as groove density, or groove frequency. The groove frequency of the grating determines the spectrometer’s wavelength coverage and is also a major factor in the spectral resolution. Ruling density \( n = 1/d \), where \( d \) is groove spacing.

**Deviation of the grating:** Deviation is the difference between the diffractive angle and the incident angle of the grating. Deviation \( \text{Dev} = \beta - \alpha \)

**Blaze grating and blaze angle:** A blazed grating – also called echelette grating is a special type of diffraction grating. It is optimized to achieve maximum grating efficiency in a given diffraction order. For this purpose, maximum optical power is concentrated in the desired diffraction order while the residual power in the other orders (particularly the zeroth) is minimized. Since this condition can only exactly be achieved for one wavelength, it is specified for which *blaze wavelength* the grating is optimized (or *blazed*). The direction in which maximum efficiency is achieved is called the *blaze angle* and is the third crucial characteristic of a blazed grating directly depending on blaze wavelength and diffraction order. Like every optical grating, a blazed grating has a constant line spacing \( d \), determining the magnitude of the wavelength splitting caused by the grating. The grating lines possess a triangular, saw tooth-shaped cross section, forming a step structure. The steps are tilted at the so-called blaze angle \( \theta_B \) with respect to the grating surface. Accordingly, the angle between step normal and grating
normal is $\theta_B$. The blaze angle is optimized to maximize efficiency for the wavelength of the used light. Descriptively, this means $\theta_B$ is chosen such that the beam diffracted at the grating and the beam reflected at the steps are both deflected into the same direction. Commonly blazed gratings are manufactured in so called Littrow configuration.

![Littrow Condition:](image)

The Littrow configuration is a special geometry in which the blaze angle is chosen such that diffraction angle and incidence angle are identical. The light is diffracted back toward the direction from which it came (i.e., $\alpha = \beta$); this is called the Littrow configuration, for which the grating equation becomes:

$$2 \sin \alpha = m n \lambda$$

**Relative Efficiency**: Relative efficiency is the ratio of the grating efficiency to mirror efficiency. 

% Relative Efficiency = (Grating Efficiency/Mirror Efficiency) x 100

Grating efficiency is the ratio of first order diffracted power to the incident power. Mirror efficiency is the ratio of zero order diffracted power to the incident power.

**EXPERIMENTAL SETUP AND PROCEDURE**: The ruling density of the grating and deviation angle is measured for three different wavelengths – 632nm, 457nm and 532nm. Steps of the experiment are as follows:

1) The mirror is aligned in front of the laser so that laser falls on the mirror properly and it reflects according to the fig 4.
2) After that the grating is aligned in front of the mirror such that the reflected ray from the mirror which is the incident ray for grating falls properly on the grating.
3) Then different orders of the diffracted ray observed with the help of the white boards and rotating scale on the grating mount.
4) After getting the zeroth order of the diffracted ray, it was marked on the white board for different incidence angles by moving the rotating scale anticlockwise. All the incidence angles noted. The first incidence angle assumed as zero degree.
5) Then the zeroth order of the diffracted ray made zero-degree angle with the normal of the grating. After that the first order of the diffracted ray placed on the same marked places on the white board by moving the rotating screw and all the angles have been noted.
6) The same experiment has been repeated for other two wavelengths (457nm and 532nm).

![Image of a diagram showing light diffraction through a grating]

**Fig 4: Setup for measuring the ruled density**

7) After measuring the ruling density of the grating and deviation for 1st order diffraction for three wavelengths another setup was made to find the Littrow condition, blazing angle and relative efficiency at those three different wavelengths.
8) The total setup is similar like previous setup which is shown in fig 4.
9) In this case first the zeroth order of diffraction was placed into the normal of the grating and angle noted. At the same time the first order of the diffraction was marked on the white board.
10) Then the zeroth order was placed into the marked place on the white board by rotating scale and the angle noted. The blaze angle is the difference between these two angles. This condition is the Littrow condition.
11) After that the power of the incident ray, reflected ray and the 1st order of diffraction was measured by the detector and a power meter to determine the relative efficiency.
12) The same experiment has been repeated for the same three wavelengths (632nm, 457nm and 532nm).
Sample results to be reported:

1. Ruling density measurement and comparison with specification
2. Blazing angle of diffraction grating
3. Relative efficiency of grating

References:

Title: Fabry-Pérot Interferometry

Objective: Use Fabry-Perot interferometer to determine:

a) To determine transmittance curve for different laser sources
b) To determine finesse for different laser sources

Apparatus required: Laser source, Fabry-Perot interferometer, Spectrum analyser controller (SA-201), Oscilloscope

Theory: Fabry-Perot interferometer is used to examine the fine structures of the spectral characteristics of CW lasers. It consists of a confocal cavity that contains two high reflectivity mirrors; by varying the mirror separation with a piezoelectric transducer the cavity acts as a very narrow band-pass filter. The transmitted light intensity is measured using a photodiode, amplified by the trans-impedance amplifier in the SA201 controller, and then displayed or recorded by an oscilloscope.

Figure 1: Schematic representation of a Confocal Fabry-Perot Interferometer

Free Spectral Range

To scan the spectra of the laser beam entering the Scanning Fabry-Pérot interferometer, a small displacement is applied to one of the cavity mirror mounted on piezoelectric transducers. This is done by fine tuning the ramp voltage applied to the piezoelectric elements using the controller SA201. When the mirror spacing becomes equal to an integral number of half the wavelength of
the laser, constructive interferences occur. That spectral response of the signal can be visualized with a scope. A series of periodical peaks appear on the screen of the scope. The distance between consecutive peaks is called the free spectral range (FSR) of the instrument. The free spectral range of a confocal cavity given by

$$FSR = \frac{c}{4d},$$

where $c$ is the speed of light and $d$ is the cavity length, instead of $c/2d$ as would be the case for a plano-plano cavity; the factor of 2 in the denominator can be understood by inspecting the ray trace (Figure 2). Note that a ray entering the cavity at a height ‘H’ parallel to the optical axis of the cavity makes a triangular figure eight pattern as it traverses the cavity. From this pattern it is clear that the ray makes four reflections from the cavity mirrors instead of the two that would result in a plano-plano cavity. Hence the total round-trip path through the cavity is given as $4d$ instead of $2d$.

![Figure 2 (a) Illustration of the confocal cavity design, where the mirror spacing is chosen equal to the radius of curvature of the mirrors.](image1)

![Figure 2 (b) Shows simplified ray-trace for a ray entering the cavity at height ‘H’. The curvature of the mirrors ‘r’ and the separation being set precisely to ‘r’ ensures that the input ray is imaged back onto itself after traveling a distance of approximately 4r or 4d.](image2)
Finesse and Resolution

The finesse, $F$, of the Scanning Fabry-Perot interferometer is a quantity which characterizes the ability of the interferometer to resolve closely spaced spectral features, it is determined solely by the reflectivity of the mirrors involved. For an infinitely narrow input spectrum, the finesse determines the width of the measured spectrum. In combination with the mirror spacing and its resulting free spectral range, the finesse defines the resolution of the instrument by

\[ \text{finesse } F = \frac{4f^2}{\pi^2}; \text{ where } f = \frac{FSR}{\Delta} \]

Figure 3 When two equal Gaussian line-shapes just meet the Taylor criteria for being resolvable, they are separated by their common FWHM ($\Delta$) as shown in the plot.
Figure 4 Schematics of experimental set-up
Procedure:

1. Make connections as shown in figure 4.
2. To align Fabry-Perot interferometer, close the input iris to its minimum aperture and center the beam on the iris opening, which most conveniently is achieved by aligning the beam via two folding mirrors onto the input iris.
3. Leave the back iris completely open and start to scan the unit. Make sure that a full sweep is visible on the oscilloscope, as well as that the signal from the detector is displayed; for ignition alignment adjust the oscilloscope gain to maximize sensitivity.
4. Use the mirror mount's tip/tilt adjustment until the beam is centered through the body of the interferometer, i.e., until you start to see modes on the oscilloscope.
5. Slowly close the back iris while adjusting mirror mount to keep the beam in the center of the device. Once the beam is centered, the alignment can be fine tuned with the two input mirrors by monitoring the shape and size of the transmission modes on the oscilloscope (see figure 5).

![Figure 5](image)

(a) Figure 5 (a) shows the higher order transverse modes are still visible. This setup requires further tweaking to optimize alignment. (b) Here, the higher order modes are suppressed. This setup is properly aligned.

6. The interferometer will then be ready for measurements. Now find the full FSR (in terms of time difference say t(msec)) and use it to find calibration factor which will be 1.5GHz /t(msec). Once the time scale calibration is known, we can find FSR of laser by measuring separation between successive peaks and by zooming in on one of the peaks we can measure the full width at half maxima (FWHM, Δ).
Sample results to report:

1. Transmittance curve
2. Finesse
3. Resolving power
4. Fabry-Perot ring structure

References:

Experiment no. 10
Part-1

Title: Measurement of temporal coherence of different light source using Michelson interferometer

Objective: To calculate temporal coherence using Michelson Interferometer of:

1. He-Ne laser of $\lambda = 632.8$ nm
2. Solid state Laser of $\lambda = 655$ nm
3. Diode Laser of $\lambda = 635$ nm

Equipment Required: Lasers with power supply, Microscopic-objective, Spatial filter, Spherical beam splitter, Two plane mirrors, Translational stage, Screen, CCD camera, X-Y position controller and Computer.

Theory:

The Michelson interferometer produces interference fringes by splitting a beam of monochromatic light so that one beam strikes a fixed mirror and the other a movable mirror. An interference pattern results, when the reflected beams are brought back together. The experimental set-up is shown. A light beam falls on a beam splitter (which is usually a partially silvered plate), and the waves reflected from mirrors $M_1$ and $M_2'$ interfere. If distance $M_1 M_2'$ is denoted by $d$, then the beam which gets reflected by mirror $M_2$ travels an additional path equal to $2L/c$. Thus, the beam reflected from $M_1$ interferes with the beam reflected by $M_2$ which had originated $2L/c$ seconds earlier. If the distance $L_c$ is such that $2L/c \ll \tau_c$ then a definite phase relationship exists between the two beams and well-defined interference fringes are observed. On the other hand, if $2L/c \gg \tau_c$ then, in general, there is no definite phase relationship between the two beams and no interference pattern is observed. There is no definite distance at which the interference pattern disappears; as the distance increases, the contrast of the fringes becomes gradually poorer and eventually the fringe system disappears. There are a lot many applications of this interferometer one of which is measuring temporal coherence of light. This can be done by measuring the coherence length of laser. Coherence length of laser is the distance over which light waves it produces are in phase. For any light source with frequency distribution of width $\Delta \nu$, coherence time $\tau_c$ can be given as

$$\tau_c = L_c/c = 1/\Delta \nu$$

Where, $\tau_c$, $L_c$, $c$ are the coherence time, coherence length and velocity of light respectively. The coherence time is the finite time over which interference fringes can be observed.
**Procedure:**

1. Laser is aligned to get the parallel beam. Proper care is required to make the beam strike at the centres of the mirrors.

2. Objective lens and pinhole arrangement (spatial filter) is used to filter out the higher spatial frequencies of the beam. Pinhole should be placed at the exact focus point of the objective lens. Uniform intensity light is falling on beam splitter.

3. Then the angle of the first beam splitter arrangement is aligned so that the reflected beam hits the first mirror at its centre. Similar has been done with the second mirror to get out reflected light which has to hit the second beam splitter also at its centre.

4. In this position two sets of bright patches come out in the screen from two mirrors simultaneously. Adjustment is done properly with the help of the movable mirrors and beam splitters to overlap these two patches finely.

5. Beams passing from beam splitter interfere and interference pattern is observed on screen.

6. Use CCD camera and lens arrangement to capture the interference pattern as lens focus the pattern on camera aperture.

7. CCD camera is triggered using computer.

5. When the setup is arranged as the interference pattern is appeared on screen.
   
   a. For He-Ne laser, the coherence length in cms, to calculate the coherence length, slide the movable mirror on slider and interference pattern is observed at different positions.
   
   b. For diode laser and solid state laser, the mirror attached to position controller is moved using position controller suite (installed in computer) and pattern is observed at different positions.

**Experiment Setup**
Source of error:

1. Least count error of scale over which mirror is moved.
2. Fluctuation of position of mirror.
3. Least count error of mirror position controller.
4. Saturation of intensity in image taken by ccd camera.
5. Vibration of optical bench.
6. Refractive index variation due to airflow and vibration.

Sample results to be reported:

1. Fringe visibility
2. Coherence length of laser and comparison with specification

Reference:

Experiment no. 10

Part-2

Title: Fred Simulation of Michelson Interferometer

Objective:

To Find the coherence length of He-Ne laser

1. Creating the Geometry
   i. The details of the experimental arrangement are given in figure 1. Open the fred software. Open a blank FRED document (File>New>Fred Type, keystroke Ctrl+N or Toolbar button).
   
   ii. Create a new Subassembly by one of three methods:
       From the Main Menu, Create>New Subassembly
       Keystroke Ctrl+Alt+S
       Right-click on Geometry folder and select option Create New Subassembly
       Name this entry “Beam splitter”. The new Subassembly now appears in the Tree as shown in the Figure 1.

![Figure 1](image-url)
iii. Create a prism by following method, Right-click on either a Subassembly or the Geometry folder and select option Create New Prism. Name it as “Beam splitter”. And set the optical parameters as shown in the figure 2.

![Image of Prism Creation Interface]

**Figure 2**

iv. Now in similar fashion add another subassembly and name it as “MIRRORS”. Right-click on either this Subassembly or the Geometry folder and select option Create New mirror. Name it as “REFERENCE MIRROR”. And set the optical parameters as shown in the figure 3. Go to the position/orientation and Left-click anywhere inside the green highlighted entry Geometry>Beamsplitter and select the surface 3 of and hit the OK button. Geometry. Beamsplitter.Surf 3(+Z output face) should now appear as the Starting Coordinate System of mirror. Right-click again and select Append to add shift operation to move the REFERENCE MIRROR with respect to beam splitter surface 3.
Figure 3

Figure 4
Type in the 4 mm shift as the z-component shift and hit the Apply button to see the Analyzer move to its correct relative position. See figure 5.

v. Right-click on either “MIRRORS” Subassembly or the Geometry folder and select option Create New mirror. Name it as “TEST MIRROR”. And set the optical parameters as shown in the figure 6. Go to the position/orientation and Left-click anywhere inside the green highlighted entry Geometry>Beamsplitter and select the surface 2 of and hit the OK button. Geometry. Beamsplitter.Surf 2(+Y output face) should now appear as the Starting Coordinate System of mirror. Right-click again and select Append and the select rotate and write the properties as given in Figure. Right-click again and select Append to add shift operation to move the TEST MIRROR with respect to beam splitter surface 2.
Type in the -4 mm shift as the z-component shift and hit the Apply button to see the Analyzer move to its correct relative position. See figure 8.
vi. Create a plane by one of the following methods, From the Main Menu, Create> New Element Primitive> Surface. Or, Right-click on either a Subassembly or Geometry folder and select option Create New Element Primitive> Surface. Name the plane as “Detector”. And set the optical parameters as shown in the figure 9.

![Surface Trimming Specification](image)

**Figure 9**

The click on the location/orientation then set the parameters as shown in figure 10.
2. **Adding a source**

   i. Let us now add a source. We begin by adding a Simplified Source. This source type can be invoked by following methods:

      From the Main Menu, Create>New Simplified Source
      Keystroke Ctrl+Alt+I
      Right-click on Optical Sources folder and select option <Create New Simplified Optical Source.

      Select “Collimated plane wave” from the drop down menu in “Type”. Set the location/orientation by the method previously described steps and set it the way in the figure 4. Also make sure other source parameters are same as that in figure 11.
3. Analysis surface

The Analysis Surface on the image plane provides a user-defined planar grid on which various calculations are made. An Analysis Surface is created by one of three methods:

From the Main Menu, Create>New Analysis Surface

Keystroke Ctrl+Alt+N

Right-click on Analysis Surface(s) folder and select option <Create New Analysis Surface>

Set all the parameters as in figure7a. Also set the location/orientation by the method previously described steps.

Drag and drop this analysis surface to the detector surface. So that detector surface will be our analysis surface.
4. Coating

Right click on the coating – select create a new coating then click ok. Then set the parameters as the figure 13 given below.
Drag and drop this coating to the beam splitter surface 5.

5. **Ray trace**

We are now in position to trace our ray grid through the lens. While there are numerous options for raytracing in FRED, we restrict ourselves at this stage to a basic raytrace initiated by one of three methods:

1. From the Main menu, Raytrace>Trace and Render
2. Keystroke Ctrl+Shft+F7
3. Raytrace Toolbar button

Then we will find result as given in figure 13.
6. **Result analysis**

Click on Analyses tool bar in FRED. Select irradiance spread function the click ok.

We will get the irradiance. Now change the position of the test mirror and see the irradiance function.

Initially when both the mirrors were at same position, no fringes will be present. When we slightly move the position of the test mirror we will start getting fringes. So, we will have to find the position of the test mirror at which fringes disappear again. Then the difference between these positions will give us coherence length.
EXPERIMENT NO- 11

Title: Alignment, acquisition, processing and reconstruction of holograms

Objective:

1. To create the transmission holograms of 3D object using He-Ne laser.
2. To create the transmission holograms of diffraction grating using He - Ne laser and measure the grating efficiency.

Equipment’s Required:

He-Ne Laser, Beam steerer, Beam splitter, Spatial filter, High reflecting folding mirrors ,3D object, Diffraction grating, Measuring scale, Solutions A and B, Bleach, De-ionized water, Optical table, Stand, Photographic plate.

Theory:

The hologram is a record of the interference pattern created when two beams of laser light interfere on the holographic surface. One beam, called the reference beam, strikes the holographic plate directly from the laser, or after bouncing off several mirrors. The other beam, called the object beam, reaches the holographic plate after scattering off of an object which is being holographed. These two beams are initially coherent and in phase with one another, but after the object beam bounces off of an object, it will be out of phase with the reference beam. The two beams will interfere at the plate and create areas of high amplitude and low amplitude, light and dark bands. These are recorded by the holographic surface, and preserved through the developing process. The bands of light and dark act as an extremely sophisticated diffraction grating, so that when light passes through the plate or film, it interferes to form the exact image of the object that was recorded. Viewing the hologram at different angles will give a different view of the object, thus giving it its three dimensional appearance. The exact wave front produced by an object is duplicated by the hologram.
Experimental Set-up:

![Figure 1 Schematics of experimental set-up](image)

Procedure for recording the Hologram:

1) Align the laser beam to be straight i.e., Adjust the beam such that its horizontal position and vertical position is same as beam propagates.

2) To do the above, take board with white paper near the beam steerer and locate the position of beam, subsequently move the board forward and observe the beam spot and the direction of beam. Adjust steerer vertical screw to bring near the middle and again observe the beam direction. If vertical height of beam is ok then go for horizontal adjustment and don't touch vertical screw again.

3) After alignment, use variable beam splitter at an angle (around 45deg) to divide beam into reference and object beams.

4) Reference and object beam ratio is to be about 4:1. Adjust beam splitter by rotating the wheel such that reference is brighter than object beam.

5) For diffraction grating hologram, if object beam is brighter than reference then use second order reflected beam which is low intensity compared to reference beam.
6) After beam splitter, use the spatial filter. Remove the pinhole and adjust height such that the beam goes through the centre of the object lens and the enlarged (focused and then diffracted by lens) beam at the same spot as before spatial filter.

7) Place the pinhole tightly and adjust horizontal and vertical screws such that maximum light observed at the same spot of the beam before.

8) Bring the object lens closer to the pinhole i.e., less than 1mm and observe the intensity by adjusting pin hole screws such that uniform maximum intensity is observed without any circular rings around it.

9) Adjust height of mirror such that beam is at the centre of uniform beam spot.

10) Do the adjustment of spatial filter and mirror for object beam also as above.

11) Place blazed diffraction grating or object on magnet stand and its face towards photographic plate then focus object beam on grating or object by adjusting the mirror such that total beam spot incident on grating or object.

12) For grating, observe the grating zeroth, first and second order beams and notice that first order intensity is more than the zeroth order intensity (because of blazed grating).

13) The grating that we use is the reflection type grating i.e., the orders that we observe, is the reflection from the grating.

14) Adjust mirror angle in a way that second order from the grating falls on the photographic plate.

15) Measure the distance of reference beam and object beam from the beam splitter to the photographic plate stand with the help of rope or the scale.

16) Adjust reference beam mirror by moving backward or forward such that both the beams distance is approximately same.

17) Adjust mirror of reference beam such that it falls on the photographic plate without touching the grating or the object.

18) Adjust the photographic plate stand and mirrors such that both beams fall on the plate at same spot by blocking one beam at a time. Carefully adjust with the help of the white paper because both beams spot mismatch makes the interference pattern differ.

19) Prepare chemical solutions:

   a) Wear hand gloves; clean all containers with water and again with deionized water also.
   b) One container fills completely with deionized water.
   c) Second container (written developer) fills completely with the bleaching solution.
   d) Third container fills with 35ml solution A plus 35ml solution B.
   e) Pour enough deionized water in large beaker for cleaning the measuring beaker and the photographic plate.
20) Close all doors and switch off lights except green light. Block the laser source before placing photographic plate with black paper. Take out the photographic plate in the dark surroundings and check for its silver halide face then place silver halide face towards the object, in stand tightly. Carefully handle the photographic plate.

21) Expose the beams on photographic plate for 1min, measure 1min by stopwatch carefully. Then stop the laser source.

22) Remove the plate then put it in the solution A plus B by holding with the holder. Don’t leave in the container, hold at the edge within the solution and start stopwatch. Wait for about 2min and observe the photographic plate turn into black.

23) After the plate turn into black, place it in deionized water container and rinse it for 1min. And then place it in bleaching solution for 1min to become transparent.

24) Then place it in deionized water and clean and rinse it and let it dry outside. You can see rainbow pattern on the plate as well as interference pattern.

25) After chemical process, photosensitive part is removed from plate then we can see the image formed on it in the presence of light by letting the reference beam on it.

26) Determine the grating efficiency of hologram. Compare and discuss the results with the true value.

**Precautions:**

1. Take care of the laser beam during the alignment.
2. Spatial filter must be aligned properly so that reference beam does not hit the object.
3. While using the chemical processing to develop the hologram, always take care of the photographic plate so that it may not fall down.
4. Multimeter connection must be properly done with the photo detector.

**Sample results to be reported:**

1. Picture of the 3D object along with the corresponding reconstructed image from the hologram
2. Comparison of the holographic grating with the actual reflective grating

**References:**

3. http://experimentationlab.berkeley.edu/holography
Experiment No. 12 (Part-I)

Title: Characterization of optical fibre

Objective:

1. Optical Fiber Coupling Loss for single mode
2. Bending loss in Single mode optical fiber
3. To determine NA of single mode optical fiber at two different positions
4. To determine Misalignment loss for single mode optical fiber
   i. Longitudinal misalignment
   ii. Transverse misalignment
   iii. Angular misalignment

Apparatus Required:

1. He-Ne Laser
2. Focusing objective (20X)
3. Optical fiber with alignment with (x, y, z & angular) mounts (quantity 2)
4. Translation stage
5. Photo-detector with mount
6. Digital multi-meter

Warning: The fibre end has very sensitive surfaces. Please do not touch them. Check with your instructor if the output beam profile is not smooth.

Introduction to Optical Fiber

An optical fiber is a cylindrical structure made from a transparent material such as glass and consists of a central core of refractive index $n_1$, surrounded by a cladding of refractive index $n_2$ (see Fig. 1.1). Light gets guided through the fiber by total internal reflection, in which a light ray incident on an interface between a denser medium (a medium of higher refractive index) and a rarer medium (a medium of lower refractive index) at angles greater than the critical angle, gets totally reflected, i.e., undergoes complete reflection. Thus light rays impinging on the core-cladding interface at an angle greater than the critical angle \( \theta_c = \sin^{-1}(n_2/n_1) \) get total internally reflected, and can propagate through very long distances. In order to satisfy the condition of total internal reflection at the core cladding interface, the rays must be incident at appropriate angle at the entrance of the fiber. Assuming the surrounding medium to be air, the angle of incidence \( \phi_0 \) (see Fig. 1) should be smaller than acceptance angle, \( \phi_a = \sin^{-1}\sqrt{(n_1^2 - n_2^2)} \). Also sine of the acceptance angle is called Numerical Aperture (NA).
1. To determine coupling losses of optical fibre

The design of fiber optic systems depends on how much light is launched into an optical fiber from an optical source and how much light is coupled between fiber optic components, such as from one fiber to another. The amount of power launched from a source into a fiber depends on the optical properties of both the source and the fiber. The amount of optical power launched into an optical fiber depends on the radiance of the optical source. An optical source's radiance, or brightness, is a measure of its optical power launching capability. Radiance is the amount of optical power emitted in a specific direction per unit time by a unit area of emitting surface. For most types of optical sources, only a fraction of the power emitted by the source is launched into the optical fiber. The loss in optical power through a connection is defined similarly to that of signal attenuation through a fibre. Optical loss is also a log relationship. The loss in optical power through a connection is defined as:

\[
\text{loss} = 20 \log_{10} \frac{V_o}{V_i}
\]  

(1)

Where,

\(V_o\) = Voltage measured for light emitted from the fibre.

\(V_i\) = Voltage measured for light emitted by the source.

2. To measure bending loss in single mode optical fibre

There are two types of bends in optical fibres:

(a) Macroscopic bending loss (due to bend having radius much larger than that of the fibre diameter)

(b) Microscopic loss (due to random microscopic bends of radii much smaller than fiber diameter)
Here we will be measuring Macroscopic Bending loss in fibres.

Macro-bending of an optical fiber is the attenuation associated with bending or wrapping the fiber. Light can "leak out" of a fiber when the fiber is bent; as the bend becomes more acute, more light leaks out. This effect is shown schematically in the figure 2 below. In the figure on the left, a small percentage of the light is refracted out of the waveguide when it is bent. The figure 2 on the right schematically illustrates that more light is shown refracted out of the fiber when it is bent to a smaller diameter.

![Figure 2](image)

Figure 2 shows loss due to macroscopic bending

Macro-bending is commonly modeled as a "tilt" in the refractive index profile based on the radius of curvature of the fiber bend. The attenuation increases exponentially as bend radius decreases.

It is known that any bound core mode has an evanescent field tail in the cladding which decays exponentially as a function of distance from the core. Since this field tail moves along with the field in the core, part of the energy of a propagating mode travels in the fibre cladding. When a fibre is bent, the field tail on the far side of the centre of curvature must move faster to keep up with the field in the core, for the lowest order fibre mode. At a certain critical distance $x_c$, from the centre of the fibre; the field tail would have to move faster than the speed of light to keep up with the core field. Since this is not possible the optical energy in the field tail beyond $x_c$ radiates away. Since higher order modes are bound less tightly to the fibre core than lower order modes, the higher order modes will radiate out of the fibre first.

3. Misalignment Losses

When two optical fiber ends are brought close to each other to form a joint (temporary or permanent) there always remains a possibility of mechanical errors which causes the fibers to get misaligned. These misalignments are shown below.
The fibers may get misaligned laterally, wherein the axes of the two fibers get misaligned as shown in the above figure. This is also called transverse misalignment. Thus the loss in dB is given as:

$$\alpha_t (\text{dB}) = 4.34 \left( \frac{u}{w} \right)^2$$

Where, $u$ is the transverse misalignment and $w$ is the spot size.

The second common type of misalignment is the longitudinal type of misalignment in which there remains a gap between the two fiber ends in the final joint as shown in figure 3 (axial separation). For this misalignment loss is given as:

$$\alpha_l = 10 \log (1 + \tilde{D}^2)$$

Where,

$$\tilde{D} = \frac{D\lambda_0}{2\pi n_1 w^2}$$

Here, $\lambda_0$ is the free space wavelength, $n_1$ is the refractive index of the medium between the fiber ends, with spot size $w$, $D$ is the longitudinal misalignment.

The third type is the angular misalignment (axial tilt) where the two fiber axes are not parallel to each other as shown in the above figure. The loss is given by:

$$\alpha_\omega (\text{dB}) = 4.34 \left( \frac{\pi n_1 w \theta}{\lambda_0} \right)^2$$
Here, $\lambda_0$ is the free space wavelength, $n_1$ is the refractive index of the medium between the fiber ends, $\theta$ is angular misalignment between the axes of two single mode fibers with spot size $w$. All these mechanical misalignments lead to a loss of energy at the point of defect. Hence proper orientation of the two fiber ends must ensure a loss-less before coupling of signal from one fiber to another.

**Experimental Setup & Procedure:**

This experiment involves the following setup and procedure of fiber characterization, but prior to the performance of the experiment it is mandatory to cleave the fiber end in order to make the fiber end flat and clean from any dust particle. The process of the cleaving involves first stripping of the fiber acrylic coating then cleaning the residual dust on the fiber with acetone gently and finally cleaving the with fiber cleaver.

a) To determine Optical Fiber Coupling Loss for single mode fiber (SMF):

1. Make the arrangement as shown in figure 4.
2. Turn on the He-Ne laser source and wait for 5 minutes so that the laser gets stabilized.
3. Place an objective lens (20X) in front of the source. Align it in such that laser light is passing through it and then adjust the focus of the lens and the horizontal and vertical axis such that back reflection should fall at the center of the source in a circular symmetry.
4. Observe the power value on the photo-detector.
5. Place a fiber cable on a mount as shown in figure 4.
6. Adjust the height and position of the fiber with the help of alignment screws in the mount so that maximum light propagates in the fiber (see in multi-meter).
7. Measure the light intensity at the laser input right after the lens and also at the output end of fiber.
8. Note down the readings and then calculate the coupling loss.
b) To determine bending loss in Single mode optical fiber:

1. Align all the components as shown in figure 5 as explained.
2. Bend the fiber for different radius of curvatures using a mandrel.
3. Measure the variation of the output intensity falling at the photodiode for these curvatures.
4. Calculate the loss for each reading.
5. Curve fit the loss with respect to the radius of curvature.
6. Calculate the value of critical radius.

![Figure 5: Optical fiber bending loss measurement](image)

(c) To measure NA of Single Mode Optical fiber:

1. Make the arrangement as shown in figure 6.
2. This time place the output end of fiber over an angular stage.
3. Measure the output power of the fiber with a photo-detector and read it on a multi-meter.
4. Vary the angle of the stage to find the output power variation from minimum to maximum then to minimum.
5. Plot these readings and find the data points at which the maximum power goes $1/e^2$ of its value. These two angles would be $\phi_1$ and $\phi_2$.
6. Calculate the acceptance angle with following formula
   $$2\phi_a = \phi_2 - \phi_1$$
7. Calculate the numerical aperture by using measured acceptance angle as follows:
   $$NA = n_0 \sin \phi_a$$

![Figure 6: Optical fiber Numerical aperture measurement](image)

d) Misalignment loss in Single mode optical fiber:
1. Align the components as shown in figure 7.
2. Place another SMF near the end of the input SMF as shown in figure 7.
3. Couple the output intensity coming out from the Input SMF to the output SMF.
4. Align two of the fiber edges until the maximum power starts coupling between them.
5. Place a detector at the end of second SMF.
6. Measure the intensity with the help of a multi-meter.
7. Move output SMF with the help of an angular stage as used in figure 6 but mounting second SMF.
8. Take the readings for very small steps of angular movement. Curve fit the plot.
9. For the observation of transverse misalignment loss, we repeat 1 to 4 steps and then mount the second SMF on a linear stage and then take the readings in a very small steps in transverse direction until the two fibers cross each other completely.

10. For observing the longitudinal misalignment loss after step 4 we mount the second SMF on a linear stage and then move this fiber in longitudinal direction. Start taking the reading from where are getting maximum intensity up to the point where we get minimum value of intensity.

Figure 7: Optical fiber misalignment loss measurement

**Observations & Results:**

**Sources of Error:**
Coupling between source and fibre is very important and avoid touching the bare fibre tip with hands or with other objects because it may break the fibre tip or change the output power and also be careful while fixing the fibre in the fibre mount.

**Sample results to be reported:**

1. Coupling loss, bending loss, misalignment loss for an optical fiber
2. NA of optical fiber and comparison with literature

**References:**

(3) “Optics” by Hecht & Ganashan
Experiment No. 12 (Part-II)

Title: Demonstration of Optical Fiber kit “Light Runner Basic”

OBJECTIVE:
1. To measure the Attenuation, Dispersion & Eye Pattern in an optical fiber
2. To determine the position of the fault in a fiber optic link using OTDR method.

EQUIPMENT USED: Optical fiber spool (1 km, 2 km, 3km), Connectors, BNC connectors, Fiber connectors, PC link cable, Fiber Optic Light Runner Kit, PC

Note: Switch ON Laser only after making connections!

THEORY: a) To measure the attenuation loss in an optical fiber
Reduction in the intensity of light as it propagates within the fiber is called “attenuation”. The finite attenuation present in any optical fiber requires that fiber system design address degradation in signal strength through such approaches as signal amplification, interconnect optimization, fiber geometry design, and environmental isolation.

Several factors contribute to the loss spectrum (Fig. 1) with material absorption and Rayleigh scattering contributing dominantly.

(a) Material absorption: Silica glass has electronic resonances in the ultraviolet region, and vibrational resonances in the far-infrared region beyond 2 μm, but it absorbs little light in the wavelength region extending from 0.5 to 2 μm. However, even a relatively small amount of impurities can lead to significant absorption in that wavelength window. From a practical point of view, the most important impurity affecting fiber loss is the OH ion, which has a fundamental vibrational absorption peak at ≈2.73 μm. The overtones of this OH-absorption peak are responsible for the dominant peak seen in Fig. 1 near 1.4 μm and a smaller peak near 1.23 μm.

(b) Rayleigh scattering: Rayleigh scattering is a fundamental loss mechanism arising from density fluctuations frozen into the fused silica during manufacture. Resulting local fluctuations in the refractive index scatter light in all directions. The Rayleigh-scattering loss varies as λ⁻⁴ and is dominant at short wavelengths. As this loss is intrinsic to the fiber, it sets the ultimate limit on fiber loss. The intrinsic loss level (shown by a dashed line in Fig. 1) is estimated to be (in dB/km): \( \alpha_R = C_R/\lambda^4 \), where the constant \( C_R \) is in the range 0.7–0.9 dB/(km-μm⁴) depending on the constituents of the fiber core. As \( \alpha_R \) is in the range of 0.12–0.15 dB/km near \( \lambda =1.55 \mu m \), losses in silica fibers are dominated by Rayleigh scattering. Among other factors that may contribute to losses are bending of fiber and scattering of light at the core-cladding interface.
Calculations:

Light travelling through an optical fiber exhibits a power that decreases exponentially with the distance. The overall optical throughput (transmission) of an optical fiber can be quantified in terms of the input optical power, \( P_0 \), and the output power, \( P(z) \) observed after light propagates a distance, \( z \), along the fiber length:

\[
P(z) = P_0 e^{-\alpha z}
\]

where \( \alpha \) is attenuation coefficient. The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses. Optical losses of a fiber are usually expressed in decibels per kilometer (dB/km). The expression is called the fiber’s attenuation coefficient \( \alpha \) and the expression is

\[
\alpha = \frac{10}{z (km)} \log \left( \frac{P(z)}{P_0} \right)
\]

where \( P(z) \) is the optical power at a position \( z \) from the origin, \( P(0) \) is the power at the origin. For a given fiber, these losses are wavelength-dependent. The value of the attenuation factor depends greatly on the fiber material and the manufacturing tolerances.

Setup:

Fig. 2: Measurement of attenuation in optical fiber
**Procedure:**

1. Switch ON the LIGHT RUNNER kit.

2. **Help** → **Attenuation in optical fiber** → **Enter**

3. Connect 1550 laser source to the photodetector PD1 with the help of a patch cord.

4. Connect BNC connector adjacent to PD1 to any channel (CH1) of the digital storage oscilloscope (DSO).

5. Enable the 1550 laser and set the following parameters:
   (a) frequency = continuous, 5 KHz
   (b) duty cycle = 50%
   (c) laser power = 50%

6. Click on the START button, waveform will appear CH1 on the DSO screen.

7. In case of detector saturation, reduce the laser power level below the saturation level by using software control.

**NOTE:** while operating LIGHT RUNNER, if the detector is fed with high optical power it will be saturated and will not give correct readings and waveforms (on DSO). For reliable results, users are expected to keep optical power fed to detector below the saturation limit by adjusting source power through variable optical attenuator. *One also carried out the absolute optical power measurement using optical power meter.*

8. Note down the power level at PD1 as $P_1$.

9. Click on the STOP button.

10. Disconnect the patch chord from PD1 and connect it to a fiber spool of known length (L).

11. Connect the other end to PD1.

12. Click on the START button.

13. Note down the power level at PD1 as $P_2$.


15. Repeat the experiments with various length of fiber by combining the individual spools.
16. Each time a patch cord is connected to a spool, an extra connector loss ($\alpha_C$) would appear in Eqn. (2). So, the actual attenuation loss in all the configurations can be computed by subtracting CL from ‘$\alpha$’.

17. Repeat the procedure 3–16 for the other wavelength 850 nm. Here, the patch cord needs to be connected to the other photodetector PD2 which would be connected to the other channel (say CH2) via a BNC connector.

Observation:

(i) Determining the connector loss:

Input frequency = 5 KHz, duty cycle=50%, laser power=50%

Connect a patch chord to the 1550nm laser diode and measure input power. Then connect two patch chords using ‘Fiber Connector’ and measure output power .

- Input power from LD @ 1550 nm …µW
- Power observed after connector = …. µW
- Decease in power due to connector = ….µW
- Connector loss ..... dB.

(ii) Determining the fiber attenuation:

Input frequency = … KHz, duty cycle = ….%, laser power = ….%

<table>
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<tr>
<th>$\lambda$ (nm)</th>
<th>L (km)</th>
<th>$P_1$ (µW)</th>
<th>$P_2$ (µW)</th>
<th>Attenuation (A) in dB = $10\log\left(\frac{P_1}{P_2}\right)$</th>
<th>No. of connectors (n)</th>
<th>Connector loss ($\alpha_C$) (dB)</th>
<th>$A' = A - n\alpha_C$</th>
<th>Attenuation loss (A) in dB/km= $A'/L$</th>
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b) To measure the dispersion in an optical fiber
When a short pulse of light travels through an optical fiber its power is dispersed in time so that
the pulse spreads into a wider time interval. The broadening of light pulses, called dispersion, is
a critical factor limiting the quality of signal transmission over optical links. Dispersion is a
consequence of the physical properties of the transmission medium. Single-mode fibers, used in
high-speed optical networks, are subjected to Chromatic Dispersion (CD) that causes pulse
broadening depending on wavelength, and to Polarization Mode Dispersion (PMD) that causes
pulse broadening depending on polarization. Excessive spreading will cause bits to “overflow”
their intended time slots and overlap adjacent bits. If a single-mode fiber is specified by the
dispersion coefficient ‘D’ in units of ps/km-nm, then the accumulated dispersion through L km
long fiber for a source of spectral width $\Delta \lambda$ would be $DL\Delta \lambda$ ps. To preserve the transmission
quality, the maximum amount of time dispersion must be limited to a small proportion of the
signal bit rate, typically 10% of the bit time.

There are four sources of dispersion in single mode optical fibers: material dispersion and
waveguide dispersion. Material dispersion arises due to the dependence of the refractive index of
fiber material on the wavelength while waveguide dispersion arises due to waveguide geometry.
A G652 fiber has a dispersion of 17 ps/km-nm at the 1550 nm. Thus, if we take a laser source of
spectral width 2 nm and a fiber of 5 km, the accumulate dispersion would be 170 ps. This is a
very small dispersion value and measurement of this would require sophisticated
instrumentation. In order to have a measurable effect, we choose two wavelengths which are
wide apart namely, 850 nm and 1550 nm. The difference in the propagation time between these
two wavelengths will be primarily due to material dispersion.

Calculations:
A pulse of light travels at a velocity referred to as the group velocity. If $n(\lambda)$ is the refractive
index of fiber at $\lambda$, then group refractive index $n_g(\lambda)$ is given by,

$$n_g(\lambda) = n(\lambda) - \lambda \frac{dn}{d\lambda} \quad (1)$$

And the speed of a light pulse at a wavelength $\lambda$ would be given,

$$v_g(\lambda) = \frac{c}{n_g(\lambda)} \quad (2)$$

Thus the group index and hence the pulse speed depends upon on how the refractive index varies
with the wavelength. This dependence is usually described by a relation referred to as the
Sellemeier relation. For pure silica, an approximate relation is given by,

$$n(\lambda) = 1.451 - 0.003 \left( \lambda^2 - \frac{1}{\lambda^2} \right) \quad (3)$$

Where $\lambda$ is in $\mu$m. Using Eqn. (2) and (3), we obtain for the group refractive index,
\[ n_g(\lambda) = 1.451 + 0.003 \left( \lambda^2 + \frac{3}{\lambda^2} \right) \]  

(4)

Using the above equation, we can estimate the speed of a pulse at two different wavelengths due to material dispersion. Thus, the approximate speed of a light pulse at \( \lambda \) of 850 nm is \( 2.036 \times 10^5 \) km/s and at 1550 nm is \( 2.052 \times 10^5 \) km/s. Thus, if two pulses one at 850 nm and the other at 1550 nm are simultaneously launched into an optical fiber, then after a distance of \( L \) km, the difference in arrival times between the two pulses would be,

\[ \Delta \tau = \frac{L}{v_g(0.85)} - \frac{L}{v_g(1.55)} \]  

(5)

For a fiber length of 1 km, this comes out to be about 14 ns.

Using the experiment, it is also possible to check if the lower wavelengths travel slower or faster than longer wavelengths, whether the time difference increases linearly with increasing length of the fiber or decreases.

**Setup:**

![Fig. 3: Measurement of dispersion in optical fiber](image-url)
Procedure:

1. Switch ON the LIGHT RUNNER kit.

2. Connect the 850 nm laser to the appropriate port of the 3dB coupler which delivers more power as compared to the other port.
   
   **NOTE:** Connect the 850 nm to both the ports of the 3 dB coupler and connect the ‘COM’ port of the coupler to the power meter by using a patch cord.

3. Connect the 850 nm laser to the appropriate port of the 3 dB coupler which delivers more power as compared to the other port.

4. Connect 1550 nm laser to the other port of the 3 dB coupler by using a patch cord.

5. Connect the ‘COM’ port of the coupler to the ‘COM’ of the WDM (wavelength division multiplexor) coupler by using a patch cord.

6. Connect 15XX and 980 port of the WDM coupler to the photodetector PD1 and PD2 respectively.

7. Connect BNC connectors adjacent to PD1 and PD2 to the CH1 and CH2 of the DSO.

8. Enable 1550 nm laser by using stylus and set the following parameters:

   - (a) frequency = 50 KHz
   - (b) duty cycle = 50%
   - (c) laser power = 60%

9. Click on the START button, waveform will appear at CH1 on the DSO screen.

10. Enable 850 nm laser by using stylus and set the following parameters:

    - (a) frequency = 50 KHz
    - (b) duty cycle = 50%
    - (c) laser power = 60%

11. Click on the START button, waveform will appear at CH2 on the DSO screen.
12. In case of detector saturation, reduce the laser power level below the saturation level by using software control.

**NOTE:** while operating LIGHT RUNNER, if the detector is fed with high optical power it will be saturated and will not give correct readings and waveforms (on DSO). For reliable results, users are expected to keep optical power fed to detector below the saturation limit by adjusting source power through variable optical attenuator.

13. By keeping the power level of both the lasers fixed, enable both the laser and run the experiment.

14. Measure the time delay between the rising edges of both the pulses at CH1 and CH2.

15. Now connect a fiber spool of known length between the ‘COM’ of the coupler and ‘WDM’ coupler using patch cord and measure the time delay.

16. Repeat the experiment with various fiber length.

**NOTE:** Since, laser output at 850 nm is collected from the 980 port of WDM coupler, there will be finite loss as the coupler response depends upon the wavelength.

**NOTE:** Due to finite response time of both the detector PD1 and PD2, the waveform may get distorted for the high frequency of the input laser. So, a moderate frequency in the range of 5-10 KHz is desirable.

**NOTE:** The power level of the 850 nm laser must be maintained at a higher power value than the 1550 nm laser, as the former suffers larger attenuation loss.

**Observation:**

Rise time when no-fiber (only patch chords) was connected in between source and PDs

For 1550 nm = …… ns  
For 850nm = …… ns

Rise time when following fibers lengths were connected:

<table>
<thead>
<tr>
<th>Fiber length (km)</th>
<th>Rise time of 1550 nm pulses (in nsec)</th>
<th>Rise time of 850 nm pulses (in nsec)</th>
<th>Delay between positions of 850 nm and 1550 nm pulses (ns)</th>
<th>Dispersion (ps/km-nm)</th>
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c) To determine the position of the fault in a fiber optic link using OTDR method

Light pulses in a fiber optic cable suffers Fresnel’s reflection loss of 4% as it encounters a break in the circuit. The loss would be reduced in case the fiber break is not good or if the break is not perpendicular to the axis. This loss is much larger than the Rayleigh scattered power and is easily measurable. If we know the speed of light pulse within the optical fiber, by knowing the time taken between the launch of the pulse and the detection of the reflected pulse, it is possible to estimate the distance of the fiber break (Fig. 1).

Fig. 4: Principe of operation of OTDR

One of the main considerations in locating the break is the resolution of the distance of the break from the input end. If we consider a pulse of duration ‘t’, and if ‘v’ is the speed of light in the optical fiber, then the physical length of the pulse would be v.t. For example, if the speed of the pulse is assumed to be 2.052×10^5 km/s, and if the pulse duration is 150 ns then the pulse length would be about 30.8 m. Now, if the fiber has breaks which are separated by a distance shorter than 30.8 m, then it would become impossible to resolve them as separate breaks. So, pulse with shorter duration are smaller in length and correspondingly would give better resolution.

Calculations: The delay between the input pulse and the reflected pulse can be simply written in the following from:

\[ \Delta \tau = \frac{2L}{v_g} \]  

(1)

Here, L is the fiber length, \( v_g \) is the group velocity of the input pulse in the medium.
Setup:

![OTDR setup diagram](image)

**Fig. 5: OTDR setup**

**Procedure:**

1. Switch ON the LIGHT RUNNER kit.

2. [Help] → [Optical Time Domain Reflectometer] → [Enter]

3. Connect 1550 nm laser source to the port 1 of the optical circulator with the help of a patch cord.

4. Connect the port 2 of the circulator with a patch cord and keep the other end of the patch cord free. (Assume that patch cord is having a break at the free end).

5. Connect the port 3 of the circulator to the photodetector PD1 with a patch cord.

6. Connect the BNC connector adjacent to the PD1 to CH2 of the DSO with a BNC cable.

7. Now set the pulse width at 1 μs (i.e. corresponding to minimum fiber detection length of \( \sim 206 \text{ m} \) as \( v_g \sim 2.06 \times 10^8 \text{ m/s} \)) with the help of stylus and run the experiment by clicking START button.

8. Decrease the detection voltage of DSO CH2 to display the low power reflected signal on DSO.

9. Connect a BNC cable OTDR clock to CH1/TRG of the DSO for the input reference clock.

**NOTE:** Keep the toggle switch under INT MOD to DIGITAL/OTDR clock.
10. Measure the time delay between the rising edge of the reference clock pulse at CH1 and rising edge of the reflected pulse.

11. Repeat the experiment with fiber spool having different lengths.

**NOTE:** When more than one spools are connected by patch cords, one can observe multiple reflected pulse by keeping the patch cord end a bit loose.

**Observation:**

<table>
<thead>
<tr>
<th>Fiber length (in km)</th>
<th>Approx. time delay between the pulses, t (in µs)</th>
<th>Fiber length, L = v_g ∙ t/2 (in km)</th>
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d) **To measure Bit Error Rate and Eye Pattern Analysis**

**Bit Error Rate**

In a digital communication system information is coded in the form of bits represented by 1s and 0s. In optical fiber communication each 1 is represented by a light pulse and each 0 is represented by the absence of light. In order to decode the information, the detector identifies the 1s and 0s in the incoming pulse sequence using a threshold level. Now as the light pulse propagates through the fiber, it gets affected by different mechanisms such as pulse broadening due to dispersion, attenuation, nonlinear effects etc. This results in the distortion of the received optical pulses and could result in wrong identification of the 1s and 0s in the received pulses. Thus the receiver can commit errors if the power is too low or if adjacent pulses start to overlap too much and the information gets corrupted. This effect is termed as the Bit Error Rate (BER).

If the receiver makes n errors in receiving N bits, then the bit error rate is defined by the ratio n/N. For example, out of a total number of $10^{12}$ bits received 3 errors are committed, and then the bit error rate becomes $3 \times 10^{-12}$. With this bit error rate in a communication system at a bit rate of 10 Gb/s the number of errors committed per second would be $3 \times 10^{-2}$, thus an average of 3 errors will be committed in a period of 100 seconds.

Errors come randomly and sometime in bursts. Thus to measure BER it is necessary to count the errors committed over a period of time and then average the rate of errors. An incorrect estimate of BER may take place if short periods of time are chosen. If the BER is expected to be $10^{-10}$
when communication is taking place at a rate of 100 Mb/s, then the expected number of errors in a second would be $10^2$. Thus in order to accumulate some errors, measurements has to be performed over at least 1000 seconds so that at least 10 errors would have been committed (as an average). The larger the sample of measurements, the better would be the estimation.

**Eye pattern**

In the non return to zero (NRZ) scheme, each '1' is represented by a pulse of duration equal to the bit period and each '0' is represented by the absence of a pulse. Each time slot can randomly have a value of 1 or a value of 0. If we consider a sequence of three pulses then the following eight combinations are possible:

000, 001, 010, 011, 100, 101, 110, 111

Now if we superimpose these on an oscilloscope display then the output would appear as shown in fig 6.

![Fig 6: Clean Eye Pattern](image)

The above pattern is called an eye pattern and gives an indication of the performance of the system. Now in the above figure we have just superimposed the eight combinations assuming that there is no jitter, no broadening and no noise. In general as the pulses propagate through the fiber link then they will accumulate dispersion, jitter and loss. Thus the detected signal would suffer from these imperfections and the eye pattern would not look like that shown in Fig 6. For example you may get an eye pattern as shown in fig 7.

![Fig 7: Distorted Eye Pattern](image)
The above figure shows the eye pattern when the pulses suffer from dispersion, jitter etc. and as can be seen the pattern has its eye closed. From the eye pattern it is possible to measure Bit Length, Suitable Sampling Period, Jitter and Noise of a fiber optical communication system (given in Fig8). Eye pattern analysis is a very useful tool in the performance evaluation of the system, and an open eye is an indication of good performance of the system.

**Aim**

To determine BER as a function of the laser transmitted power. To calculate bit length, noise, noise margin, jitter, suitable sampling period for various optical powers.

**Components Used**

C-Band Laser - 1 (1550nm), InGaAs photodetector - 1 (PD1), VOA

**Formula**

\[
\text{Bit error rate} = \frac{n}{N} \quad N \text{ is number of data bits transmitted and } n \text{ is number of error bits produced.}
\]
**Procedure:**

NOTE: MODULATION SELECTION by default should be in 'DIGITAL'

1. Select the corresponding experiment from the experiment drop down menu with the help of stylus and the experimental window will appear on the screen
2. Connect 1550nm laser source to the photo detector PD1 through a VOA with the help of patch cords. (Refer the connections shown in Fig 9).
3. Set the manual power knob and VOA to its minimum position by rotating it in anticlockwise direction
4. Set the 1550nm laser power with the help of stylus
5. Select any 'Pattern' and 'No. of repetitions' from the drop down menu given in experimental window
6. Click on the 'Start' button, the number of error bits with the number of iterations will display on the screen which is given on the right side in the experimental window.
7. If the number of error bits is 0, means the laser power is sufficient for data transmission and if error bits are there, shows that the laser power is insufficient to transmit the data.
8. In case, if no error bits are there, reduce the 1550nm laser power level with help of VOA (or) manual control knob, till the laser power is insufficient for data transmission (say for example at 10%) and displays error bits.
9. Consider the last iteration to get an accurate value of the no. of error bits, noted on the software screen.
10. Disconnect the patch cord from PD1 and connect it to optical power meter for the power measurement.
11. Set the power meter in 1550nm range and measure the corresponding laser power.
12. Repeat the above experiment for various laser power levels.
13. With the help of above measurement, calculate the 'Bit Error Rate' by using the formula

   **Calculation of 'Bit Error Rate':** To calculate the BER, total number of bits should be known. The total no. of bits can be calculated by using the following method

   (a) Convert the selected pattern into HEX using ASCII table and then to its binary equivalent
   (b) Count the total no. of 1's from its binary equivalent and consider it as total no. of bits
1. Select the corresponding experiment from the experiment drop down menu with the help of stylus and the experimental window will appear on the screen.
2. Connect 1550nm laser source to the photo detector PD1 with the help of patch cords. (Refer the connections shown in Fig 10).
3. Set the manual power knob to its minimum position by rotating it into anticlockwise direction.
4. Connect the BNC connector adjacent to PD1 to CH1 of the DSO only with the help of BNC cable.
5. Enable the 'Eye pattern experiment' with the help of stylus and observe the 'Eye Pattern' on the DSO screen.

**Eye Pattern**

![Diagram of Bit Error Rate Setup](image)

Fig 9: Bit Error Rate Setup
Fig 10: Eye Pattern Diagram and its parameters

**Observations**

**Transmitted Power vs BER**

<table>
<thead>
<tr>
<th>Laser Power (µW)</th>
<th>Data Received, N (bits/sec)</th>
<th>Errors Generated, n (bits/sec)</th>
<th>Bit Error Rate, n/N</th>
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**Eye Pattern vs Signal Level and Modulation Frequency**

<table>
<thead>
<tr>
<th>Laser Power (µW)</th>
<th>Frequency (kHz)</th>
<th>Noise Level on the DSO (mV)</th>
<th>Noise Margin on the DSO (mV)</th>
<th>Bit Length (ms)</th>
<th>Suitable Sampling Period (ms)</th>
<th>Jitter (ms)</th>
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**PRECAUTIONS:**
(1) Take care of the connections while using the patch cords.
(2) Do not twist the patch cords too much.
(3) While doing the experiment take care of the Fiber Optic Light Runner Kit & DSO.
(4) Do not touch tip of the patch cords.

**Switch ON Laser only after making connections!**

**Sample to be reported:**
1. Attenuation of optical fiber
2. Dispersion of optical fiber
3. Position of the fault in a fiber optic link using OTDR method
4. Eye pattern from the optical fiber

**References:**
(3) “Optics” by Hecht & Ganashan