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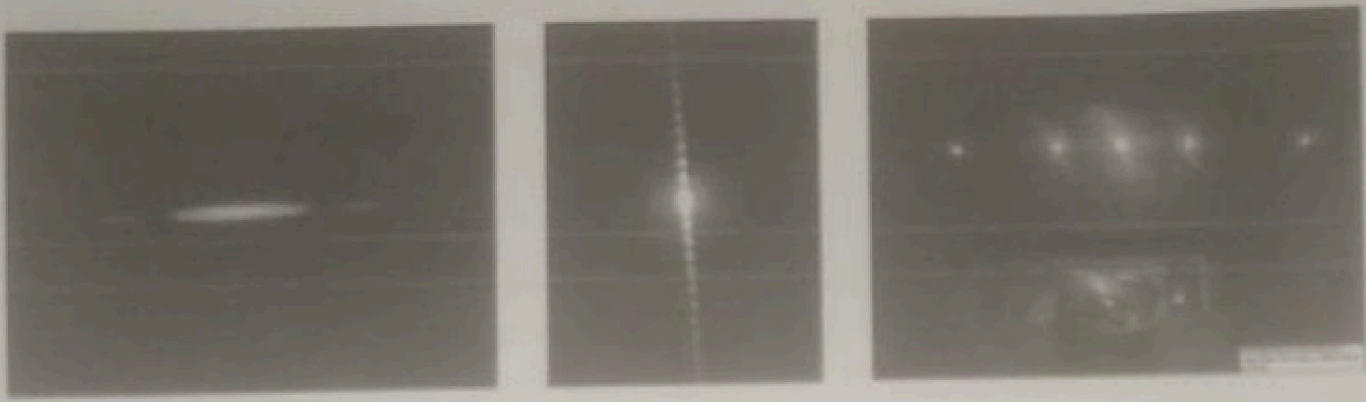
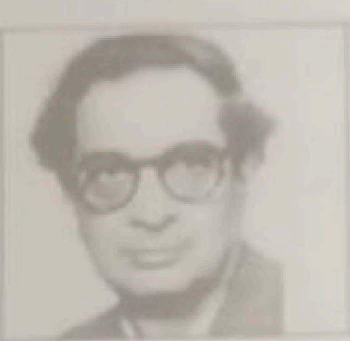
Preamble for Experiment 5: Laser: Thin Slit, Wire and Grating



Diffraction patterns of a narrow slit, a thin wire and diffraction grating obtained by using He Ne laser. He Ne Laser can be used for precise measurement of dimensions of extremely narrow objects and also counting the enormously large number of slits in a grating. How?

Ali Javan, a student of Charles Towns received a patent for constructing the first He Ne laser

	**Ali Javan (1926-2016):** He obtained his education at Columbia University. His thesis advisor was Charles Towns. He then joined Bell Telephone Laboratories where he designed and fabricated the first gas laser, i.e. He Ne laser for which he received a patent. In 1960 he joined MIT Boston remained there as a faculty. His other contributions in Physics are atomic clocks, optical antenna for emitting and receiving light, accurate measurement of speed of light etc

Pledge

I solemnly affirm that I am presenting this journal based on my own experimental work. I have neither copied the observations, calculations, graphs and results from others nor given it to others for copying.

Signature of the student

Experiment 5: Laser based experiment II: Measuring width of an ultra-thin slit, diameter of an ultra-thin wire and counting number of slits in diffraction grating using He Ne laser

Aim:

Using He-Ne laser to

1. Measure width of a narrow slit
2. Measure diameter of a thin wire
3. Counting the number of slits in a diffraction grating.

Apparatus: He-Ne laser, a narrow slit, thin wire, and diffraction grating, optical bench with stands to mount slit, wire and grating, screen, scale etc.

Significance of the experiment: *This experiment demonstrates three out of several applications of laser. The conventional techniques for measuring the width of narrow slits and thin wires are tedious and error prone. Laser provides an easy and accurate method to measure these quantities. Secondly, counting enormously large number of slits in the grating using any other method is almost impossible, however, laser makes it possible.*

Theory: Laser is an extremely coherent, monochromatic, directional, focusable, polarized and powerful light. These extraordinary features make it greatly applicable in day-to-day life, science and technology. A few notable applications of laser include medical diagnosis and treatments, fiber optic communications, CD-ROMS, CD players, laser printers, defense, cutting, welding, drilling, surveying, aligning etc.

Laser is produced due to stimulated radiation; a process where a resonating photon stimulates the de-excitation of an excited atom. This results in to emission of two coherent photons, which are identical in all respects. These photons further stimulate the de-excitation of other excited atoms and this continues to generate an avalanche of coherent photons. For stimulated emission to take over spontaneous emission and stimulated absorption, a few conditions are necessary. These are availability of metastable state (life time = 10^{-3} sec), population inversion (greater number of atoms in metastable state than in lower energy state) and enough number of photons in the cavity (mirrors).

He-Ne laser

He-Ne laser is a low power, continuous gas laser, which is used in supermarket scanners, student laboratories and holography. The active system is neon, which is pumped electronically via helium in a resonant cavity made of discharge tube (Fig. 5.1) . The main lasing occurs in neon between the levels E_6 (metastable) and E_3 which produces an intense coherent beam of red color (wavelength 6328°). (refer Fig 5.2). The population of photons necessary for stimulated emission is maintained by mirrors (one is semitransparent) on both sides. Brewseter windows are used to polarize the laser light.

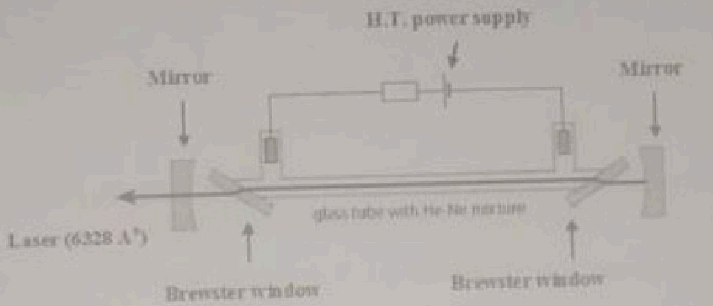


Fig. 5.1: Schematic diagram of He-Ne laser

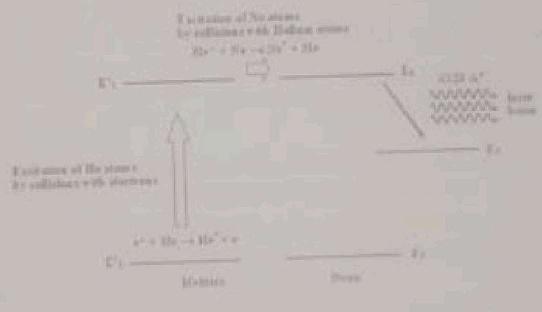


Fig. 5.2. The simplified energy level diagram of He-Ne laser

1. **Measuring width of a narrow slit:**

Consider a narrow slit of width a exposed to a laser of wavelengthλ. The laser is diffracted through the slit and a diffraction pattern, as shown in Fig 6.1 is produced. It consists of central maximum, minima and secondary maxima. According to theory of single slit diffraction, the angular position, θ of the m^{th} minimum is given by

$$a\sin\theta = m\lambda \quad \ldots(5.1)$$

The central maximum is the principle image of the slit and it is bounded by 1^{st} minima on both the sides. Therefore taking $m = 1$ and rearranging for a, Eqn 6.1 becomes

$$a = \frac{\lambda}{\sin\theta} \qquad ...(5.2)$$

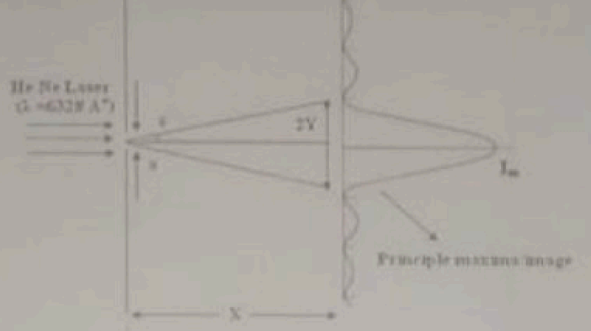


Figure 5.3: Diffraction pattern of single slit. Linear width of a central maximum (principle image of the silt) is quite wider than the slit itself.

Thus, the width of the slit can be measured if λ is known and θ is measured. The geometry of the Fig 6.1 suggests that

$$\tan\theta = \frac{Y}{X} \qquad ...(5.3)$$

Where $Y = \frac{2Y}{2}$, (2Y = full linear width of the central maximum) and
X = distance between the slit and the screen

Equations 5.1, 5.2 and 5.3 collectively indicate that narrower the slit, greater is the value of θ, thus greater is the value of $2Y$. $2Y$ i.e. the principle image of the slit is considerably larger than the slit itself. The relatively large value of $2Y$ makes its measurement easy. As against this, the conventional techniques, which are based on direct measurements, find it more difficult to measure the width of the slit if it is narrower.

2. Measuring the diameter of a thin wire:

Consider a thin wire having diameter d exposed to a laser of wavelength λ. The wire diffracts the light and a diffraction pattern similar to as shown in the Fig 6.2 is observed. The diffraction pattern consists of a central maximum surrounded by maxima of almost same intensity on the upper and lower side. These three distinct maxima are surrounded by several secondary maxima and minima. If x is the distance between the first maximum on upper side and the first maximum on the lower side of the central maximum and if D is the distance between wire and screen, then it can be shown that

$$d = \frac{\lambda \times D}{x} \qquad ...(5.4)$$

Thus if λ is known, and if x and D are measured then the diameter of the thin wire can be calculated. It can be noted from Eqn 6.4 that the dependence of x on d is inverse. Thus if the wire is thinner, then x is large and thus can be measured more conveniently. Thus laser technique is particularly advantageous for thinner wires. On the contrary, thinner the wire, more it is difficult to measure its diameter by using conventional techniques.

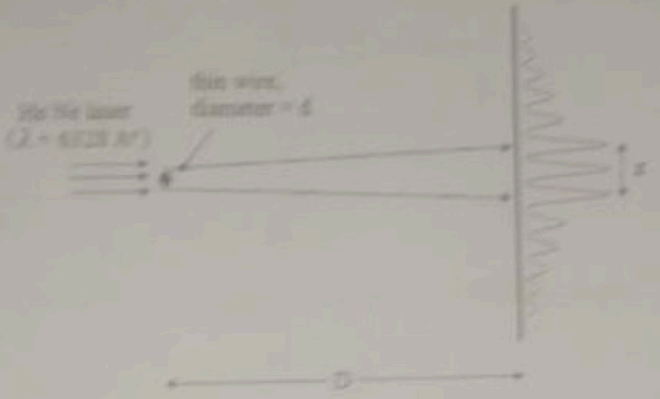


Figure 5.2: Measuring diameter of a thin wire using laser. Smaller the d, larger is the x

We know that diffraction is prohibited when the obstacle is smaller than the wavelength of light. Thus laser cannot be used for measuring the dimensions of the slits and wires having dimensions smaller than the wavelength of the laser. It may also be noted that if the dimensions of the obstacle is considerably larger than the wavelength of the light then diffraction effects are feeble. Thus the dimensions of slits and wires having size considerably larger than the wavelength of laser cannot be measured using laser.

3. Counting the number of slits in the diffraction grating:

Diffraction grating is a device consisting of very large number of parallel slits of equal width and equal spacing. It uses principle of diffraction to disperse the white light in to a colored spectrum. The resolving power and dispersive power of grating are considerably large as compared to prism. These qualities depend upon number of slits. The number of slits in the grating are typically 15000 to 20000 per inch. Counting these slits directly is almost impossible.

Consider a monochromatic light of wavelength λ incident on a grating having grating element d (spacing between the slits). The light is diffracted and a diffraction pattern as shown in Fig (6.3) is produced. According to theory of diffraction grating, the angle of diffraction θ of a principle maxima of order m is given by

$$d\sin\theta = m\lambda \tag{5.5}$$

The first order maxima is most intense, hence $m = 1$. Thus

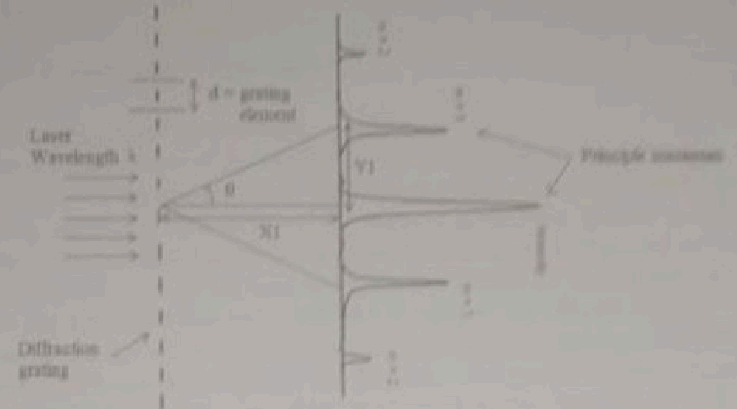


Figure (5.3). Diffraction grating and it's diffraction pattern

$$d = \frac{\lambda}{\sin\theta} \qquad \ldots(5.6)$$

As seen in Fig 5.3, θ can be calculated using following relation

$$\tan\theta = \frac{Y_1}{X_1} \qquad \ldots(5.7)$$

Where Y_1= the distance between the central maximum and the first maximum and

X_1= distance between the grating and the screen

Thus according to eqn (5.6) if λ and θ are substituted, then the grating element d can be calculated.

If a grating consists of N number slits per unit length, then it consists of N number of grating elements (d) per unit length. Thus

$$d = \frac{1}{N} \Rightarrow N = \frac{1}{d} \qquad \ldots(5.8)$$

If d is expressed in A°, then

$$N\ (number\ of\ slits\ per\ A^o) = \frac{1}{d(A^o)}, \Rightarrow N\ (number\ of\ slits\ per\ inch) = \frac{2.54\times10^8}{d(A^o)} \qquad \ldots(5.9)$$

Eqn (5.9) enables us to count the number of slits in the grating even though it is very large

Procedure:

Part A. Measuring width of a narrow slit:

1. Make laser ON. **Avoid eye contact.**
2. Place the screen in front of the optical bench at *sufficiently large distance.*
3. Mount the slit on the optical bench such that the laser is *incident exactly on the slit. Align* it properly so that a well-defined and distinct diffraction *pattern consisting of central* maximum surrounded by minima and secondary *maxima is observed on the screen*
4. Measure the full width of the central maximum. This is $2Y$ (cm). Calculate Y (cm).
5. Measure the distance between the slit and the screen. Let this be X (cm)
6. Calculate θ and the width of the slit a_e (mm) by using the procedure in table 6.1.
7. Compare a_e with standard width of the slit (a_s) and calculate the percentage deviation.
8. Tabulate all observations, calculations and results as per table 5.1

Part B: Measuring diameter of a thin wire

1. Fix the wire on a suitable mount. Clamp the mount on the stand. Fix the stand on the optical bench.
2. Illuminate this wire by laser. Use trial and error method the expose the wire completely to the laser, so that a well-defined diffraction is observed on the screen. As shown in Fig (6.2), the pattern should consist of a central maximum surrounded by 1st maxima of almost similar intensity on upper as well as lower side. These three maxima are surrounded by several secondary maxima and minima on both the sides.
3. Measure the distance between the first maxima on the upper side and first maxima on the lower side of the central maximum. Let this be s (mm)
4. Measure the distance between the screen and the wire. Let this be D (mm).
5. Calculate the diameter of the wire d_e (mm) by using the procedure in table 5.2.
6. Compare d_e with standard d_s. Calculate the percentage deviation.
7. Express all observations, calculations and results as per table 5.2.

Part C: Counting the number of slits of a grating

1. Mount the diffraction grating on a stand. Clamp the stand on the optical bench
2. Place laser behind the diffraction grating. Align the diffraction grating such that the laser is incident exactly perpendicularly on the grating.
3. Place a screen in front of the grating. A well-defined diffraction pattern similar to as shown in Fig (6.3) will be observed. Only principle maxima will be observed. Secondary maxima are too weak to be observable. If the grating is sufficiently close to the screen, then central maximum, first maximum as well as second maximum will be observed.
4. As shown in Fig (6.3), measure the distance between the first maximum and the central maximum (Y_1) and the distance between screen and the grating (X_1).
5. Calculate θ, d (A^o) and N_e as per the procedure given in table 5.3.
6. Compare N_e with standard N_s Calculate the percentage deviation
7. Express the observations, calculations and results as per table 5.3

ROUGH WORK:

Table 5.1: Measuring the width of the slit

Sr. No.	Parameter	Symbol	Value	Unit
1	Full linear width of the central maximum	$2Y$	4	Cm
2	Half linear width of the central maximum	$Y = \frac{2Y}{2}$	2	Cm
3	Distance between the screen and the slit	X	184	Cm
4	Angular position of the first minimum	$\theta = tan^{-1}\frac{Y}{X}$	0.6	Deg
5	Width of the slit	$a_e = \frac{\lambda}{sin\theta}$ Where $\lambda = wavelength of\ He\ Ne\ laser = 6328 \times 10^{-7} mm$	0.059	Mm
6	Standard width of the slit	a_s	0.05	Mm
7	Percentage deviation	$\%\ deviation = \left\lvert\frac{a_e - a_s}{a_s}\right\rvert \times 100\%$	15.8	%

Table 5.2: Measuring the diameter of the thin wire

Sr. No.	Parameter	Symbol	Value	Unit
1	Distance between the first maximum on the upper side and first maximum on lower side	X	0.5	Mm
2	The distance between the screen and the wire	D	182	Mm
3	Diameter of the wire	$d_e = \frac{\lambda \times D}{x}$ Where $\lambda = wavelength of\ He\ Ne\ laser = 6328 \times 10^{-7} mm$	0.23	Mm
6	Standard diameter of the wire	d_s	0.25	Mm
7	Percentage deviation	$\%\ deviation = \left\lvert\frac{d_s - d_e}{d_s}\right\rvert \times 100\%$	8	%

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Table 5.3: counting the number of slits in the grating

Sr. No.	Parameter	Symbol/formula	Value	Unit
1	Distance between the first maximum and the central maximum	Y_1	7.7	Cm
2	Distance between screen and the grating	X_1	14	Cm
3	Angle of diffraction of the first minimum	$\theta = tan^{-1}\frac{Y_1}{X_1}$	28	deg
4	Grating element	$d = \frac{\lambda}{sin\theta}$ Where $\lambda = wavelength of laser = 6328A^\circ$	23437	A°
5	Number of slits per inch in the grating	$N_e = \frac{2.54 \times 10^8}{d(A^\circ)}$ Where d = grating element as calculated in (step 4), to be taken in A°	10837	Per inch
6	Standard value of the number of slits in the grating	N_s	15000	Per inch
7	Percentage deviation	$\%\ Deviation = \left\|\frac{N_e - N_s}{N_s}\right\|$	45.8	%

Viva Voce

1. What is the role of He in the action of He-Ne laser?
2. What is the role of Ne in the action of He-Ne laser?
3. Is He-Ne laser a continues or a pulsed laser?
4. Ideally laser is supposed to move as a parallel beam. Why does it diverge then?
5. Which element is responsible for red light of He-Ne laser? He? Or Ne?
6. Does He-Ne laser emit only 6328 A°. Or other wavelengths also? If, yes then what are these wavelengths?
7. What are the advantages of He-Ne laser?
8. What are the disadvantages of He-Ne laser?
9. What are the applications of He-Ne laser?
10. Why He atoms are at quite a higher percentage and quite a high pressure than Ne atoms?
11. In fact 80% atoms are of He and 20 % of Ne. Can this be made 70% He and 30% Ne?If this is done then how the performance of He-Ne laser will be affected?
12. Why does He-Ne laser require heavy and high tension power supply?
13. When any laser falls on any surface the illumination is never uniform or diffused. There is a grainy appearance. This called as a speckle phenomenon. What is the Physics behind it?

HOTS Questions

14. Can the width of narrow slit or thin wire be measured using an ordinary but monochromatic source instead of laser? Why? Why not?
15. If the width of the same wire or slit is measured by using the laser of other wavelength then the answer will definitely not change. Then which parameters will change?
16. Why the wire needs to be extremely thin or slit needs to be extremely narrow for its diameter or width to be measurable using laser? Why the diameter of a thick wire or width of a narrow slit can not be measured using laser?
17. A comparison of Figures shows that, the intensity of first principle maximum in case of slit is smaller than the central principle maximum. However, in case of diffraction pattern of a wire the intensity of the first principle maximum is seen to be almost equal to the intensity of central principle maximum. Why?
18. In case diffraction pattern of a slit it is understood that, the light enters in to the central principle maximum. However, in case of an opaque wire, while the common sense tells that the light should cast a shadow in the center; a maximum is seen at the center. Why?
19. When the diameter of a thin wire or width of a slit measured using laser and when the error is calculated by comparing the measurement with that made by micrometer screw gauge or travelling microscope, the measurement done using laser is assumed to be standard. Why does the measurement using laser claims more accuracy than micrometer screw gauge or travelling microscope?
20. What are the stages in the measurements in this experiment, where human error plays a role?
21. When the slit is made wider, what changes are expected in the diffraction pattern?

22. When the slit is made narrower, what changes are expected in the diffraction pattern?
23. When the wire is made thicker, what changes are expected in the diffraction pattern?
24. When the wire is made thinner what changes are expected in the diffraction pattern?
25. Discuss the effect of non-uniformity of a slit on its diffraction pattern.
26. Discuss the effect of non-uniformity of a wire on the diffraction pattern.
27. Imagine that two narrow slits of equal slits are placed very close each other. Discuss the qualitative changes in the diffraction pattern.
28. Discuss the qualitative changes in the diffraction pattern when 2, 20, 200, 2000, 20000 slits are used.
29. Imagine that two extremely thin wires are placed very close to each other. Discuss the nature of diffraction pattern.
30. Imagine that a mesh of slits with number 2, 20, 200, 2000, 20000 are exposed to laser. Discuss the qualitative changes in the diffraction pattern.
31. Draw a sketch of diffraction pattern when a pin hole or a circular aperture is exposed to laser instead of a rectangular slit.
32. Draw a sketch of the diffraction pattern, when a disc having a small diameter is exposed to laser instead of a wire.
33. Can thickness of a human hair be measured using laser diffraction method? Why? Why not?
34. Imagine a combination of a thin wire and a narrow slit exposed to laser placed very close to each other. What kind of diffraction pattern will be produced?
35. In case of diffraction pattern of slit as well as a wire the intensity of maxima keeps on decreasing when one moves away from the center. Why?
36. What is the significance of keeping screen quite away from the slit or wire (> 150 to 200 cm) Why can not a well-defined and distinct diffraction not be observed when the screen is placed close to slit or the wire?
37. Discuss the uppermost width of slit after which laser fails to measure its width. Justify your answer with calculations.
38. Discuss the uppermost diameter of a wire after which laser fails to measure its diameter. Justify your answer with calculations.
39. Can laser be used to measure the width of a slit smaller than its wavelength? Why? Why not?
40. Can laser be used to measure the diameter of a thin wire whose diameter is lesser than the wavelength of laser? Why? Why not?
41. Imagine a situation where a thin wire is vertically adjusted at the center of a narrow slit. What kind of diffraction pattern will be produced?
42. Can the width of a slit or wire be measured using a well collimated but white light? Why? Why not?
43. Diffraction grating consists of very large number of slits ranging from 10000 to 20000. Why?
44. Consider diffraction gratings having 10000 slits per inch, 20000 slits per inch and 30000 slits per inch. In what way do they differ? In what way their diffraction patterns differ? Which of these gratings will calculate the wavelength of the laser with greatest accuracy? Why?

45. Consider three diffraction gratings having 10000 slits per one inch, 20000 slits per two inch and 30000 slits per three inch. Do they differ? Why? Why not? Which of these gratings can calculate the wavelength of the laser with greatest accuracy? Why?
46. Consider three gratings having 10000 lines per one inch, 10000 lines per 0.5 inch and 10000 lines per 0.1 inch. In what way these gratings are different? In what way they are same? In what way their diffraction patterns will be different? Which of these gratings can calculate the wavelength of laser with greater accuracy?Why?
47. Can a pocket comb be used as diffraction grating? Why? Why not?
48. The Eqn $a\sin\theta = m\lambda$ for the diffraction pattern of single slit indicates that if the angle of diffraction θ of first minimum in the diffraction pattern of a single slit is measured, if $m$is taken as 1 and if the width of slit is measured by some other technique, say by using say travelling microscope, then the wavelength of laser can be calculated using single slit also. Then what is the need of diffraction grating having 15000 to 20000 slits for calculating the wavelength?
49. What will happen if the diffraction grating is exposed to white light?
50. Common sense expects that of the number of slits of a grating is increased from 10000 to 50000 to 100000 then it's 'quality' will increase. But while it is technically difficult to design and fabricate a diffraction grating having such a large number of slits per unit inch, the Physics also imposes a typical limitation on compressing the number of slits per unit length. What is this Physics?
51. What do you mean by 'quality' of the grating? Common sense tells that quality depends upon number of slits per unit inch. However, keeping apart the common sense, what is the Physics behind the relation between the quality of the grating and the number of slits per unit length?
52. The grating that you use in the experiment is at least 1 inch wide, while the laser which is allowed to fall on the grating has diameter of 1 to 2 mm only. This means that when laser falls on the grating, effectively only an area of 1 to 2 mm of the grating is used. Then what's the use of remaining part of the grating? What is the use of several other slits which are not exposed to the laser light?
53. Do you think that grating is in any way better that prism? If yes, then in what way?
54. Imagine that there are two gratings of the same number of slits per unit inch, same width of the slits and same distance between the slits. These gratings are made to overlap on each other and a laser is allowed to fall on them. What kind of diffraction pattern is expected? Discuss on the basis of Physics, the changes in the diffraction pattern that will occur of one grating is laterally moved across another.
55. Typically most of the student gratings consist of 15000 slits per inch. Such gratings produce central (zeroth) maximum, first principle maximum and the second principle maximum. But they do not produce the third and higher principle maxima. Why?
56. Indeed the grating equation $d\sin\theta = m\lambda$ indicates that the angle of diffraction θ is proportional to the wavelength λ. This means that when white light falls on the grating then the different colors on account of their different wavelengths will get separated. But this does not happen in case of central maximum. Why?

57. Imagine that a white light isat first passed through a prism and then it is allowed to pass through grating. The prism will produce the spectrum of the light. In what way this spectrum will get affected when it passes through the grating?
58. Diffraction gratings are the inevitable component of all spectrometers ranging from visible to ultraviolet-visible to infrared. Why? What is the exact role of gratings in the spectrometers?
59. Do you think that a same grating will be equally useful for visible, ultraviolet-visible and infrared spectrometers? Why? Why not?
60. Joseph Von Fraunhofer was the first Physicist to produce sophisticated diffraction gratings. He also analyzed 200 distinct spectral lines of the solar spectrum using his grating which were later on called Fraunhofer lines to honor him. Why Sun should produce these many spectral lines?
61. Consider that five different sources are exposed to a grating, which are Hydrogen, Mercury, Krypton, Helium and Uranium. In what way their diffraction patterns will be different? Indeed, why they will be different?
62. A grating having its grating element *d* smaller than the wavelength of light doesn't work Why?
63. There are two kinds of gratings, a grating with large number of slits per unit length and another having very large number of slits, irrespective of length, or distributed over a wide length. Which of these gratings will separate the colors with larger separation? Which of these gratings will be able to just separate (resolve) the colors, even of the difference between their wavelengths is exceedingly small?Explain your answer on the basis of Physics of gratings.
64. There are two kinds of gratings, a grating with large number of slits per unit length and another very large number of slits, irrespective of length, or distributed over a wide length. Which of these gratings will not be able to separate the colors at a large distance? Which of these gratings will not be able to just separate the colors if the difference between them is exceedingly small? Explain the answer on the basis of Physics of gratings.

My Understanding of the Experiment

(Not exceeding 5 to 6 lines)

In the above Experiment we found out how to find the width of slit, diameter of wire, number of slits. We observed all this with the help of He-Ne lazer. The lazer provides precise measurements of the dimentions required.