Michelson Interferometer

Expt. No : 2 B

:: Product Features

In this model of Michelson interferometer, sodium vapor lamp is used as light source. Components are assembled on an Optical breadboard for setting up the experiment. Both the mirror mounts have kinematic adjustments and one of the mirror mounts is placed on a translation stage with fine and coarse adjustments. Diode laser is used for setting up the interferometer initially and the source is replaced by Sodium vapor lamp.

:: Getting Started

a. **Quick Start**

Please check if the following items are present while the instrument package is delivered.

1. Optical Bread board with Rigid Support
2. Diode Laser with power supply
3. Sodium vapor lamp with power supply
4. Kinematic Laser mount
5. Beam splitter with mount
6. Front coated Mirrors with mount (2no.)
7. Rotation stage
8. Glass slide
9. CCD with mount
10. LCD screen Optional
11. Screen
12. Thumb screws

b. Safety and Installation Instructions

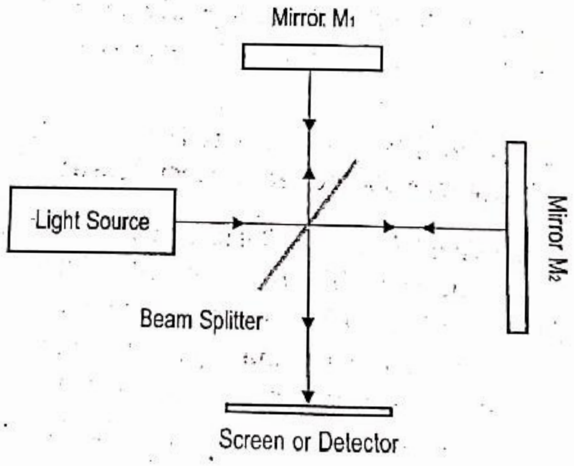
- Laser radiation predominantly causes injury via thermal effects; avoid looking directly into the laser beam.
- It is best that students work in low light dust free atmosphere.
- Care must be taken while handling the Optical components since this experiment uses precision optical lenses and other high quality components.
- Please don't put your fingers on the main optical surfaces but hold components by their edge.
- Always keep the equipment in a moisture and dust free atmosphere.

:: Fundamentals

Aim :

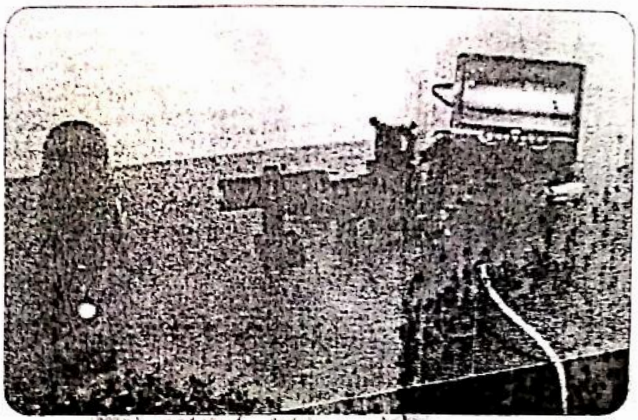
1. To determine the wavelength of monochromatic light.
2. To find out the difference in wavelength of D_1 and D_2 lines of sodium light.

Theory :



M_1 and M_2 are two plane mirrors silvered on the front surfaces. They are mounted vertically on two translation stages placed at the sides of an optical platform. Screws are provided at the back of the holders. Adjusting of which allows M_1 and M_2 to be tilted. M_1 can also be moved horizontally by a micrometer attached to the M_1 holder.

The beam splitter, a planar glass plate partially silvered (50% - 50%) on one side. It is mounted vertically at an angle 45° to the incident light. When light from the source is allowed to fall on the beam splitter, one portion is transmitted through the beam splitter to M_1 and the other is reflected by beam splitter to M_2. The reflected beams from M_1 and M_2 superimpose at the beam splitter and interference pattern can be observed on the screen.



The two beams of a Michelson interferometer interfere constructively when the waves add in phase and destructively when they add out of phase, producing circular interference fringes as a result. With Sodium source the wavelength is given by

$$\lambda = (2d / N)\,\Delta,$$

Where 'd' is the change in position that occurs 'N' fringes to pass and Δ is the calibration constant of the micrometer.

The interference pattern observed with the sodium lamp contains two sets of fringes which disappear when the bright bands of one set are superimposed on the dark bands of the other.

The wavelength separation of the Na D-line doublet is easily determined by observing the successive coincidence and discordance of the two sets of fringe systems produced by the doublet of wavelengths (λ_1 and λ_2 with $\lambda_1 > \lambda_2$). As D is increased, the two systems gradually separate and the maximum discordance occurs when the rings of one system are set exactly halfway between those of the other system. The discordance positions are most clearly seen as minima in the contrast of the pattern. Then the wavelength separation $\lambda_1 - \lambda_2$ is given by

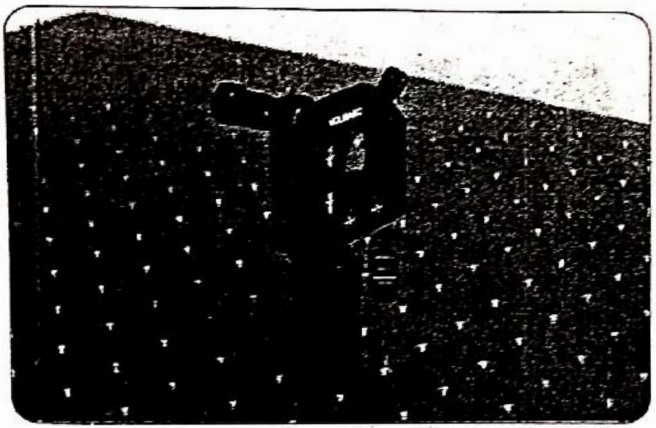
$$\lambda_1 - \lambda_2 = \lambda_1 \lambda_2 / 2D$$

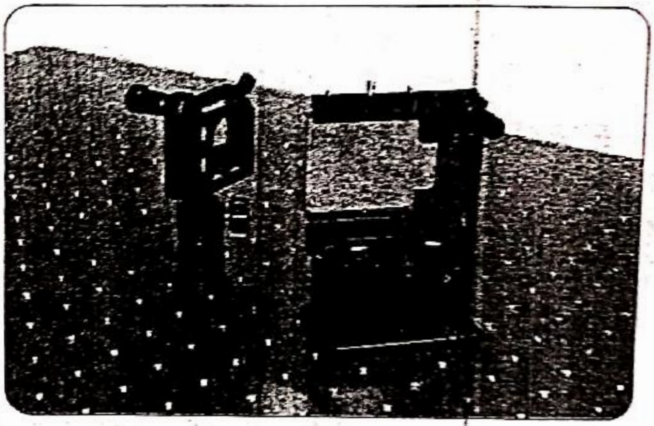
$$\lambda_1 - \lambda_2 \approx \lambda^2 / 2D$$

Where λ is the average wavelength of Sodium, D is the is the change in position of the micrometer for two successive discordance / coincidence.

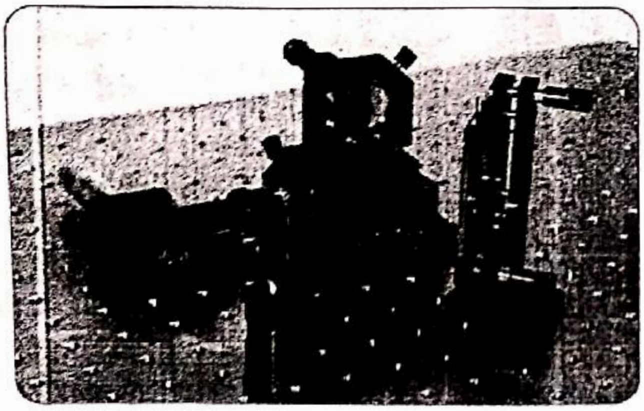
:: Experimental Set-up

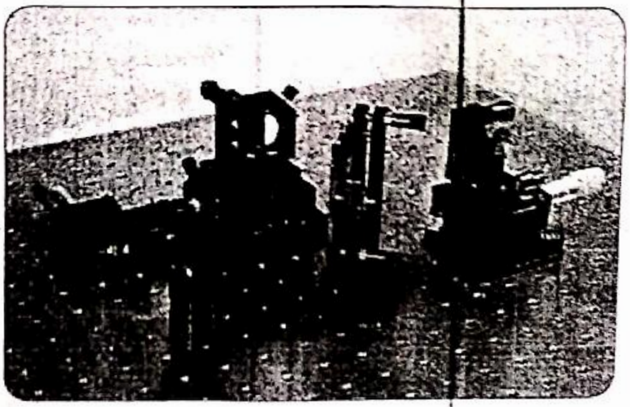
1. Fix the laser mount on the bread board and place the beam splitter at 45°



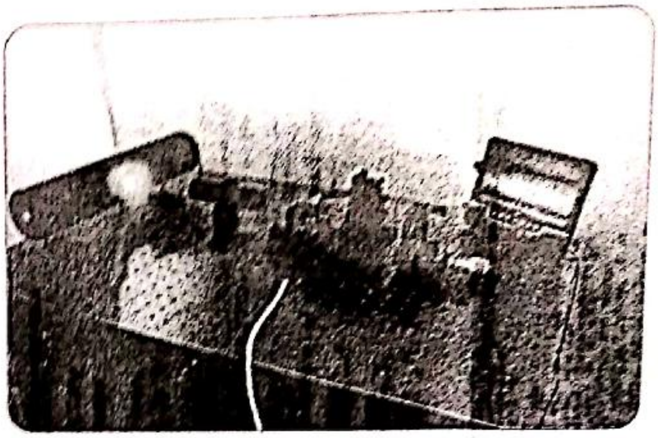


2. Fix the high precision mirror with translation stage (M_1) & mirror with coarse movement (M_2) in equal distance from the beam splitter.

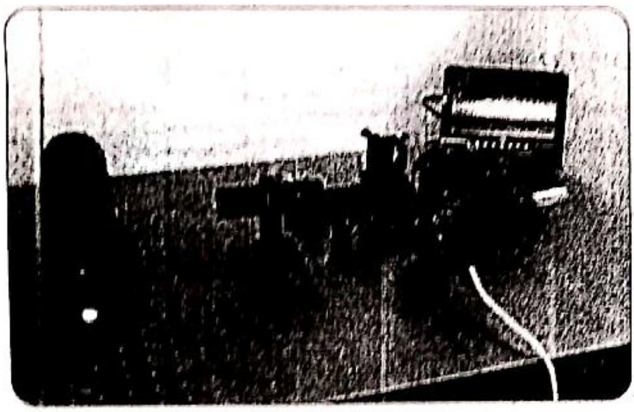


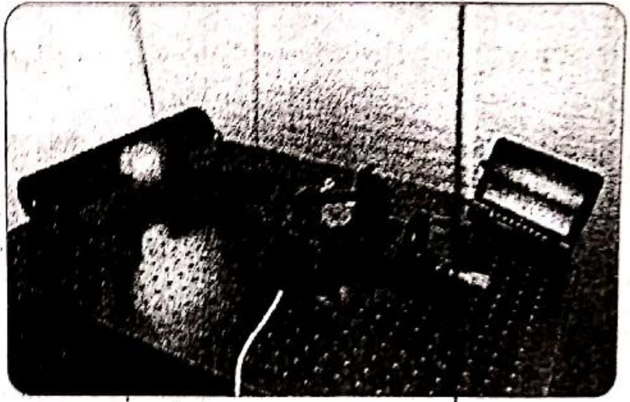


6. Replace the screen with camera. Observe the fringe pattern on the display.



7. Adjust the mirror tilt and position of the camera for clear and sharp circular fringes.





Procedure

To determine the wavelength of monochromatic light.

1. Firstly set up the Michelson Interferometer with laser. You will get clear circular fringes.
2. Rotate the micrometer of high precision mirror translation stage (M_1) to count 20 nos. of fringes and note down the distance moved for 20 fringes. This distance is taken as 'd'.

3. We know the wavelength of laser $\lambda = 650nm$ and $N = 20$ nos.

We have the equation, $\lambda = (2d / N) \Delta$

$$\Delta = \lambda / (2d / N)$$

So we can find out the calibration constant of the micrometer.

4. Replace the laser with Sodium lamp and screen with camera. You can see the clear circular fringes on the LCD display.
5. Rotate the micrometer of the high precision mirror translation stage and find the distance moved for 20 nos. of fringes. This distance is taken as 'd'. We also know N=20 nos. and Δ from above calculation.
6. Then we can find out the wavelength of sodium light by using the equation

$$\lambda = (2d / N) \Delta$$

To determine the wavelength separation between D_1 & D_2 lines of Sodium light.

1. Firstly set up the Michelson interferometer with sodium light and get the clear circular fringes.
2. Then rotate the micrometer of the mirror translation stage (M_2) and you can see that the fringes are most clear at certain positions of the micrometer. In some other positions of the micrometer you can notice that the fringes disappear.
3. When the sodium D lines are in phase together, the fringes are clear and sharp. When one line is in phase at a point but the other is out of phase, and vice versa, the fringes are washed out and indistinct
4. So note the reading of the micrometer when there are no fringes.
5. Then rotate the micrometer to get the same condition (no fringe) again. Note this position of the micrometer.
6. Find the difference and take this as D (change in position of the micrometer for two successive discordance / coincidence.)
7. Then wavelength separation $\lambda_1 - \lambda_2 = \lambda^2 / 2D$
   where λ is the average wavelength of the sodium.

Measurements

1. Calibration Constant

Wavelength of laser λ = ...

Least count of the micrometer = ...

Trial No	Fringes Moved (N)	Micrometer reading		Distance Moved (d) mm	Calibration Constant $\Delta = (\lambda N / 2d)$
		Initial	Final		
1.					
2.					
3.					
4.					

Average Calibration Constant Δ = ...

2. Combined wavelength of Sodium

Trial No	Fringes Moved (N)	Micrometer reading		Distance Moved (d) mm	Wavelength $\lambda = (2d / N) \Delta$ nm
		Initial	Final		
1.					
2.					
3.					
4.					

Average wavelength λ = ...nm

3. Wavelength separation of D_1 and D_2 lines of Sodium

Trial No	Micrometer reading		Distance Moved (d) mm	$\lambda_1 - \lambda_2 = \lambda^2 / 2D$ nm
	Initial	Final		

Average $\lambda_1 - \lambda_2 =$ ....nm

Result :

1. The wavelength separation of D_1 and D_2 lines of sodium is ....
2. Error percentage ....

CHAPTER 1

INTRODUCTION

Zavoisky in 1945 performed the earliest magnetic resonance experiments in a solid observed strong electron spin resonance absorption in several paramagnetic salts. Applicatior electron magnetic spin resonance in solid state physics are of great importance. It is a sensitive technique and has been applied in many fields. The chief of these are :

(a) Paramagnetic ions in crystals,

(b) Unpaired electron in semi-conductors and organic free radicals,

(c) Colour centres, and radiation damage centres,

(d) Ferro and anti-ferro magnetic materials.

ELEMENTARY MAGNETIC RESONANCE

The fundamentals of elementary magnetic resonance may be understood in terms of simple classical concepts. Suppose a particle having a magnetic moment $\bar{\mu}$ is placed i a uniform magnetic field of intensity $\overline{H_0}$ (Fig. 1 a). Then the moment $\bar{\mu}$ will precess around with an angular Larmor frequency

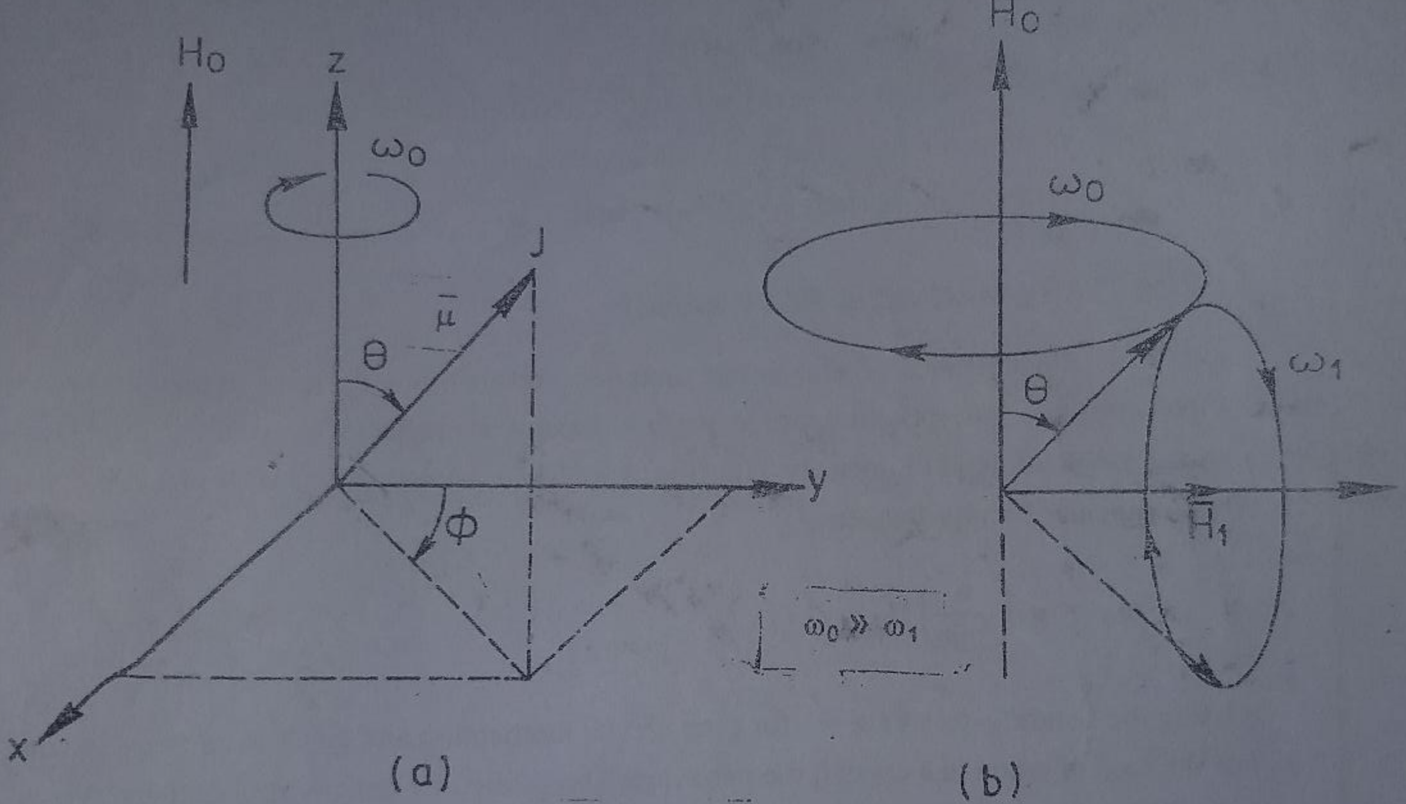
$$\omega_0 = g\left(\frac{e}{2mc}\right)H_0 \tag{1}$$

g being the Lande' g-factor (g = 1 for pure orbital momentum and g = 2 for a free electron sp For the case of anion in a crystal, the behaviour is modified by the environment and the g- fac may differ from the Lande' g-factor. This effective g- factor is known as the spectrosco splitting factor.

We now introduce an additional weak magnetic field oriented in the xy plane and rotate about the z axis (in the same direction as the "Larmor precessing") with an angular frequency ω If the frequency ω_1 is different from ω_0 the angle between the field $\overline{H_1}$ and the magne moment $\bar{\mu}$ will continuously change so that their interaction will average out to zero. however, $\omega_1 = \omega_0$ the angle between $\bar{\mu}$ and $\overline{H_1}$ is maintained and net interaction is effect (Fig. 1 b). If we look at the system in a reference frame that is rotating about the z axis with angular velocity ω_0 then the spin will appear to make an angle $\psi = 90 - \theta$ with $\overline{H_1}$, according to the previous argument will start to precess (in the rotating frame) about $\overline{H_1}$. T

ESR

4



(a) (b)

Fig. 1 : Precession of a magnetic moment $\bar{\mu}$ when placed in a magnetic field $\overline{H_0}$ (a). The spin precesses with angular frequency $\omega_0 = \gamma H_0$; the angle θ is a constant of the motion. (b). In addition to $\overline{H_0}$ a week magnetic field $\overline{H_1}$ is now also applied. $\overline{H_1}$ is rotating about the z axis with angular frequency ω_0 and therefore $\bar{\mu}$ precesses about $\overline{H_1}$ with angular frequency $\omega_1 = \gamma H_1$; θ is not any more conserved.

corresponds to a "nutation" and a consequent change of the angle which implies a change in the potential energy of the particle in the magnetic field. The change in θ is the classical analogy to a transition between sublevels with different m. We see that such transitions may take place only if the rotating field has an angular frequency $\omega_1 = \omega_0$

Let us proceed to consider the quantum picture of elementary magnetic resonance. Suppose that the intrinsic angular momentum of the electron $\bar{S}$ couples with the orbital angular momentum of electron $\bar{L}$ to give a resultant $\bar{J}$. We know, that J + 1 magnetic sublevels labelled by the magnetic field $\hat{\bar{H}}_0$ by equal energy difference,

$$\Delta E = g \mu_0 H_0$$

between adjacent sublevels, where μ_0 is the Bohr magneton and g is the Lande' g factor or g - factor whose correct quantum mechanical value is

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

Now, if the particle is subjected to a perturbation by an alternating magnetic field with a frequency ν_1 such that the quantum $h\nu_1$ is exactly the same as the difference between the levels, ΔE and if the direction of the alternating field is perpendicular to the direction of the static magnetic field, then there will be induced transitions between neighbouring sublevels according to the selection rules $\Delta m = \pm 1$ for magnetic dipolar radiation.

Therefore, the condition for resonance is

$$\Delta E = g \mu_0 H_0 = h\nu_0 = h\nu_1 \tag{2}$$

Where ν_1 is the resonance frequency in cycles/sec. This requirement is identical with the classical condition $\omega_1 = \omega_0$.

In atomic spectroscopy, we do not observe the transitions between sublevels with different m (labelled a, a and selection rules $\Delta L = \pm 1$. Instead the splitting of a level is observed through small change in frequency of the radiation emitted in the transition between widely distant levels (Fig. 2). It is clear that, if we could directly measure the frequency corresponding to a transition between the sublevels of the same state, a much more precise knowledge of the energy splitting would be obtained.

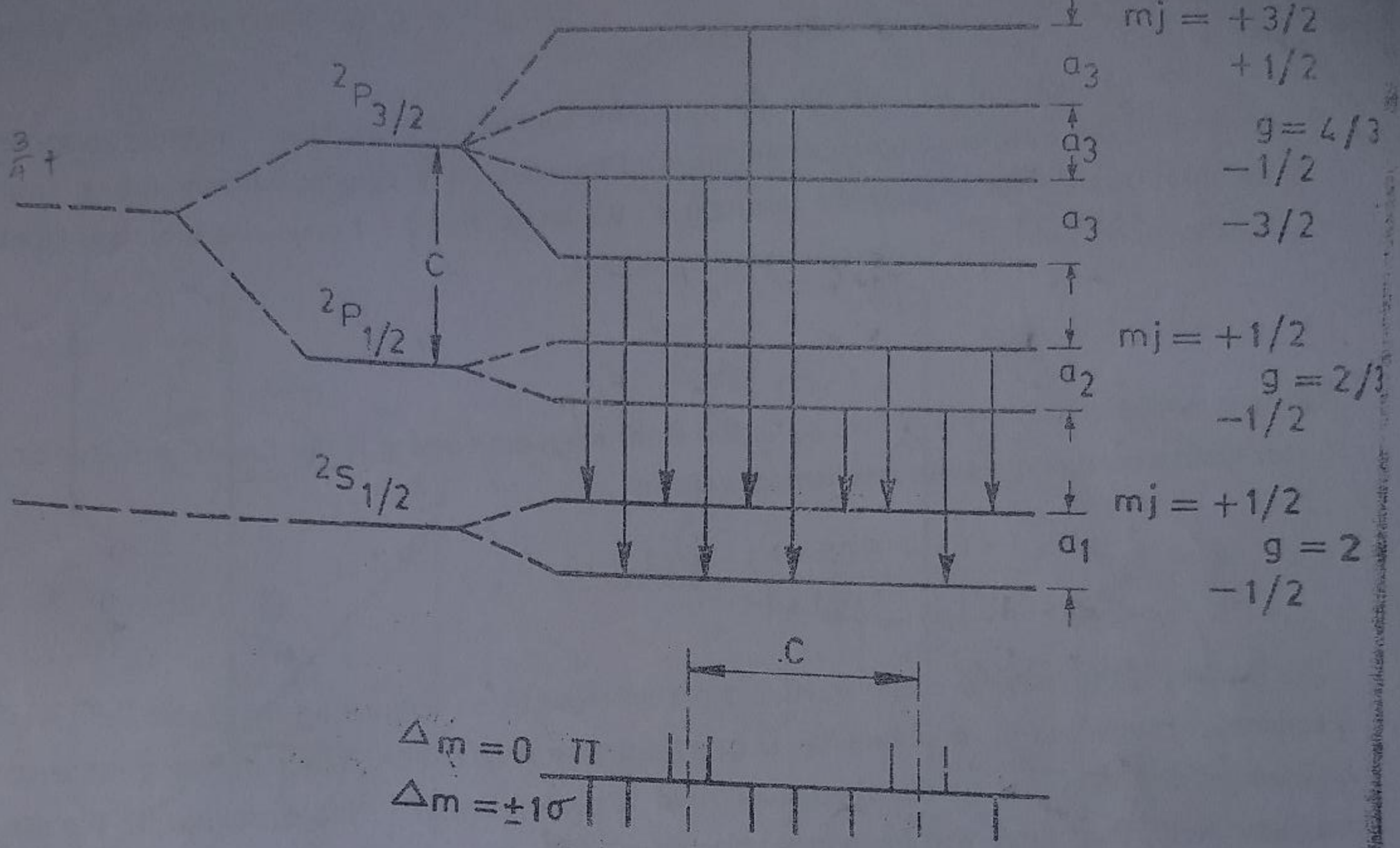


Fig. 2 : Energy levels of a single valence electron atom showing a P state and an S state. Due to the fine structure, the P state is split into a doublet with j = 2/3 and j = 1/2. Further, under the influence of an external magnetic field each of the three levels is split into sublevels as shown in the figure where account has been taken of the magnetic moment of the electron. The magnetic quantum number m_j for each sublevel is also shown as is the g factor for each level. The arrows indicate the allowed transitions between the intial and final states, and the structure of the line is shown in the lower part of the figure.

ELECTRON SPIN RESONANCE IN SOLIDS

Let us proceed from the treatment of an isolated magnetic particle to a macroscopic body. The behaviour of a paramagnetic substance in a magnetic field will depend on the interaction of the particles with one another and with the diamagnetic particles. There are mainly two types of interactions.

(a) Spin - Spin In which the spin interacts with a neighbouring spin but the total energy of the spin system remains constant.

(b) Spin - Lattice in which the electron spin interact with entire solid or liquid, transforming energy from the spin system to the lattice which act as a thermal reservoir. As a matter of fact it is the spin-lattice interaction that makes possible the observation of energy absorption from the radio- frequency field when the resonance frequency is reached.

To understand this last statement, consider a paramagnetic substance in a magnetic field $\overline{H_0}$ and say the equilibrium state has been reached., The population of individual energy levels will be determined by the Boltzman distribution $e^{-g\mu_0 H_0 m / kT}$ where m is the magnetic quantum number. It can be seen that the population of the lower energy levels are greater than those of the upper levels and, therefore when a periodic magnetic field with a resonance frequency is switched on; the number of induced radiation events will be more and as a result the substance will absorb energy from the radio-frequency field. Thus, two opposing processes take place in ESR. The radio frequency field tends to equalise the population of various levels and the spin lattice interaction tends to restore the Boltzman distribution by conversion of the energy absorbed from the radio-frequency field into heat.

RELAXATION AND SATURATION

In the preceding para, we see the mechanism through which the electron return from an excited state to the ground state or relax back to the ground state, This process in the field of magnetic resonance's (ESR, NMR, NQR etc.) is know as relaxation and the time taken by the process is called the relaxation time, This complete process may be considered as two state process (provided the spin-spin interactions are much stronger than the spin-lattice interaction). First, the energy is absorbed from the radio frequency magnetic field and the equilibrium is established inside the 'spin system'. The time taken by this process is known as the **spin-spin relaxation time** and is a measure of the rate at which magnetic energy can be distributed within the spin system though total energy is conserved. Secondly, an exchange of energy occurs between the spin system and the lattice. The time taken is known as the spin lattice relax time and is a measure of the rate of transfer of energy from the spin system to the lattice.

In optical spectroscopy of the relaxation time is usually very short (~ 10^{-8} sec) so that th relaxation time does not impede the absorption rate. In radio frequency, on the other hand, typical relaxation times are in milliseconds or longer and the spin do not have time to relax if the energy is supplied at a faster rate. This situation is called the '**Saturation State**'. In other words, no additional energy is absorbed, if the radio- frequency field power is increased beyond certain level.

LINE WIDTH AND THE SPIN-SPIN AND SPIN-LATTICE INTERACTIONS

The effect of the spin-spin interaction is to slightly shift the exact position of energy level of any individual spin in the external field. This energy shift clearly depend on the relative orientation and distance of the spin and thus is different for each spin, resulting in apparent broadening of the energy level. Another way of thinking of the spin-spin interaction is that one electron spin produce a local magnetic field at the position of another spin. Thus, the width of absorption line due to spin-spin interaction may be estimated as $\frac{1}{T'}$, where T' is spin-spin relaxation time.

If the spin-lattice interactions are not weak the spin lattice relaxation time T will also be introduced. Let us consider the probability of a transition of an individual paramagnetic particle from one magnetic level to another under the influence of thermal motion. If the probability per second equal A , $T \sim \frac{1}{A}$ and the absorption line width would be of the order of $\frac{1}{T}$. In general case, however, the absorption line width may be estimated as $\frac{1}{T} + \frac{1}{T'}$.

Thus, we see that from the width of absorption line it is possible to measure the relaxation time. In fact most of the research in this field involve the study of relaxation phenomena which in turn provide information about internal interactions in solids and liquids.

The position and number of lines of paramagnetic resonance absorption also depend on the internal interactions.

ELECTRON PARAMAGNETIC RESONANCE AND SPECTROSCOPY :

Paramagnetic resonance is an integral part of spectroscopy, as it provides a means for determining the position of the energy levels of magnetic particles. It is interesting to consider the peculiar features of Paramagnetic resonance in comparison with optical spectroscopy.

1. Let us first note that the frequencies used in magnetic resonance experiments range from 10^9 to 10^{11} cps. These frequencies situated below the limits of the infrared part of the spectrum, allow highly accurate investigation of energy level splitting so small that they are inaccessible or almost inaccessible by optical methods.
2. The probability of spontaneous transition in the radio- frequency region is very small, since this probability is proportional to v^3. Therefore, in paramagnetic resonance studies one is forced to deal only with induced absorption and emission.
3. While in the great majority of cases optical spectra arise from electric dipole transitions between energy levels, the lines of paramagnetic resonance absorption arise exclusively from magnetic dipole transitions. Consequently, the Einstein Coefficients for induced absorption and emission will, in the case of paramagnetic resonance, be smaller by roughly four orders of magnitude.
4. As a result, the paramagnetic resonance effect is exceedingly small; if it can be observed at all is due to the high sensitivity of electronic methods of detection and the enormous number of photons coming into play (1 mW corresponds to $n \cong 10^{20}$ photons per sec at a frequency of 10^{10} cps).
5. In the optical frequency region the line width is always very small in comparison with the fundamental frequency. In paramagnetic resonance the relation between these quantities becomes quite different, since the interactions causing a broadening of the lines can be of the same order of magnitude as the energy splitting which determines the resonance frequency. Because of this the width of paramagnetic resonance lines is often comparable to the fundamental frequency and can be measured with great accuracy. This opens up wide possibilities for investigation of different types of interactions in paramagnetic substances by means of analysis of the shape and width of a paramagnetic resonance line and of the character of its dependence upon various factors.
6. The most important factors determining the line width are magnetic dipole interactions, exchange forces, local electrical fields created by neighbouring magnetic particles, and

finally, thermal motion; the natural line widths of radio- frequency spectra are comple negligible.

7. In contrast with optical experiments, in radio-frequency spectroscopy it is customary to use radiation which is so monochromatic that the generated band of frequencies is incomparably narrower than the absorption line width.
8. Paramagnetic resonance spectra are not studied by varying the frequency of the incident radiation, but by varying the characteristic frequencies of the absorbing systems. This is achieved by varying the static magnetic field.

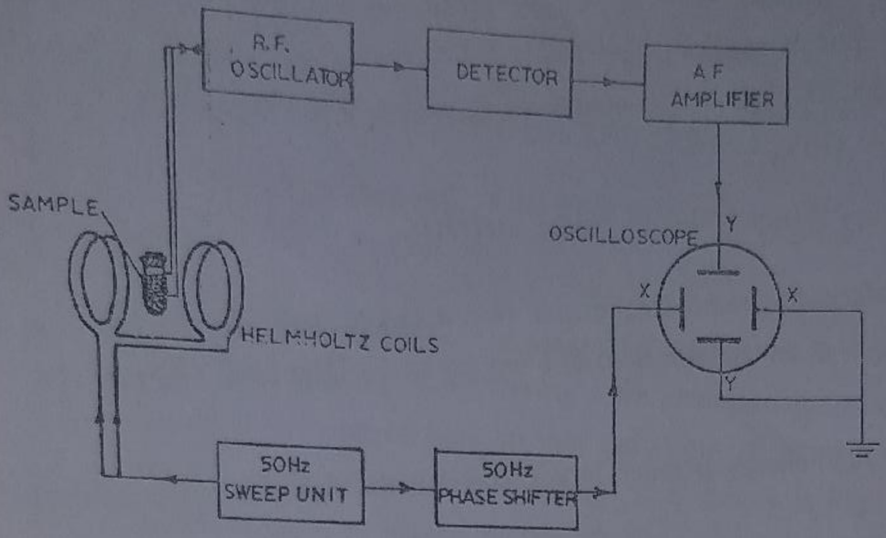
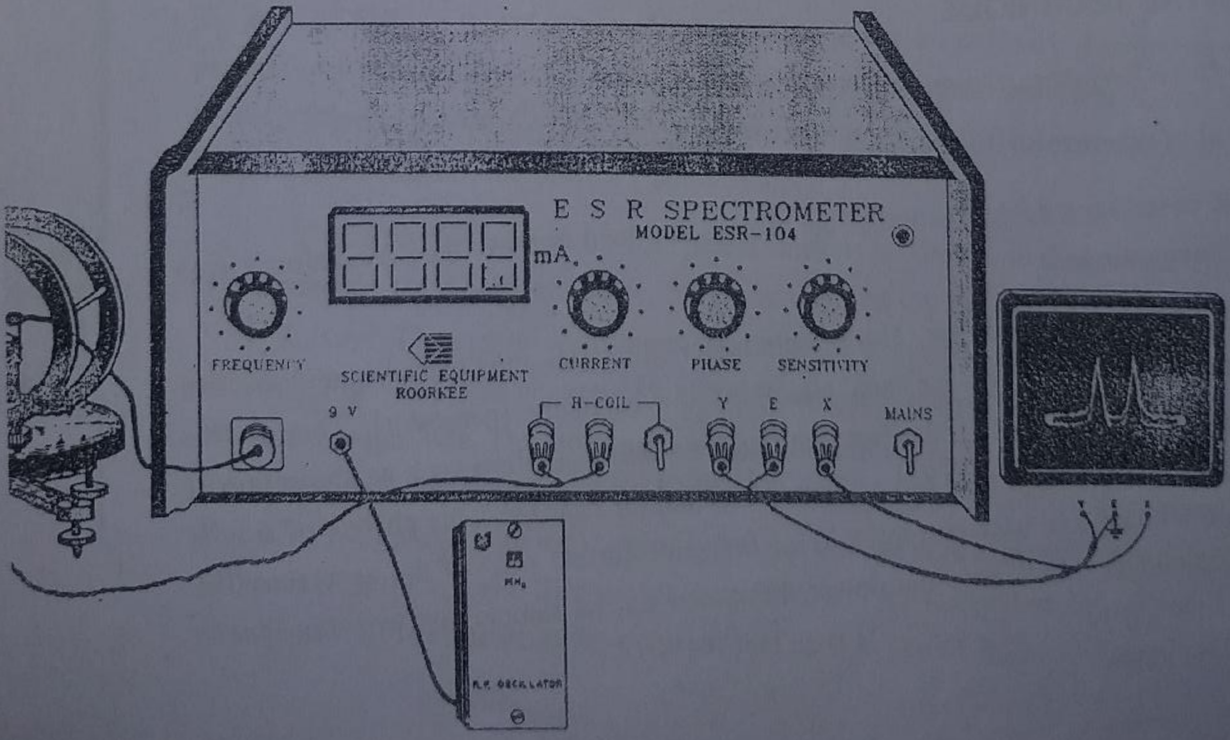


FIG.3 Block diagram of the E S R set.



CHAPTER 2

GENERAL CONSIDERATIONS

For a free electron, by substituting the proper values of constants : $g = 2.00$, $\mu_0 = 0.927 \times 10^{-20}$ erg / Gauss and $h = 6.625 \times 10^{-27}$ erg. sec. in equation (2), we get,

$$\frac{\nu_0}{H_0} = 2.8 \text{ MHz / Gauss}$$

That is ESR can be observed at radio frequencies in a magnetic field of few gauss or otherwise in the microwave region in a magnetic field of a few kilogauss. The latter alternate has many distinct advantages :

(a) For each transition the absorbed energy is much larger, and thus the signal-to-noise ratio is much improved.

(b) A high magnetic field is used, thus providing separation between levels that are intrinsically wide and would remain partially overlapped at low fields.

Because of these advantages, ESR in microwave region is preferred for research purpose, though, it is very sophisticated and expensive.

The former is preferable, where simplicity, easy operation and cost factor are the main considerations and no high resolution is required **ideal for postgraduate level experiments.**

EXPERIMENTAL TECHNIQUE

In the radio frequency region, two types of methods are chiefly used :

1. The method of reaction on the generator
2. The method based on a determination of the change in a load factor of the oscillatory circuit due to paramagnetic loss.

The latter method has been used here. The sample under investigation is placed in an induction coil, which is the component of the tank circuit of the oscillator (generator). This is the Zavoisky's technique. It is based on the fact that under certain conditions such as absorption of power from generator, the watt load (Δ w) on the generator changes. This change of Δ w is proportional to the change in base current ΔI_b or collector current ΔI_c of the generator. The proportionality, however, holds only the power dissipated by the sample due to paramagnetic absorption is small in comparison to the total losses in the circuit. This change in ΔI_c is detected with the conventional circuits. To make the detection simple and more sensitive, the magnetic field and hence the Larmer frequency of the sample is modulated with a low frequency field 50 Hz in the present set-up.

DESCRIPTION OF THE ESR SPECTROMETER

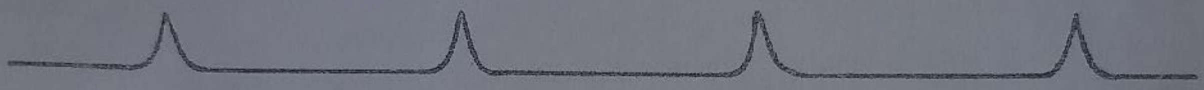
A block diagram of the ESR Spectrometer is given in Fig. 3 and line-sketch on the next page.

1. **Basic Circuit :** The first stage of the ESR circuit consists of a critically adjusted (marginal) radio frequency oscillator having a frequency range of approximately 10–17 MHz. A marginal oscillator is required here so that the slightest increase in its load decreases the amplitude of oscillation to an appreciable extent. The sample is kept inside the tank coil of this oscillator, which in turn, is placed in the 50 Hz magnetic field, generated by the Helmholtz coils. At resonance, i.e. when the frequency of oscillation equal to the Larmer's frequency of the sample, the oscillator amplitude registers a dip due to the absorption of power by the sample. This obviously, occurs periodically - four times in each complete cycle of the Helmholtz coils supply voltage. The result is in amplitude modulated carrier (Fig. 4A) which is then detected using a diode detector and amplified by a chain of three low noise, high gain audio - frequency amplifiers of excellent stability. A sensitivity control control is provided in the amplifier to suit the input requirement of any oscilloscope.

2. **Phase Shifter :** In order to make it possible to use an ordinary displaying type oscilloscope, instead of a measuring oscilloscope which preserve the phase between X and Y plates signals, a phase shifter is provided. This can compensate the phase difference which is introduced in the amplification stage of the ordinary oscilloscope.

The circuit diagram of the phase shifter is shown in Fig. 4B. The primary of the transformer is fed from the 230 V, 50 Hz mains and the secondary is centre tapped developing V_1-0-V_1 (say). The operation of the circuit may be explained with the help of the vector diagram shown in Fig. (4B). The vectors OA and BO represent the voltage developed in the secondary, in phase and magnitude. The current flowing in the circuit ADB leads the voltage vector BA due to the presence of capacitor C and is shown in the diagram as I. voltage developed across resistance R, i.e. V_R is in phase with the current I, and the voltage across across capacitor V_c is 90°(lag) out of phase with the current. The vector sum of V_c and V_R is equal to $2V_1$. These are also plotted in the diagram. It is clear from the diagram that as R is varied, V_R will change and the point D will

At A



At B

FIG. 4(A)

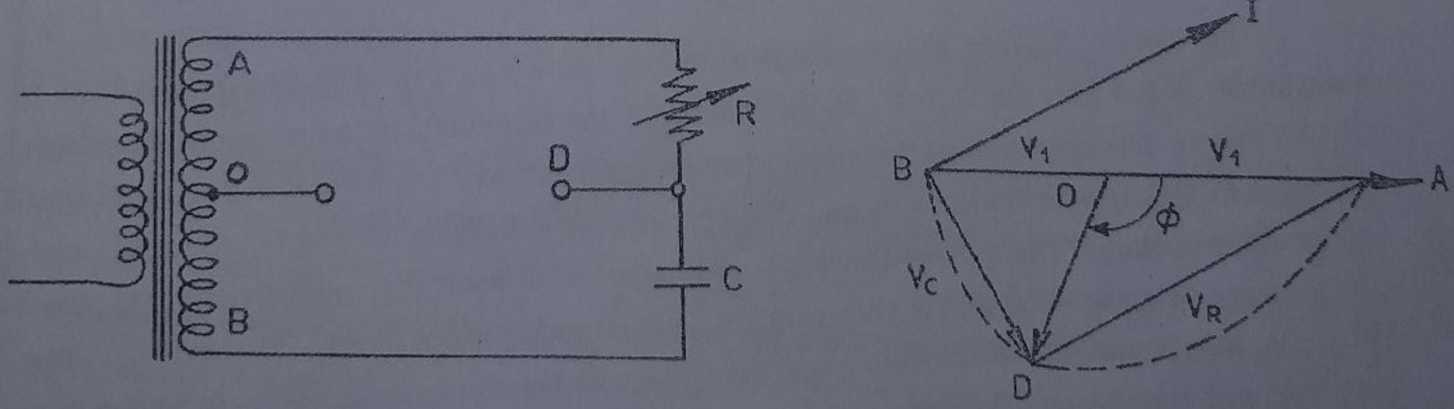


FIG. 4 (B)

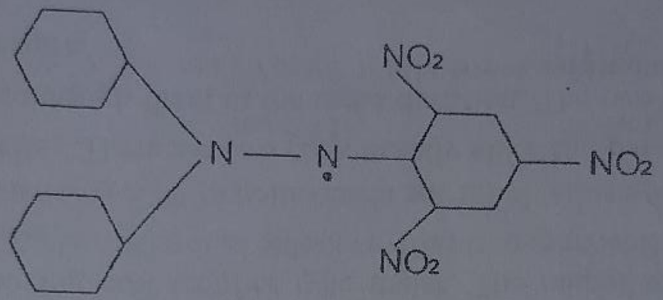


Fig.: Chemical structure of DPPH (2,2-Diphenyl-1-picrylhydrazyl, (free radical, 95%))

trace a semicircle, shown dotted. The vector OD, or the voltage across points 0 and therefore, have a constant magnitude equal to V, and its phase, variable from 0 to 180° the voltage which is fed to the X-amplifier of the oscilloscope to correct for any phase ch. which might have taken place in the rest of the circuit.

3. 50 Hz Sweep Unit : For modulation with a low frequency magnetic field, a 50 Hz current flows through the helmholtz coils. As the resonance in this frequency range occurs at low magnetic fields, no static D.C. magnetic field is required.

4. Power Supplies :

(a) D.C. Power Supply : The ESR circuit requires a highly stabilised almost ripple free voltage. It is obtained using an Integrated circuit regulator. The specification of the D.C. power supply are :

(i) *D.C. Voltage* : 20 V
(ii) *Load regulation* : 0.3%
(iii) *Line regulation* : 0.01%
(iv) *Ripple* : < 3 mV
(v) *Long Term stability* : 0.1% per 1000 hrs.

(b) Helmholtz Coils Power Supply : The Helmholtz coils power supply consists of a step down transformer (220 to 35 V AC) separate winding on the mains transformer, a potentiometer (12 - 15 W) and a moving coil rectifier type meter. The output is taken from the two terminals provided on the panel.

5. Helmholtz Coils : There are two coils exactly alike and parallel to each other, so connected that current passes through them in the same direction. The two coils increase the uniformity of the field near the centre.

Number of turns : 500 in each coil
Diameter of the Windings : 15.4 cm
Separation of the coil : 7.7 cm

In the centre of the coils, an attachment is provided to keep the sample in place and to minimise shocks and vibrations.

6. **Test Sample :** A test sample, Diphenyl Picryl Hydrazyl (DPPH) is placed in a plastic tube which itself is in the induction coils. This increases the filling factor to the maximum. DPPH is a free radical and widely used as a standard for ESR measurements.

7. **R.F. Oscillator :** it is a transistorised radio frequency Oscillator suitable for the determinatio of resonance frequency. The power to it is provided from the ESR Spectrometer through a cable.

Frequency range : 9.5 MHz - 18.0 MHz

Accuracy : Better than 0.5%

8. **Controls & Terminals :** (Please refer to Fig. No. 4)

(1) *Mains* : To switch 'ON' or 'OFF' the ESR Spectrometer.

(2) *Sensitivity* : To adjust the amplitude of the output signal.

(3) *Phase* : To adjust the phase between X and Y plates signals.

(4) *Current* : To control current in Helmholtz coils.

(5) *'H' Coils* : Terminals and switch for Helmholtz coils.

(6) *Frequency* : To adjust the frequency of the Oscillator.

(7) *X, Y, E* : For X, Y and Earth terminals of the Oscilloscope.

9. **Oscilloscope :** As the Oscilloscope is not supplies with the spectrometer, it is presume the worker is already familiar with the control knobs and functioning of the Oscillosc question.

Any Oscilloscope, normally available in the laboratory of the following specificati better, will be quite suitable for the observation of ESR resonance :

Screen diameter : 12.5 cm

Vertical amplifier sensitivity : 50 mV / cm

INSTALLATION

The instrument is thoroughly tested and checked before it is despatched factory. Please check for all the components from the list given in the delivery challan.

It is strongly recommended to read the description of the ESR Spectrom carefully and get familiar with various knobs and terminals given in the preceding

Now for installation proceed as follows :

1) Connect the Coaxial cable of the induction coil to the Oscillator through the socket.

2) Connect the Helmholtz coils to the terminal marked 'H' coil.

3) Connect the terminal marked X, Y, and E on the ESR Spectrometer to the X plate, Y plate input and earth of the Oscilloscope respectively and switch the Oscilloscope.

4) Connect the spectrometer with the AC mains 200 to 230 Volts, 50 Hz and switch - on the power. Ensure that the equipment is properly earthed.

OPERATION

1) Switch on 'H COIL' power and adjust the current at 150 mA.

2) Set the front panel controls of ESR Spectrometer as follows

Frequency : Centred
Sensitivity : Fully clock-wise
Phase : Centred

3) Observe four peaks on the Screen of CRO. Now adjust the FREQUENCY and SENSITIVITY knobs of the Spectrometer and Sensitivity of the CRO to obtain the best results (i.e. sharp peaks and good signal to noise ratio).

4) Adjust the PHASE knob to coincide the two peaks with the other two as far as possible.

CHAPTER 3

ORIGIN OF FOUR PEAKS

The observed peaks are in fact absorption dips, because the sample absorb power from the induction coil, reasons explained in Chapter 1. The reason for getting peaks is due to odd number of amplifying stages in the circuitry.

The spin precesses with Larmor's frequency ($\omega_0 = \frac{eH_0}{2mc}$) and hence varies in magnitude and direction due to variation of magnetic field $\overline{H_0}$ which is due to an alternating current in the Helmholtz coils. Now if the radio frequency field, ω_1 falls in the range of ω_0 the resonance occurs. The positions of the four peaks can be understood with Fig. (5).

If the X plate signal (50 Hz) and Y plate signal (ESR output) are in phase the I and II peaks and III and IV peaks will coincide. The coincidence of peaks on the x-scale needs to be calibrated for magnetic field measurements. The coincidence ensures that the magnetic field is zero at the centre and has the peak values at the two ends. Complete merger of the peaks on y-scale may not occur due to many reasons such as 50 Hz pick-ups, ripples in the power supply etc. Though, every effort has been made to minimise these factors but the large amplification ($\cong$ 4000) in the circuitry make them substantial. However, any non- coincidence on the y-scale is immaterial as neither any measurement of the y-scale is involved in the calculation of g- factor nor any measurement is made on it.

DETERMINATION OF MAGNETIC FIELD

To calibrate the X-plate of CRO in terms of magnetic field proceed as follows :

1. Adjust the X amplifier (CRO) to obtain the maximum X deflection (say 'P' divisions).
2. Read current flowing in Helmholtz coils and calculate the magnetic field.

$$H = \frac{32\,\pi\, n}{10\,\sqrt{125}\,.\,a}\,.\,I$$

Where 'n' is the number of turns in each coil

'a' is the radius of the coils

'I' is the current (in amp) flowing through the coils.

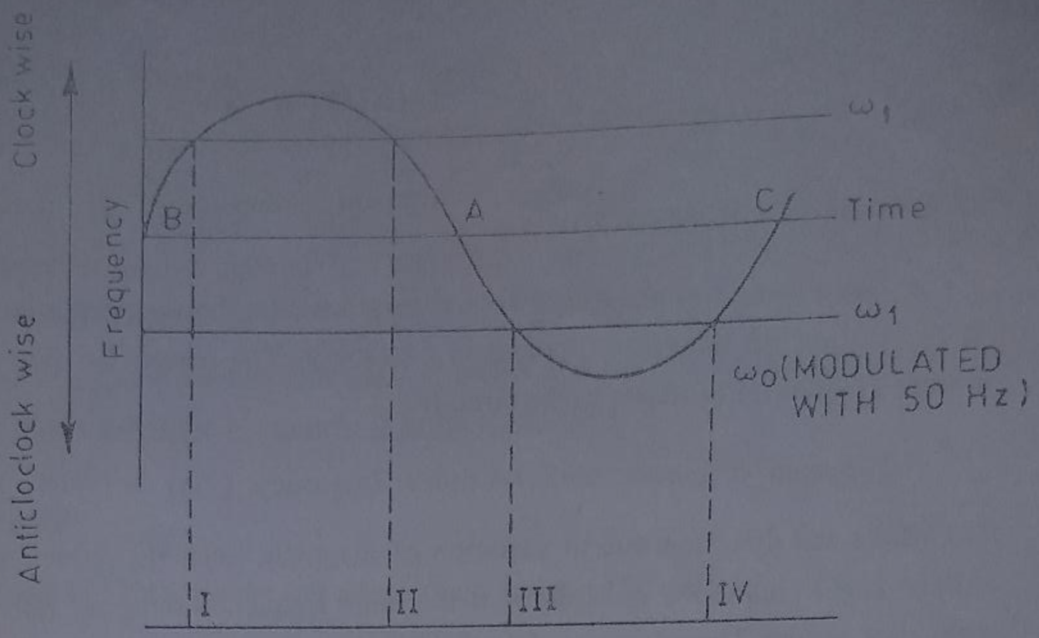


Fig. 5 : The radio frequency field is linear pollarised, which can be regarded as two circularly polarised field of opposite direction (say clockwise and anti clockwise) is due to change in direction (clockwise and anti clockwise) is due to change in direction of magnetic field $\overline{H_0}$. The resonance occurs when the two frequencies (ω_1 and ω_0) becomes equal in magnitude as well as in direction.

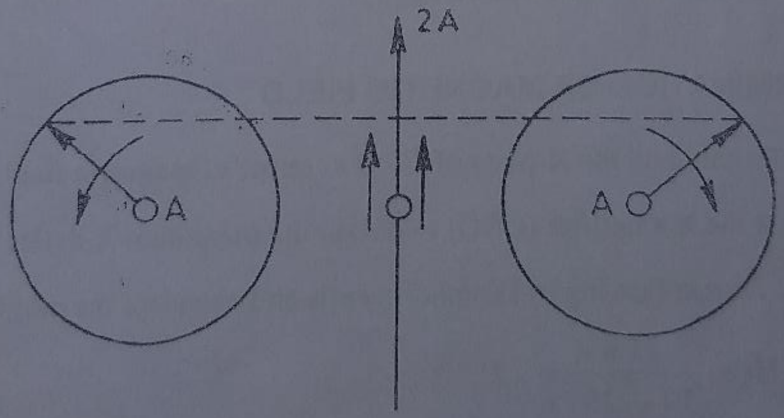


Fig. 6 : A linearly oscillating field of frequency is equivalent to two fields rotating in appo site directions with the same frequency ω.

This is the root mean square (rms) field. The peak to peak field will be $2\sqrt{2}.H$ represents 'P' division of the CRO X plate. The zero field is at the middle point.

3. Measure the positions of the two peaks. These should be at equal distances from the m point (say "Q' division).The magnetic field at the resonance is thus

$$H_0 = \frac{2\sqrt{2}\,.\,H}{P}\,.\,Q \text{ gauss}$$

DETERMINATION OF RESONANCE FREQUENCY

Keep the above set-up as it is. Power up the calibrated R.F. Oscillator by inserting its j in " -9V socket " in ESR and bring it in the vicinity of the sample say at a distance of 1 feet. T the R.F. Oscillator to obtain beats (this will be seen on the CRO very easily) and read frequency on the Oscillator dial. This will be the desired resonance frequency. If one obser the beats more carefully by varying the R.F. Oscillator frequency slowly, he will obtain h frequency beats twice with a zero beat in between. The frequency corresponding to the zero b is the exact frequency. The inaccuracy involved in the frequency measurement will exceedingly small even if the zero beat position could not be detected.

CALCULATIONS

From equation (2)

$$h\nu_1 = g\mu_0 H$$

or

$$g = \frac{h\nu_1}{H_0\mu_0}$$

Substitute the measured values of H_0 and ν_1 universal constants $h = 6.625 \times 10^{-27}$ erg. se and $\mu_0 = 0.927 \times 10^{-20}$ erg / gauss to get the g factor.

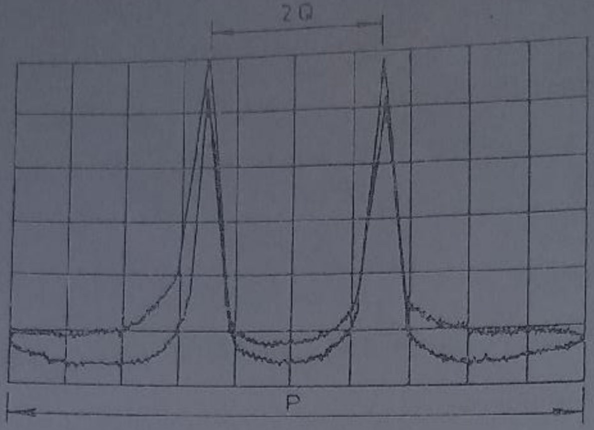


FIG. 7 LINE SKETCH OF THE RESONANCE PEAKS

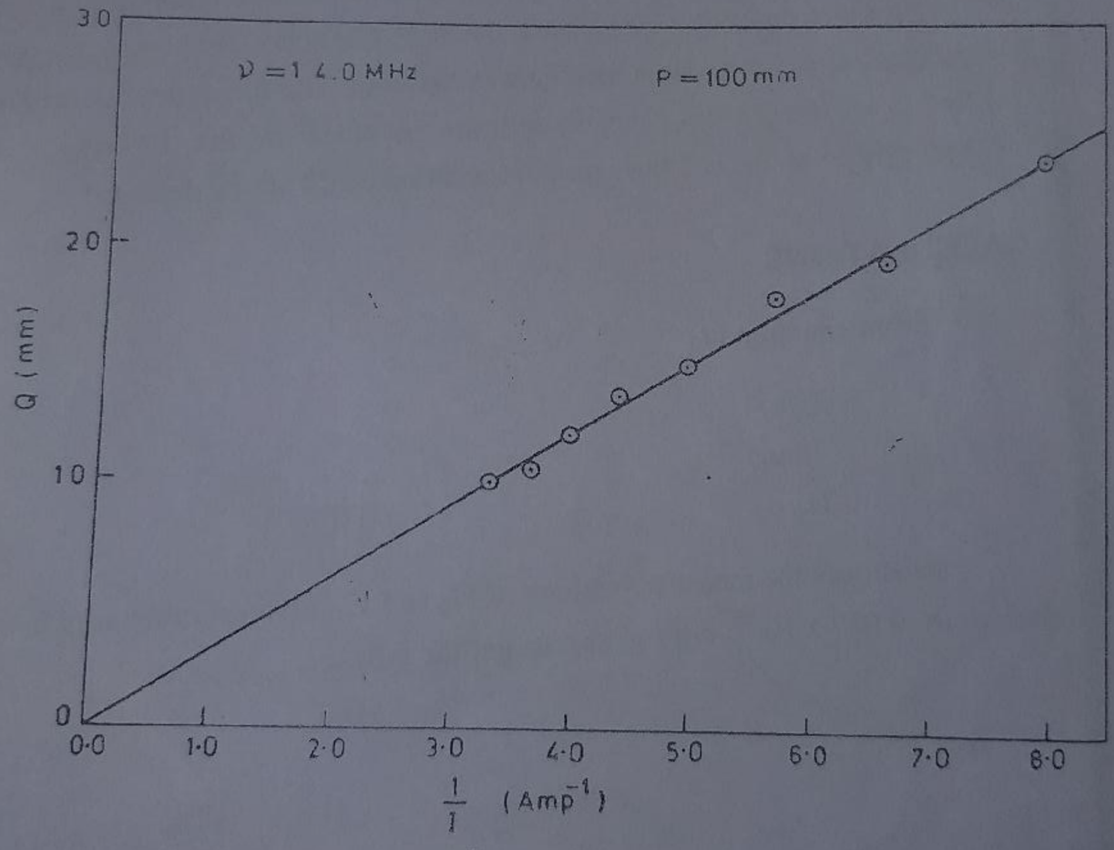


FIG. 8 GRAPH BETWEEN $\frac{1}{I}$ VS Q

APPENDIX

SAMPLE CALCULATIONS

Magnetic field at the centre of a Helmholtz coil is :

$$H_0 = \frac{32\,\pi\,n}{10\,\sqrt{125}\,.\,a}\,.\,I = K\,I \quad \text{Gauss}$$

Where I is the current in amperes and other symbols have their usual meaning. Since the cur measured is rms the magnetic field is also rms. The peak to peak magnetic field will be :

$$H_{PP} = 2\sqrt{2}\,H$$

The H_{PP} corresponds to the total X - deflection on the oscilloscope with zero field at the cen Substituting the values a : 7.7 cms. n = 500, we obtain

$$H_{PP} = 165.25 \quad \text{Gauss / amp}$$

Let us take a typical observation (Fig. 7). The measured values are :

$$\nu_0 = 14.00 \text{ MHz};\quad I = 200 \text{ mA};\quad P = 100 \text{ mm} \quad \text{and} \quad 2Q = 30 \text{ mm}$$

Since P corresponds to H_{PP}, the magnetic field per mm of the X - deflection will be H_{PP}/P hence the magnetic field for either resonance is

$$H_0 = \frac{H_{PP}}{P}\,.\,Q = \frac{165.25 \times 0.2 \times 15}{100} = 4.96 \text{ Gauss}$$

Substituting the values in the relation

$$h\,\nu_0 = g\,\mu_0\,H_0$$

$$g = \frac{h\,\nu_0}{\mu_0\,H_0} = \frac{6.625 \times 10^{-27}}{0.927 \times 10^{-20}} \times \frac{14.00 \times 10^{6}}{4.96} = 2.04$$

EXPERIMENTAL PROCEDURE

1. Increase the horizontal sensitivity of the Oscilloscope to the maximum with in th range.
2. Obtain the best possible resonance peaks by varying the frequency, detection lev vertical sensitivity of the oscilloscope, keeping the current at 150 mA (say).
3. Keep the frequency fixed but vary the current flowing through the coils and measu corresponding horizontal separation between the two peaks (2Q) after adjusting the Take five to six sets of observations.
4. Draw a graph in 1/T Vs Q which should be a straight line. Calculate the g-factor using value from the graph.
5. Repeat the experiment with different frequency.

The reason for drawing graph between 1/T and Q with fixed is that the measureme and Q are likely to contain some random errors.

PRECAUTIONS

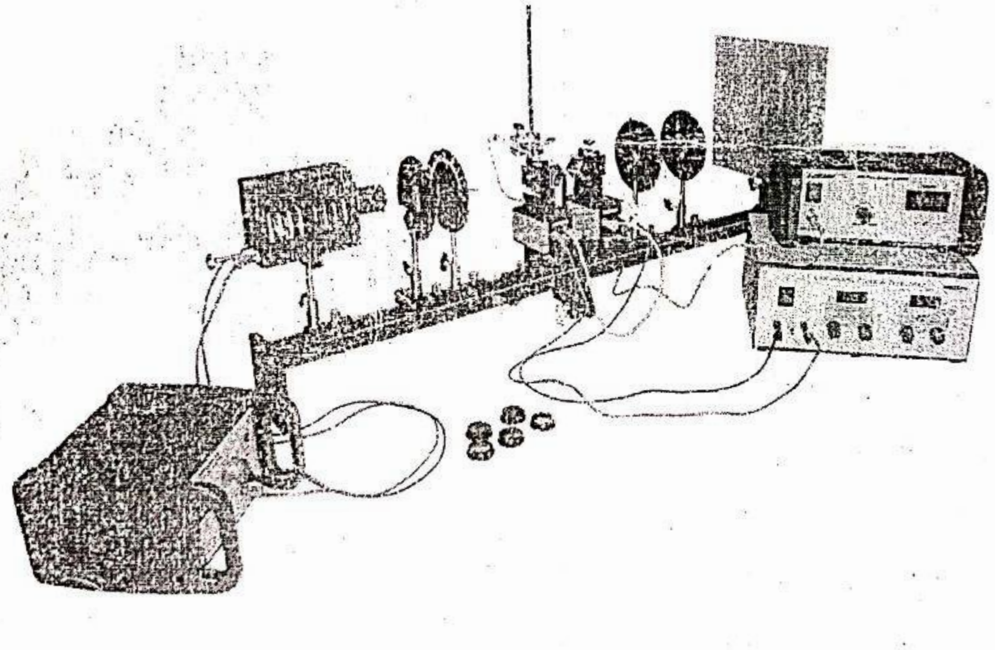
1. Experiment should be set up at a quite place free from mechanical and electrical disturb
2. Y - output from the ESR Spectrometer should be taken through shielded cable to m external pick-ups.
3. X and Y plates sensitivities of the Oscilloscope should be adjusted such that they shou the linear range only.
4. Since the Helmholtz current is unstabalised, care should be taken that it should constant during the observation.
5. High currents (~ 200 mA) should not be allowed to flow through the Helmholtz coil extended period. This will unnecessary heat the coils which may get damaged aft time.
6. If the peaks do not coincide on the x-scale, check the sinusoidal wave form of th voltage which may be distorted due to overloading of the main line due to othe gadgets working on the same line.
7. Do not use AC Stabiliser as it is likely to distort the sinusoidal wave form. If neces the variac.

Soumyadipta Chakrabarty

INDOSAW

Instruction Manual

FARADAY EFFECT



OSAW INDUSTRIAL PRODUCTS PVT. LTD.

P.O. BOX No. 42, OSAW Complex, Jagadhri Road
Ambala Cantt-133001 (Haryana) INDIA
Grams : INDOSAW
E-mail : ajaysagar@satyam.net.in
E-mail : eenquiry@indosaw.com

Phones : 0171-2699347,2699267
Fax: 0171-2699102, 2699222
New Delhi, phone : 011-6466613
E-mail : denquiry@indosaw.com

TUV South Asia
NABCB QM011
An ISO 9001 :2000
Certified Company

Faraday observed that when a transparent medium is subjected to an external field, the plane of polarisation of a plane-polarised light beam through the medium get rotated, if the direction of incident light is parallel to the line of magnetic field.

The angle of rotation ϕ is proportional to the magnetic flux density B and length L of the medium through which plane polarised light is transmitted:

$$\phi \propto LB \quad \text{...(1)}$$

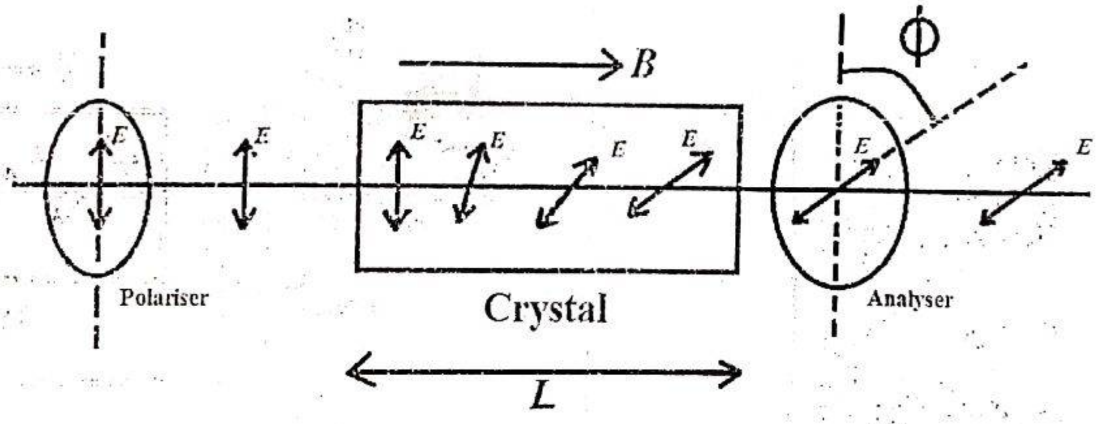
The proportionality constant V is called as Verdet Constant and depend upon wavelength λ and refractive index μ,

$$\phi = VLB \quad \text{...(2)}$$

or,

$$V = \frac{\phi}{LB} \quad \text{...(3)}$$

From the graph at a particular wavelength, we find the slope and put in equation (3) to find V at that wavelength.



B is the Magnetic Field.

L is the Length of isotropic material.

E is the Electric Field.

1 min

INDOSAW
COMMITTED TO EXCELLENCE

SYSTEMIC ARRANGEMENTS OF ITEMS FOR DETERMINATION OF V

1.1

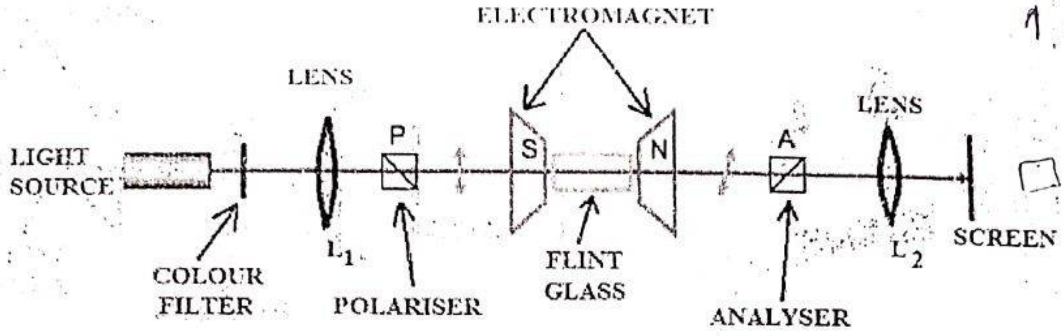


Fig. 1 : Arrangements of Components in Optical Bench Using Halogen Lamp

NOTE:

1. Lens L_1 is not required with LASER source.
2. Colour Filter is not required for LASER source.

OPTICAL BENCH SET-UP:

1. Arrange the diode laser (or source) on the optical bench according to picture.
2. Position a polarizer close to the laser on the optical bench as shown.
3. Mount the Flint Glass Holder into the central slot of the 'U' – core.
4. Insert two coils of 500 turn in both arms of the 'U' -core.
5. Place the pole piece on the U core in such a manner that the flint glass rod can be placed on the holder as depicted.
6. Mount the Flint Glass into the upper platform of the Flint Glass Holder.
7. Push the pole piece right up to the flint glass square but without damaging it.
8. Use the clamps and pins to fix the bored pole piece on the U-core.
9. Position the analyzer (another polarizing filter) close to the U-core on the optical bench.
10. Position the screen opposite to the analyzer.

NOTE : While doing the above steps, please ensure that the source light passes through the central portion of all the optical components. You may need to switch on the laser and do the necessary adjustment of all the optical components. The Laser light should be sharply focussed at the screen.

ELECTRICAL SETUP:

1. Connect the coil in series to the variable power supply 30V, 10 Amp at DC socket.
2. Connect the laser to main 230V AC.

NOTE: The maximum coil current under permanent use is 6 Amp. However the current can be increased up to 8A for a few minutes without risk of damage to the coils by overheating.

CALIBRATION OF THE MAGNETIC FIELD:

1. Remove the flint glass square.
2. Connect the digital gauss meter to main switch.
3. Place the hall probe between the pole piece. Use the stand material to hold the magnetic probe between the bored pole pieces.
4. Record the magnetic field B as function of the current I through the coils.

PRECAUTIONS:

1. By sliding the lens L_2 along the optical bench, the face of flint glass square, should be projected in sharp focus on translucent screen .

2. The electromagnet must be positioned such that path of pole pieces and optical flint square are aligned with the optical axis.

ROTATION OF THE POLARIZATION PLANE Φ AS A FUNCTION OF THE MAGNETIC FIELD

1. Arrange the apparatus as mentioned in previous section.

2. Place the flint glass square (15 mm X 15 mm X 15 mm) on the support between the drilled pole piece of electromagnet.

3. Switch on the light source.

4. Rotate the analyser so that polarisation plane is crossed in relation to that of polariser. Make the field view of the face of flint square projected on the transluscent screen appear dark. This means polariser and analyser are crossed due to which transluscent screen image appear dark.

5. Switch on the current through the coils of electromagnet. Due to the magnetic field produced the flint glass square get permeated in the direction of radiation. The image of spot due to the rotation of plane of polarisation of polarised light brighten up due to the longitudinal magnetic field generated between the pole pieces.

6. Rotate the analyser till it produces maximum extinction of light (i.e. minimum intensity of image of spot). Note the reading (say Φ_1).

7. Reverse the direction of magnetic field, by changing the polarity of the coil current.

8. Rotate the analyser in the opposite direction again in order to darken the brightness of field of view. Note the reading (say Φ_2).

9. Record the difference between (Φ_1 and Φ_2), the position of analyser in step 6 and 8. This difference is equals to the rotation $2\phi\ \{=\phi_1 - \phi_2 = \phi - (-\phi)\}$ of plane of polarisation of the light.

10. Vary the current and obtain different values of (2ϕ) for different values of magnetic field. Make the data in tabular form.

11. The magnetic field for different values of current can be found from the calibration data / graph for the magnetic field.

12. Plot the rotation (2ϕ) as a function of the magnetic field and find the slope. Determine the Verdet's Constant (V) from the slope, by using equation (3).

ALITER

ROTATION OF THE POLARIZATION PLANE 2Φ AS A FUNCTION OF THE MAGNETIC FIELD

1. Arrange the apparatus as mentioned in previous section.

2. Place the flint glass square (15 mm X 15 mm X 15 mm) on the support between the drilled pole piece of electromagnet.

3. Switch on the light source.

4. Set the analyser to 0^0 position. (The pointer of the analyser will indicate 0^0 angle.)

5. Switch on the current through the coils of electromagnet. Set the current to desired value I.

6. Rotate the polariser to darken the light spot at the screen.

7. Rotate all the knobs of the power supply to bring them back to their inital position. The current will be reduced to zero value. Switch off the power supply.

8. Interchange the leads of the power supply. Now set the current to the intital value. (So, current will change from +I to -I). As a result, the direction of magnetic field will change. (Magnetic field changes from +B to -B.)

9. Rotate the analyser again in order to darken the light spot at the screen. Note down the angle as indicated by the pointer of the analyser. This angle denotes the rotation of the plane of polarisation i.e. this angle = 2ϕ due to change in the magnetic field [+B - (-B) = 2B].

10. Vary the current and obtain different values of (2ϕ) for different values of magnetic field. Make the data in tabular form.

11. The magnetic field for different values of current can be found from the calibration data / graph for the magnetic field.

12. Plot the rotation (2ϕ) as a function of the magnetic field and find the slope. Determine the Verdet's Constant (*V*) from the slope.

OBSERVATIONAL TABLES

TABLE – 1 : CALIBRATION OF MAGNETIC FIELD

CURRENT, I (A)	MAGNETIC FIELD, B (GAUSS)
1.1	750
2.0	1300
3.0	1800
4.0	2400
5.0	3000
6.0	3600
7.0	3900
7.4	4000

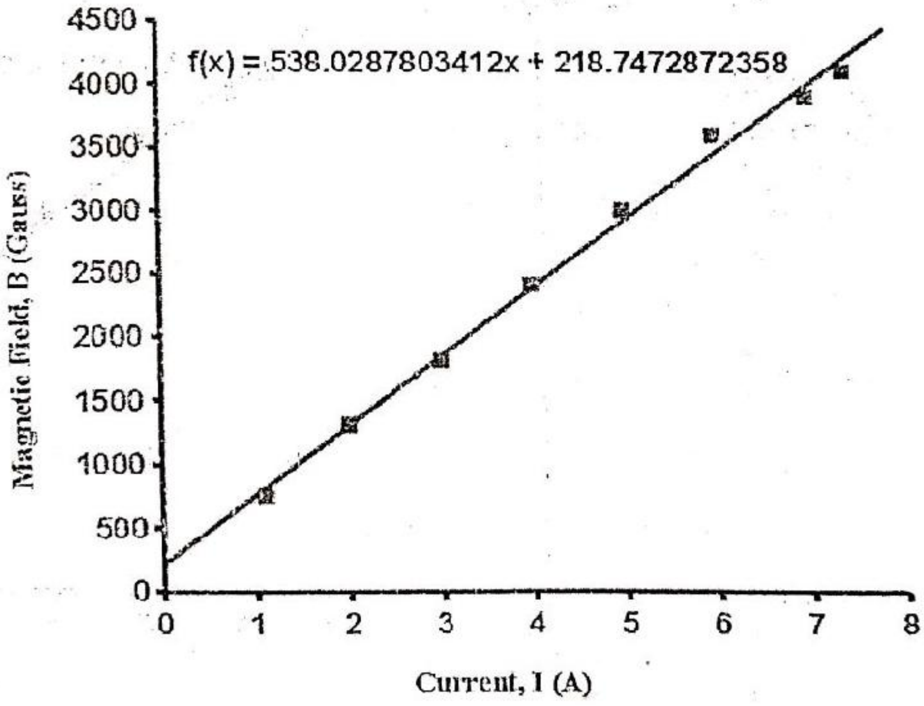


Fig. 2 : Calibration Curve for Magnetic Field [Plot of Magnetic Field, B as a function of Current, I]

The linear fit between I and B is given by, $B = 538.029I + 218.747$

TABLE – 2 : ROTATION 2Φ AS A FUNCTION OF THE MAGNETIC FIELD, *B*

Wavelength of light used, $\lambda = 632$ nm

Room Temperature = 22^0 C

Current, I (A)	Magnetic Field, B (Gauss)	Rotation, 2ϕ (Degree)
8.3	4576.8	14
7.2	3984.9	12
6.2	3500.7	10
5.2	2962.7	10
4.1	2424.6	8
3.1	1886.6	6
2.1	1348.6	4
1.1	810.6	2

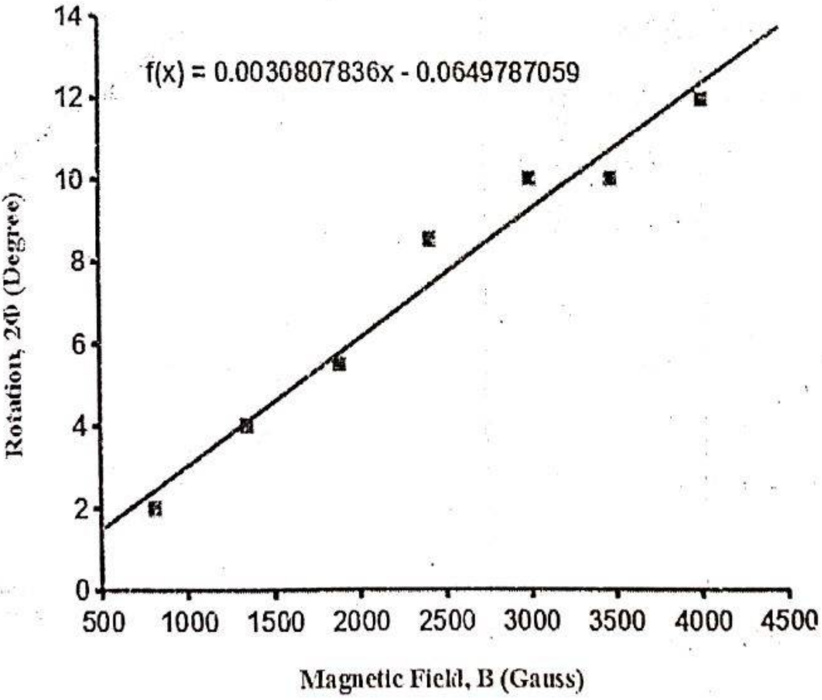


Fig. 3 : Plot of Rotation, 2Φ as a function of Current, I

Slope of the graph 30.8×10^{-4} Degree / Gauss

Verdet's Constant, $V = \frac{Slope}{2l} = \frac{30.8 \times 10^{-4}}{2 \times 1.5}$ Degree / Gauss / cm

$= 10.3 \times 10^{-4}$ Degree / Gauss / cm for 632 nm wavelength

where, l = Length of the crystal = 1.5 cm

APPENDIX

CAUSE OF FARADAY EFFECT (OSCILLATION OF ELECTRONS IN MAGNETIC FIELD)

The angle of rotation of plane of polarised light when passes through a istropic transparent material, in the direction of field,

$$\phi \propto B$$

$$\phi \propto L$$

$$\phi = VBL$$

where V is called as Verdet Constant which depend upon temperature, refractive index and wavelength of light.

This can be explained by imagining the linearly polarised light as the superposition of two opposite components, α_+ and $\alpha\_$. When an atom is subjected to magnetic field, the oscillating charges (i.e. electrons) acquire additional precession frequency equal to that of Larmour frequency.

$$\omega = \frac{e}{m} B \quad \text{..(4)}$$

Now one component (α_+) has frequency $\omega_+ = \omega + \omega_L$ (say) and another $\omega\_ = \omega - \omega_L$.

The referective index μ_+ and $\mu\_$ and phase velocities v_+ and $v\_$ differ and are the measure of optical activity.

The angle of rotation of plane of polarisation through length L, under the influence of magnetic field is given by

$$\phi = \frac{\omega B}{2c}\left(\mu_{+} - \mu_{-}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

where, ω = frequency of transmitted light.

It can be proved that μ depend upon λ ($\mu = A + \frac{B}{\lambda^2}$)

and Verdet's constant, $V = \frac{e\lambda}{2mc}\frac{d\mu}{d\lambda}$.

For the EXTRA – DENSE FLINT GLASS, we can use the following approximation,

$$\frac{d\mu}{d\lambda} = \frac{2.8\times 10^{-14}}{\lambda^3}\ \mathrm{m}^{-3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

So,
$$V = \frac{e\lambda}{2mc}\times\frac{2.8\times 10^{-14}}{\lambda^3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

or,
$$V = \frac{e}{2mc}\times\frac{2.8\times 10^{-14}}{\lambda^3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

The value of $\frac{e}{m}$ derived by using the above equation after putting the values of V as determined by Faraday Effect , agrees well with known standard value.

This justifies that natural oscillation of electrons are responsible for Faraday effect

So in this experiment we can verify,

1. The plane of polarisation rotation $\phi \propto B$.
2. The verdect constant decreases with increasing λ as $\frac{1}{\lambda^2}$.

ADDITIONAL EXERCISE

VALUES OF VERDECT CONSTANT FOR VARIOUS WAVELENGTHS

By using different LASERS of different wavewlengths, equation (8) can be verified.

EXPEREMENT NO.- 07

FEBRY PEROT INTERFEROMETER

Objective: **a)** To estimate the air spacing 'd' of etalon using red laser source.

b) Determination of wavelength of the given green laser source using air spacing 'd'.

Fabry-Perot interferometer

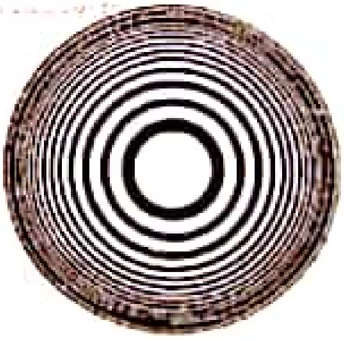
INTRODUCTION

The Fabry-Perot interferometer, designed in 1899 by C. Fabry and A. Perot, represents a significant improvement over the Michelson interferometer. The difference between the two lies in the fact that the Fabry-Perot design contains plane surfaces that are all partially reflecting so that multiple rays of light are responsible for creation of the observed interference patterns. The general theory behind interferometry still applies to the Fabry-Perot model, however, these multiple reflections reinforce the areas where constructive and destructive effects occur making the resulting fringes much more clearly defined. This, as will be discussed later, allows for much more precise measurements of wavelength, and free spectral range.

Strictly speaking, a Fabry-Perot by definition consists of two planar mirrors, but the term is nowadays very frequently also used for resonators with curved mirrors. From a theoretical viewpoint, plane-plane optical resonators are special in the sense that their cavity modes extend up to the edges of the mirrors and experience some diffraction losses. However, Fabry-Perots are usually used with input beams of much smaller diameter, which are actually not really matched to the cavity modes. For the usually small mirror spacings, where diffraction within a round trip is rather weak, this deviation does not matter that much.

For optical spectrum analysis, the Fabry-Perot interferometer is often made short enough to achieve a sufficiently large free spectral range; the bandwidth of the resonances is then the free spectral range divided by the finesse. Due to the high reflectivities, the finesse can be rather high (well above 1000, with supermirrors even much higher). For a given finesse, one can improve the wavelength resolution by increasing the mirror distance, but only at the cost of reducing the free spectral range, i.e., the range within which unique spectral assignment is possible.

Much of what we know about the structure of atoms and molecules comes from a study of the spectral lines they emit. Many decades of observations have shown that the spectrums of atomic and molecular systems have an enormous amount of fine structure which cannot easily be seen. For example the most important feature in the spectrum of sodium looks, in many spectrometers, like a single bright yellow line of wavelength of 589 nm, But on finer resolution it is seen to be a doublet, two distinct lines at 589.0 nm and 589.6 nm. Furthermore, if you apply a strong magnetic field to the system, you will find that some of the lines split into several different wavelengths, separated by perhaps 0.01 nm.



Concentric ring pattern produced by a Fabry-Perot etalon

In order to do useful spectroscopy on such systems therefore, you need a spectrometer with a resolution of something like 0.01 nm. One such is the Fabry-Perot interferometer.

Properties of Fabry-Perot Interferometer

For high resolution spectroscopy where a resolution of MHz to Ghz is required, a Fabry-Perot interferometer (FP) is used. The FP consists of two plane mirrors mounted accurately parallel to one another, with an optical spacing L1 between them. For a given spacing L1 the interferometer will transmit only certain wavelengths λ as determined by

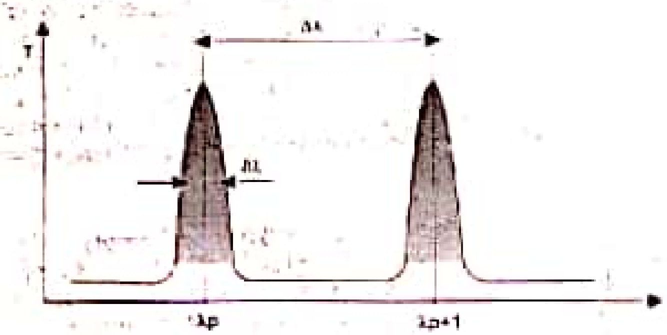
$$T = \frac{\tau_0}{1 + (4F^2/\pi^2)\sin^2(2\pi L_1/\lambda)}$$

where t°(<1) is the maximum possible transmission determined by losses in the system, and F, the finesse, is a quality factor depending primarily on the mirror reflectivity and flatness. Equation 1 shows that only those wavelengths satisfying

$$L_1 = \tfrac{1}{2} p \lambda$$

for integral values of p, will be transmitted. This is illustrated below.

The finesse F is related to the spacing between successive transmitted wavelengths Δλ (known as the free spectral range, FSR) and the width δλ of a given transmission peak by



$$F = \Delta\lambda/\delta\lambda$$

The FP is used as a spectrometer by varying the spacing L1 so as to scan the light intensity at different wavelengths. However it is immediately apparent that the measured intensity at a given spacing is the sum of the intensities at all wavelengths satisfying condition 2. An un ambigious interpretation of the spectrum is thus impossible unless it is known a priori that the spectrum of the light lies entirely within a wavelength spread <λλ. It is true that since

$$\Delta\lambda = \lambda^2/2L_1$$

one may make λλ arbitrarily large by decreasing L1. However dλ increases proportional to λλ and so the resolution decreases. In fact equation 3 shows that the ratio between FSR, λλ and the resolution dλ, is just the finesse F. In practice F cannot be made much greater than about 100 due to limitations on the quality of mirror substrates and coatings. The relationship between FSR and resolution is thus fixed within limits determined by the achievable values of F.

Vibration isolation

The interferometer requires a quiet, vibration free environment. The better solution is to mount the optical table rigidly on the floor, but to isolate the interferometer from the optical table. Note that an enclosure is required around the interferometer to protect it from sound waves which can excite high-frequency resonances in the system.

Plate Flatness

Due to the multiple reflections in a Fabry-Perot interferometer, deviations in the homogeneity of the reflecting surfaces are 'multiplied', too.

Tilting

When the system is not proper aligned the fringe will not appear. A pointed laser pass through the etalon appears as many spots. Adjust the tilting knobs properly all the spots comes in to the center spot of the etalon. Insert the lense cap in to the laser capsule. The diverged output of laser beam produce the fringe with observable size.

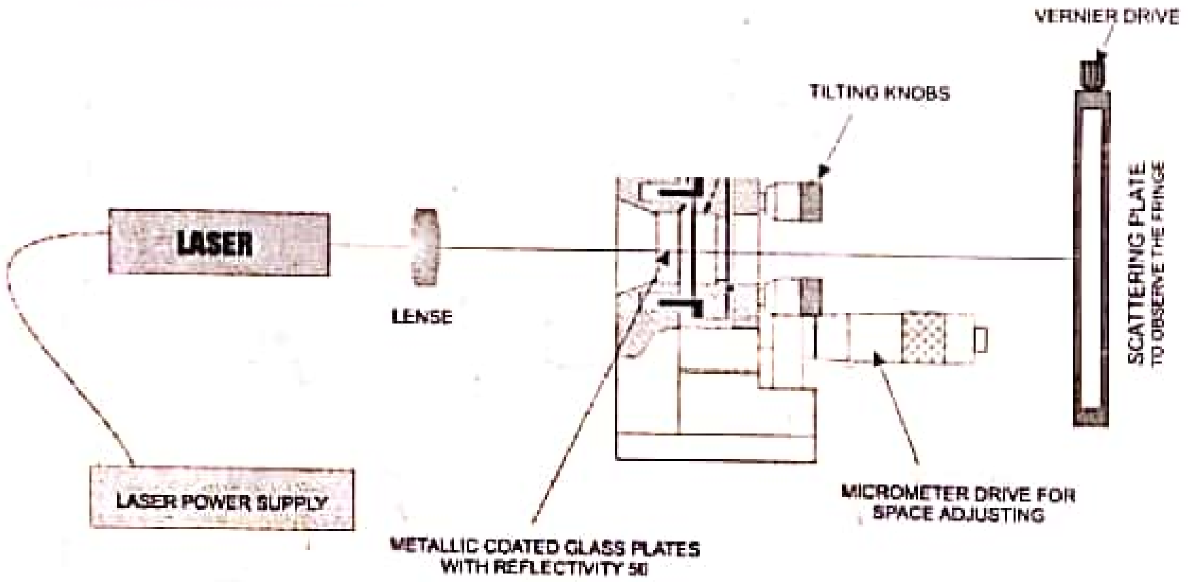


FIG. Experimental arrangement for FP Interferometer.

Note

In actual setup the laser capsule contain a diverging lens this will enough to illuminate the etalon plate.

SPECIFICATIONS

Fabrey-Perot Etalon

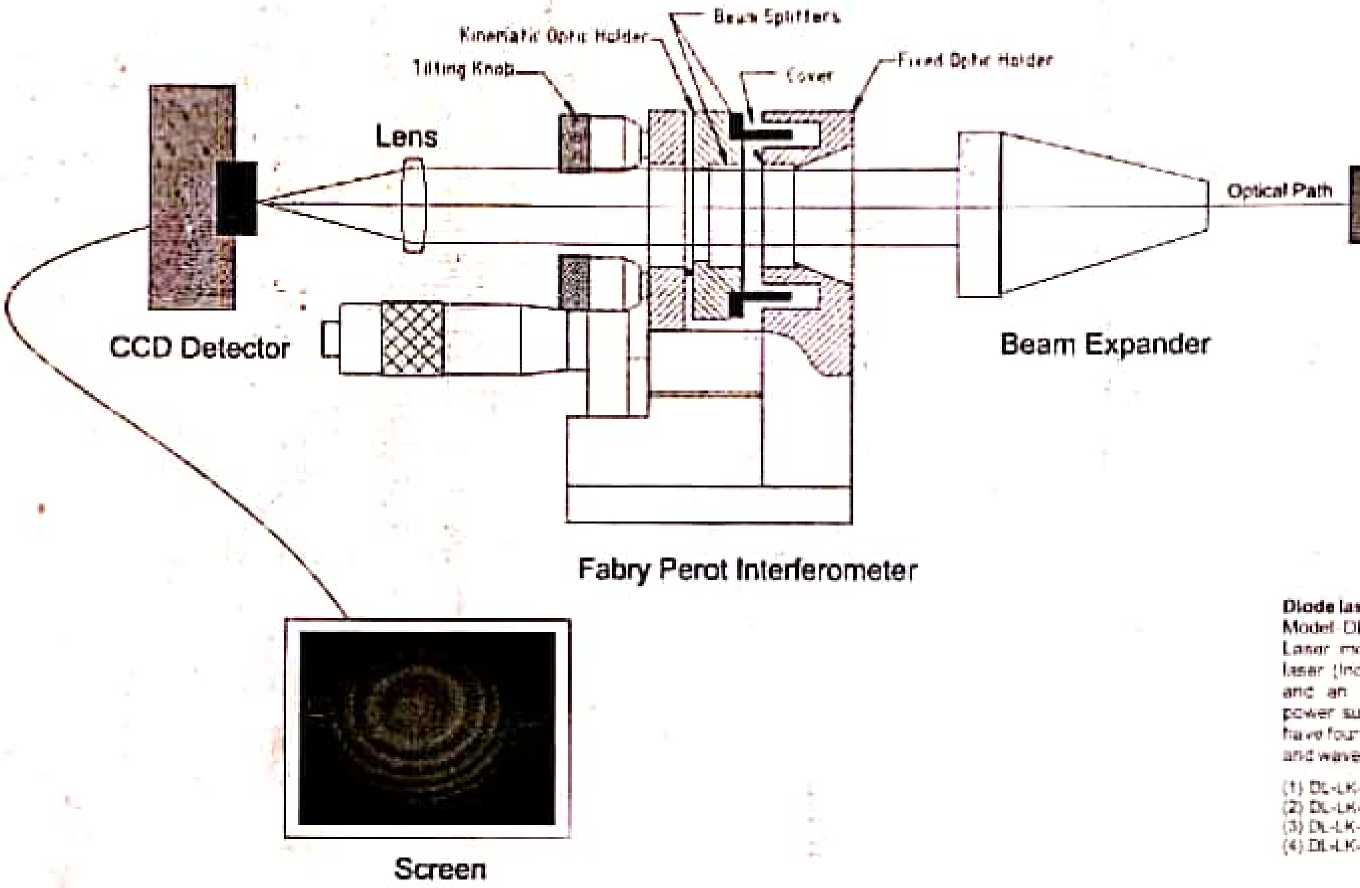
Dia:25mm
Clear aperture:20mm
Thickness:8mm
Surface finish:λ/10
Coatin to give R/T ratio 50/50
Spacer thickness: 0-10mm

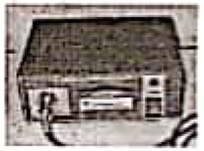
For special application use a clear optical fused silica, which has a very low thermal expansion of 0.55 x 10-6 per °C. Being highly durable and having good resistance to abrasion makes fused silica a good choice for applications that are high in wear and tear.

Experiments possible

- To find the wavelength of laser light.
- To find the air spacing 'd' of etalon
- To compare the quality of laser sorces.
- To find the finesse and free spectral range (FSR) of etalon from the fringe calibration.

Etc.



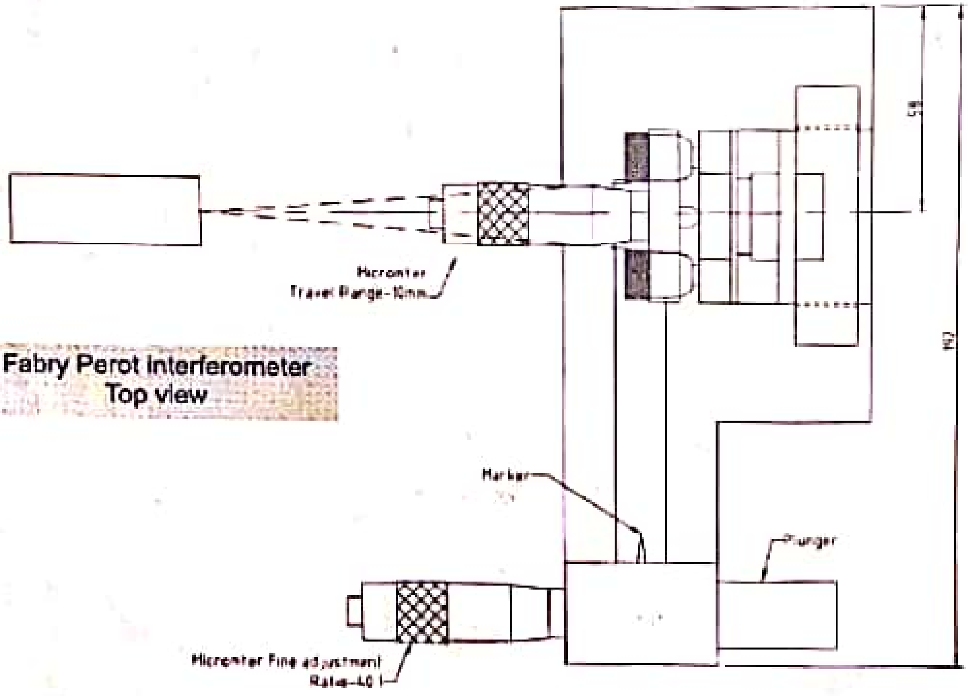


Diode laser with power supply
Model: DL LK
Laser module consists of encased diode laser (Index Guided AlGaInP laser diode) and an adjustable collimating lens. The power supply of diode laser is inbuilt. We have four models depending upon the power and wavelength

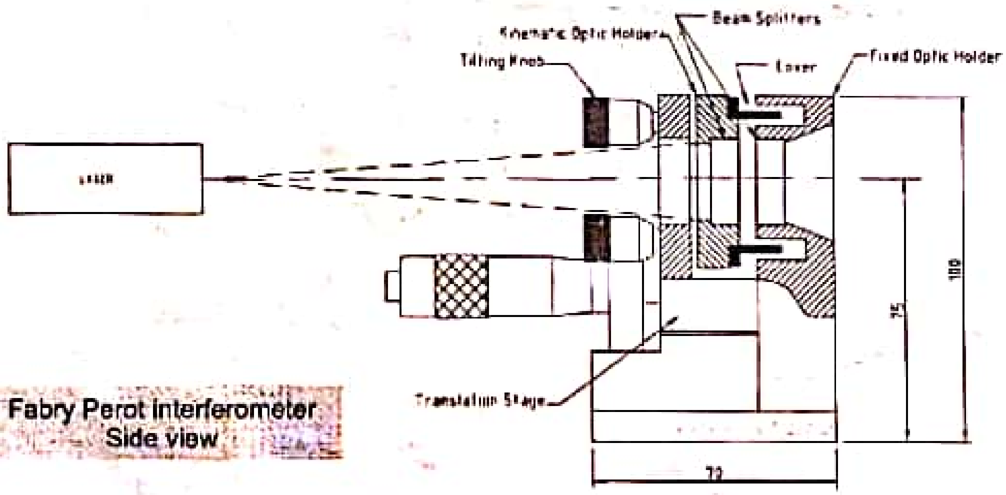
(1) DL-LK-3 [3mW O/P at 635nm wavelength]
(2) DL-LK-5 [5mW O/P at 650nm wavelength]
(3) DL-LK-10 [10mW O/P at 650nm wavelength]
(4) DL-LK-G5 [5mW O/P at 532nm wavelength]

Experimental arrangement for Fabry Perot Interferometer with video o/p
If you want to purchase the computer interfacing unit and software please specify it.

Fabry Perot Interferometer Construction Details



Fabry Perot Interferometer
Top view



Fabry Perot Interferometer
Side view

In the movable mirror mount, it is mounted in a translation stage. The micrometer shaft actuates a lever arm which pushes the translation stage carrying the beam splitter. Here 10 micron on the thimble(one division) is equal to 0.35 micron on the translation stage. Ie when we move one step on the micrometer, beam splitter is moved to 0.35 micron.

From the theory

$M\lambda = 2d\cos\theta$

As θ increses , m decreases and hence the order of the ring dimnishes as their radi increases. Then the integer nearest to 2d/λ will be the order of the fringe system at the center consider the m'th ring

$$M\lambda = 2d\cos\theta_m$$

For successive rings

$$(M+1)\lambda = 2d\cos\theta_m+1$$

$$(M+2)\lambda = 2d\cos\theta_m+2$$

$$(M+3)\lambda = 2d\cos\theta_m+3$$

……………………

So that

$$\lambda = 2d\,[\cos\theta m - \cos\theta_m+1]$$

$$2\lambda = 2d\,[\cos\theta m - \cos\theta m+2]$$

$$3\lambda = 2d\,[\cos\theta m - \cos\theta m+3]$$

……………………

$$n\lambda = 2d\,[\cos\theta m - \cos\theta_m+n]$$

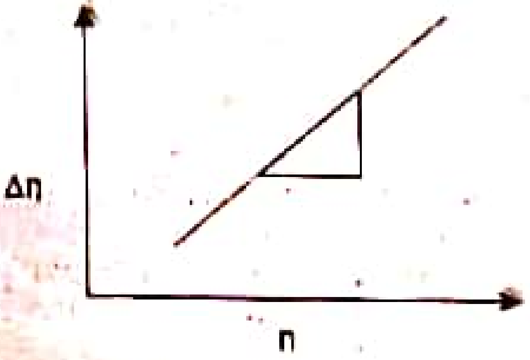
$$n = 2d/\lambda\,[\cos\theta m - \cos\theta_m+n]$$

$$= 2d/\lambda\,(\Delta n) \qquad n=1,2,3........$$

From the above expression

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

Plot n vs Δn. The slope of the straight line graph gives λ/2d



$\tan \theta_m = \chi_m/D$

$\cos^2\theta_m = 1/(1+\tan^2\theta_m)$

When 'D' is large

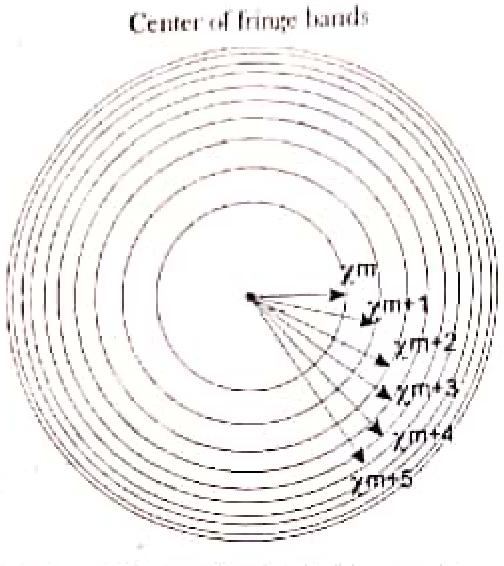
$\theta_m = \chi_m/D$

So,

$\cos^2\theta_m = 1/[1+(\chi_m^2/D^2)]$

$\cos\theta_m = \{1/[1+(\chi_m^2/D^2)]\}^{-1/2}$

$\qquad \simeq 1-(\chi_m^2/2D^2)$



Line drawing of Fabrey Perot fringe pattern

$n = 2d/\lambda\,[1-(\chi_m^2/2D^2) - \{1-(\chi_{m+1}^2/2D^2)\}$

$n = 2d/2D^2\lambda\,[\chi_{m+n}^2 - \chi_m^2]$

$n = d/D^2\lambda\,[\chi_{m+n}^2 - \chi_m^2]$

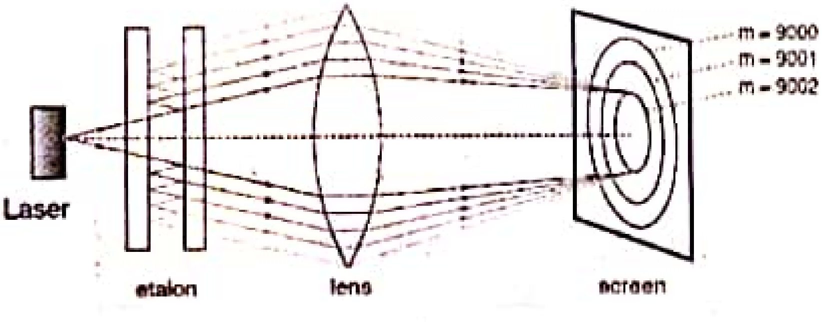
$n = d/D^2\lambda\,[\chi_n^2]$

$\chi_n^2 = \chi_{m+n}^2 - \chi_m^2$

Plot n Vs χ_n^2 is a straight line with the slope $d/D^2\lambda$. From which we can calculate 'd'. Knowing 'd' the order of the center of the fringe can be evaluated as $2d/\lambda$

Free Spectral Range

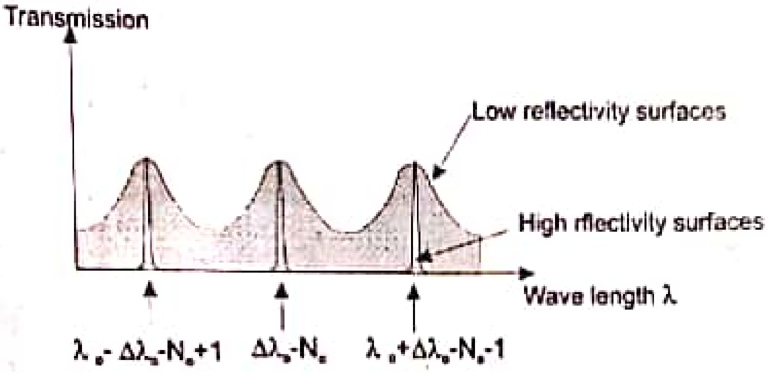
The resolution of a Fabry-Perot plate can be improved by increasing the optical path difference between the two reflecting surfaces. But, doing this, also the interference order is increased, leading to more problems with overlapping orders. As a measure for the useful working range (no overlapping orders) the Free Spectral Range of an instrument is defined.



Then the Free Spectral Range of the Etalon Is given by **FSR = c/2d**

Finesse

It is costumary to define a numerical value which characterizes the width – or better the sharpness – of the maxima. This number is called Finesse of an interferometer and defined as the ratio of peak distance to peak halfwidth.



Fabry-Perot transmission as a function of wavelength

This figure shows how the reflectivity of the surfaces affects the transmission. If the reflectivity is relatively low, the maxima in transmission will be broad. On the other hand, if the reflectivity is high, the maxima of transmission will be very narrow and sharp.

This leads to the concept of the finesse of the interferometer. The finesse is a measure of the interferometer's ability to resolve closely spaced spectral lines. The finesse F is defined by the following Equation.

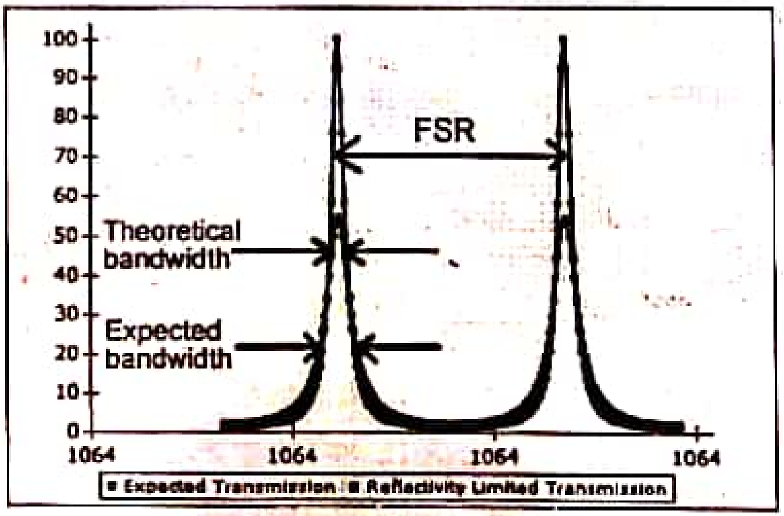
$$F = \frac{\pi\sqrt{R}}{1-R}$$

R = The reflectivity of the surfaces.

As the reflectivity approaches unity, the finesse becomes very high. For high reflectivity, the transmission maxima are narrow, so that the transmission of maxima of slightly different wavelengths can be easily distinguished. Because of this capability, the Fabry-Perot interferometer can be used as a high resolution spectrometer. In fact, the resolving power *RP* is given the equation:

$$RP = NF$$

Where
N = The order of the interference.
F = The finesse.



finesse = FSR / bandwidth

$$FWHM = \frac{2(1-R)}{\sqrt{R}}.$$

Then

$$F = \frac{FSR}{FWHM} = \frac{\pi\sqrt{R}}{1-R}.$$

Contrast

To rate the suppression between maxima, the Contrast is defined as ratio of peak height to the minimum intensity. The transmission minimum at $\delta = \pi$ and at equivalent phases define a Contrast value C of

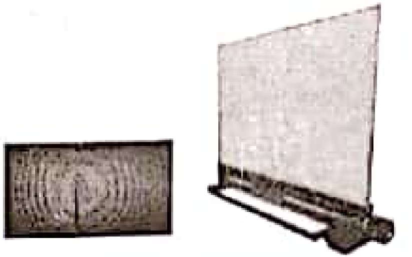
From the eqn. Of finesse

$$F = \frac{\pi}{2}\sqrt{Q_R} = \frac{\pi\sqrt{R}}{1-R}$$

Then

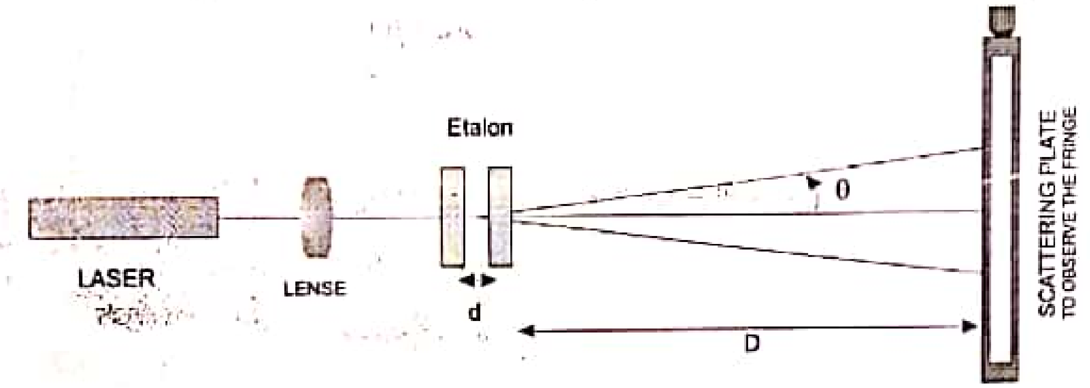
$$C = QR + 1$$

As only the influence of the reflectivity on the linewidth is considered here, often the term Reflectivity Finesse is used to distinguish it from other properties influencing the transfer function



Scattering plate with measuring pointer

Calculations



χ_m =

χ_{m+1} =

χ_{m+2} =

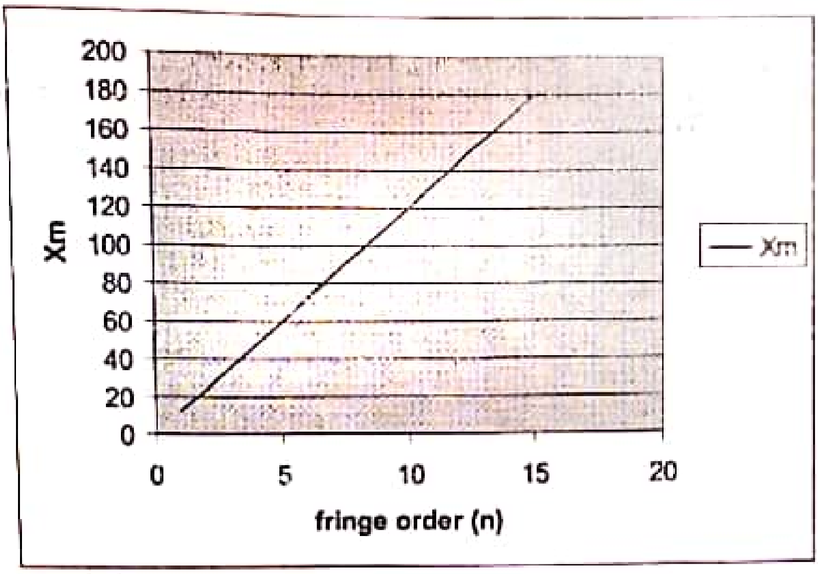
χ_{m+3} =

χ_{m+4} =

χ_{m+5} =

No.	$\chi_n^2 = \chi_{m+n}^2 - \chi_m^2$ (m^2)	D (m)	$d = nD^2\lambda/\chi_n^2$ (mm)

Mean 'd' =



Plot the graph n Vs χ_m We can find 'd'

$d = nD^2\lambda/\chi_n^2$

$d/D^2\lambda = 1/\text{slope}$

$d = D^2\lambda/\text{slope}$

R = mirror reflectivity (fraction of unity)
N = refractive index of cavity
d = distance between mirror surfaces (cavity gap)
c = speed of light
λ = wavelength

Result

The wavelength of laser light λ = ...nm

The spcing of etalon is d = ...mm

Finesse of the given etalon is *F* = ...

Free Spectral Range of the Etalon is given by

FSR = c/2d

FSR = ... in Hz

Free Spectral Range (FSR) = **1/2nd** In wavenumbers
Free Spectral Range (FSR) = **c/2nd** in frquency
Free Spectral Range (FSR) = **λ^2/2nd** In wavelength

The Gouy's method is used to determine the magnetic susceptibility of diamagnetic or paramagnetic substances in the form of powder or a solid. When an object is placed in a magnetic field, a magnetic moment is induced in it. Magnetic susceptibility χ is the ratio of the magnetization, I (magnetic moment per unit volume) to the applied magnetizing field intensity H. The magnetic moment can be measured either by force methods, which involve the measurement of the force exerted on the sample by an inhomogeneous magnetic field or induction methods where the voltage induced in an electrical circuit is measured by varying magnetic moment. The Gouy's method like the Quincke's method belongs to the former class. The force f on the sample is negative of the gradient of the change in energy density when the sample is placed,

$$f = \frac{d}{dx}\left[\frac{1}{2}\mu_0\left(\mu_r - \mu_{ra}\right)H^2\right] = \frac{1}{2}\mu_0\left(\chi - \chi_a\right)\frac{d}{dx}H^2 \qquad (1)$$

Here μ_0 is permeability of the free space and μ_r and μ_{ra} are respectively relative permeability of the specimen and the air which the specimen displaces. The specimen is in the form of a long cylinder or strip of length l and cross sectional area A. It is placed such that its lower end is between the pole pieces of the magnet and the upper end is outside the magnetizing field. The force acting on an element of area A and length dx of the sample is $fAdx$, so the total force F is

$$F = A\int f dx = \frac{A\mu_0}{2}\left(\chi - \chi_a\right)\left(H^2 - H_0^2\right) \qquad (2)$$

where the integral is taken over the whole specimen. This means that H is equal to the field at the end of the specimen between the poles of the magnet and H_0 is the field at the other end away from the magnet. This force leads to an apparent change in the weight of the specimen. We get

$$F = \Delta m\, g$$

Or

$$\chi = \chi_a + \frac{2}{\mu_0 A} g \frac{\Delta m}{\left(H^2 - H_0^2\right)} \qquad (3)$$

In actual practice χ_a is negligible and can be ignored. If the length of the specimen is so large that its upper end is outside the magnetic field created by the electromagnet, H_0 may be taken to be equal to zero. The above expression then simplifies to

$$\chi = \frac{2g}{\mu_0 A}\left(\frac{\Delta m}{H^2}\right) \qquad (4)$$

The length of the specimen that meets this condition is determined by experimental measurements. Note that Δm under this condition does not depend on the length l of the specimen. The susceptibility χ (called the volume susceptibility) can be determined from Eqs.3 or 4. It is a dimensionless quantity. This expression is in S.I. units in which $g, A, \Delta m$ and H are measured in m/s ^{2}, m ^{2}, kg and amp.turn/m respectively.

In C.G.S. units, Eq.(3) is

$$\chi = \chi_a + \frac{2}{A} g \frac{\Delta m}{\left(H^2 - H_0^2\right)} \qquad (5)$$

where $g, A, \Delta m$ and H are measured in cm/s ^{2}, cm ^{2}, mg and gauss respectively.

BRIEF DESCRITION OF THE APPARATUS

(a) Scientific Balance, KSB-07

Capacity	:	200 gms
Sensitivity	:	1/10 mg. by vernier
Beam	:	Hard Bronze/ Brass
Arrestment	:	Circular, falling away type
Air Damping	:	Very quick and positive, beam coming to rest in 2-3 sec
Chainomatic Device	:	A gold plated chain is suspended from the beam with its other end screwed on the rotating drum on which a scale graduated from 0 to 100 div each division representing 1mg is installed. By the movement of this scale before a vernier, reading upto 1/10th mg is taken. Thus the weight upto 100mg could be read from the dial directly with a resolution of 0.1mg.

(b) Sample in the form of a long rod:

Aluminium Rod

(c) Electromagnet, Model EMU-75T / 50T

Electromagnet, Model EMU-75T

Pole Peices	:	75mm tappered to 25mm
Mag. Field	:	17.5KG at 10mm airgap
Energising Coils	:	Two of approx. 13Ω each
Power	:	0-90Vdc, 3A, for coils in series 0-45Vdc, 6A, for coils in parallel

Electromagnet, Model EMU-50T

Pole Peices	:	50mm tappered to 20mm
Mag. Field	:	9.5KG at 10mm airgap
Energising Coils	:	Two of approx. 3Ω each
Power	:	0-30Vdc, 4A, for coils in series

EXPERIMENTAL SET UP

A schematic diagram of Gouy's set up is shown in Fig.1. The specimen in the form of a long cylinder or strip or filled in a long non-magnetic tube is suspended freely from the pan of a sensitive balance such that its lower end is between the pole pieces of the electromagnet but without touching them. A length (about 7 – 12 cm) of the specimen is sufficient enough to keep the upper end of the specimen well outside the field of the magnet. This is determined by preliminary experimental study. In this study the change in weight Δm on applying the field is measured for specimens of increasing lengths in steps of (say) 2 cm until Δm becomes steady. This is then repeated for several values of H. The maximum of these is the specimen length for which $H_0 = 0$. The widths of the specimen and the air gap of the electromagnet are adjusted to maximize the force on the specimen The change in the weight of the specimen due to the force on it on applying the magnetic field is measured by a sensitive balance of least count of order 10^{-3} gm.

Experimental Procedure

1. Test and ensure that each unit (Electromagnet and Power Supply) is functioning properly.
2. Level the balance with the help of leveling screws.
3. Suspend the specimen from the pan of the balance and make adjustments such that its lower end is centrally and symmetrically between the pole pieces of the electromagnet without touching them.
4. Note volume V of the specimen and measure its weight m.
5. Apply the magnetic field H and note its value from the calibration, which is done earlier as an auxiliary experiment. Note whether there is an apparent increase in weight or decrease. It increases for paramagnetic substances while decreases for diamagnetic ones. Again measure the weight. The difference of these two readings gives Δm for the field H.
6. Measure the apparent change Δm in weight as a function of applied field H by changing the magnet current in small steps. Plot a graph of Δm as a function of H^2

Results

The mass susceptibility χ' is given by χ/ρ and the molar susceptibility χ'' by $M\chi'$ where ρ is the density and M the molecular weight of the specimen.

In a paramagnetic substance there are non-interacting permanent magnetic dipoles. The magnetizing field tends to align these parallel to the field. Thermal effects on the other hand tend to destroy this alignment. The result is that the volume susceptibility χ at any temperature T is given by

$$\chi = \frac{I}{H} = \frac{N\mu_0 (p\mu_B)^2}{3kT} \qquad (6)$$

where k is Boltzmann constant, N (= $\rho N_A/M$) is the number of ions per unit volume, μ_B is Bohr magneton and N_A is Avogadro's number. p is the magneton number which may be calculated from the measured value of χ and compared with the theoretical value depending on L, S and J of the magnetic ion as given in *Appendix II.*

RECORD OF OBSERVATION

Some constants and conversion factors:

Boltzmann constant k	1.381×10^{-23} Joule/°K
Avogadro's number N_A	6.0225×10^{26} per kg mole
Bohr magneton μ_B	9.272×10^{-24} A-m^2
Permeability of free space μ_0	$4\pi \times 10^{-7}$
1 amp.turn/m	$4\pi \times 10^{-3}$ gauss

TYPICAL OBSERVATIONS

Material: Aluminium Rod

Width = 10 mm

Length = 120 mm

Thickness of the Rod = 2 mm

Weight of the Rod = 6.50 gms

Density of Aluminium = 2.7gm/cc

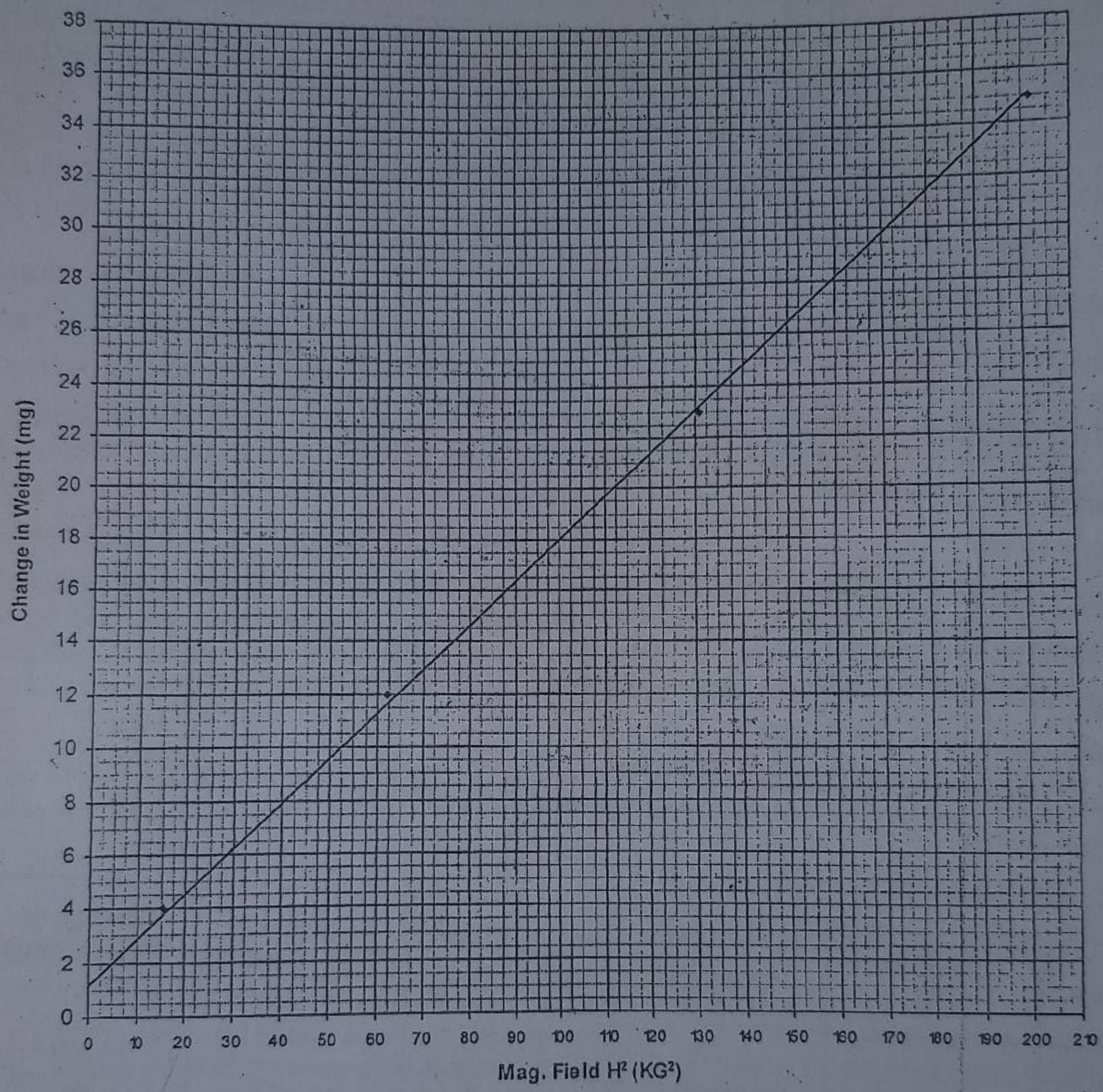
Area (A) = $2 \times 10 \times 10^{-2} = 0.2$ cm^2

g = 980 cm/sec^2

Molecular Weight of Al = 27

S.No.	Current (A)	Measured Mag. Field H (KG)	Mag. Field H^2	Measured Weight (gm)	Change in Weight (mg)
1.	0	0.370	0.137	12.830	0
2.	1.00	3.920	15.370	12.834	4
3.	2.00	7.890	62.250	12.842	12
4.	3.00	11.440	130.870	12.853	23
5.	4.00	14.190	201.350	12.865	35

Susceptibility Graph for Aluminium Sample



ALCULATIONS

$$\chi_{(Vol)} = \frac{2g}{A}\left(\frac{\Delta m}{H^2}\right) \qquad (6)$$

0.07

0.01

$\frac{1.69 \times 10^{-6} \times 2 \times 980}{0.2}$

rom graph

$$\frac{\Delta m}{H^2} = \frac{(34.0-4.0)\times10^{-3}}{(195-15.0)\times10^{6}} = 0.167\text{x}10^{-9}$$

χ' 1.32

$$\chi_{(Vol)} = \frac{2\times980\times0.167\times10^{-9}}{0.2} = 0.167\times10^{-6}$$

$$\chi'_{(mass)} = \frac{\chi}{\rho} = \frac{1.637\times10^{-6}}{2.7} = 0.606\times10^{-6}$$

$$\chi''_{(Mol)} = \chi' \times \text{Molecular weight of Al.}$$

$$= 0.606\times10^{-6}\times27$$

$$= 16.3\times10^{-6}\ \text{cm}^3$$

0.016562

×10

RESULTS

Measured Value of molar susceptibility χ'' of Aluminium is 16.3×10^{-6} cm^3

Internationally accepted value of χ'' of Aluminium is 16.5×10^{-6} cm^3.

PACKING

1) Scientific Balance, KSB-07/ 08
2) Aluminium Rod Sample
3) Electromagnet, Model EMU-75T/ EMU-50T
4) Constant Current Power Supply, DPS-175/ DPS-50
5) Digital Gaussmeter, DGM-102/ DGM-202
6) Users Manual

ENDIX I

iary Experiment

t:

t a graph of magnetic field H as a function of the magnetizing current.

dure:

Fix the air gap between the pole pieces of the electromagnet to the minimum distance required to freely suspend the sample containing tube without touching the pole pieces.

Measure the air gap. Each time the air gap changes, the graph will change.

Mount the Hall probe of the Digital Gaussmeter, DGM-102 in the wooden stand provided and place it at the centre of the air gap such that the surface of the probe is parallel to the pole pieces. The small black crystal in the probe is its transducer, so this part should be at the centre of the air gap.

Connect the leads of the electromagnet to the Power Supply, bring the current potentiometer of the Power Supply to the minimum. Switch on the Power Supply and the Gaussmeter.

Slowly raise the current in the Power Supply and note the magnetic field reading in the Gaussmeter.

Plot the graph between the current and the magnetic field. This graph will be linear for small values of the current and then the slope will decrease as magnetic saturation occurs in the material of the pole pieces.

ult:

e performing the Gouy's experiment, if the air gap is kept same as in the above experiment, an determine the magnetic field at any specific current, just by looking at the graph. Note may also be some magnetic hysteresis present and for a given current, the field may be tly different, depending on whether the current is increasing or decreasing.

Object. *Determination of magnetic susceptibility of a specimen by (i) Gouy's method. (ii) Quincke's method and to study the temperature variations of magnetic susceptibility and infer the results arrived at.*

Basic. Moving charges give rise to magnetic moments and such charges are associated with all matter and responsible for macroscopic or microscopic magnetic properties of it. However presently we aim at determining magnetic volume susceptibility of a specimen experimentally where it is defined as the ratio of intensity of magnetisation I to the applied magnetic field H, *i.e.*,

$$k = I/H \qquad \ldots(15.1)$$

Gouy's Method. In Gouy's method the magnetic volume susceptibility k is determined by relation

$$k = \frac{2g}{A} \cdot \left(\frac{m}{H^2}\right) \qquad \ldots(15.2)$$

where g is acceleration due to gravity at a place with sea level value 981 cm. sec^{-2}; m is mass in gm which corresponds to the magnetic force, *i.e.*, mg is the magnetic force in a magnetic field of intensity H gauss; and $A = \pi r^2$ is the area of cross-section of the Gouy tube with r cm as its radius. The value of H is calculated by the following relation in case of moving coil fluxmeter calibrated by means of a standard solenoid, the details of which are given in Experiment (A. I)

$$H = \frac{4\pi NN' \alpha}{10 A'} \cdot I' \qquad \ldots(15.3)$$

where N is the number of turns per cm on primary and calculated by dividing the total number of turns on the primary of the solenoid by its length in cm; N' is the number of turns in the secondary ; $\alpha = \pi R^2$ is the area of cross-section of secondary with R as its radius in cm ; A' is the effective area of search coil and determined as the product of area of cross-section of a turn and the number of turns on it, *i.e.*, $A' = \pi r'^2 n$ with r' cm as the radius of search-coil of turns n ; and I' is the current in amperes corresponding to unknown field and read from a graph plotted between the current through the primary of the solenoid and deflection of the galvanometer.

If ρ be the relative density of the specimen, then the mass susceptibility K' is calculated by relation

$$K' = k/\rho \qquad \ldots(15.4)$$

where k is given by (15.2). If M be the molecular weight of the specimen, then molar susceptibility K" is given by relation

$$K'' = K'.M \qquad \ldots(15.5)$$

where K' is given by (15.4). In case of paramagnetics the product of temperature of the specimen in °K and K" is constant and known as Curie constant C, *i.e.*,

$$C = K''.T. \qquad \ldots(15.6)$$

However the value of Curie constant for the specimen is related with magnetic moment μ of dipole of the specimen by relation

$$\mu = 2.8241 \sqrt{(K''\, T)} = 2.8241 \sqrt{C} \qquad \ldots(15.7)$$

where μ is expressed in Bohr magneton μ_B of C.G.S. value 0.927×10^{-20} erg. gauss^{-1}. The value of magnetic moment μ as given by (15.7) is used to find the number of unpaired electrons n in the molecule contributing magnetic moment by following quantum mechanical relation

$$\mu = \sqrt{\{n\,(n+2)\}} \qquad \ldots(15.8)$$

Above relations show that in Gouy's method the magnetic force on the specimen is directly measured by a sensitive chemical balance in terms of weight mg. If the force is attractive the specimen is paramagnetic and diamagnetic in case of repulsive force. The other prime determinations are the determination of H [Expt. (A-1)] and relative density ρ. However for known values of g, A and H of the order of kilo-gauss, the order of m is milli-gramme since the order of K is 10^{-6} in case of usual paramagnetic and diamagnetic substances.

Potential energy $U = -\vec{\mu}\cdot\vec{B}$

Where μ = magnetic dipole moment

Energy $E = -\vec{\mu}\cdot\vec{H}$ (attractive)

$$F = -\vec{\nabla}(-\vec{\mu}\cdot\vec{H}) \quad \text{(attractive)}$$

$$= \vec{\nabla}(\vec{\mu}\cdot\vec{H}) \quad \text{(Non-uniform field)}$$

Force $F = -\frac{dU}{dz}$

$\therefore F = \mu \frac{\partial H}{\partial z}$ ($\because \mu$ = constant)

Magnetization $\vec{M} = \frac{\vec{\mu}}{V} = \frac{\mu}{V}$, V = volume

Susceptibility $\chi = \frac{M}{H} = \frac{\mu}{VH}$

$\Rightarrow$

$$\mu = \chi V H$$

$$\therefore F = \chi V H \frac{\partial H}{\partial z}$$

$$= \frac{1}{2}\chi V . \frac{\partial (H^2)}{\partial z}$$

Force is balanced by the

Here $\frac{1}{2}\chi V \frac{\partial H^2}{\partial z} = mg$ (weight of the bar)

Now, $V = A . dz$

$$\therefore \frac{1}{2}\chi A dz . \frac{\partial H^2}{\partial z} = mg$$

$$\Rightarrow \frac{1}{2}\chi A dH^2 = mg$$

$$\therefore \chi = \frac{2mg}{A dH^2} = \frac{2g}{A}\cdot\left(\frac{m}{H^2}\right)$$

$$\Delta m = \frac{\chi A H^2}{2g}$$

Experimental set up. The experimental set up with Gouy's tube G is shown in Fig. (15.1). The tube G is made of glass tube of suitable uniform bore with a central partition. It is provided with hooks to suspend it to an arm of a sensitive chemical balance, preferably a semi-micro balance. The upper half of the tube G is filled with the specimen material and suspended vertically such that the central partition lies exactly symmetrically within the pole-pieces of an electromagnet shown as N-S. The diameter of the tube depends upon the availability of the specimen; however diameter lies between 0.1 to 1 cm. The length of the tube is sufficient as to have the magnetic field practically zero at the extremities of the tube. However tube lengths between 20 to 30 cm are usual. Further the pole-pieces NS are shaped by manufactures to provide a sharp gradient of magnetic field in the vertical direction and they are kept as close as possible. BB' is a power pack to feed current to the electromagnet coils shown as (1, 2), (1', 2') with series ammeter A and switch. The voltage of BB' is varied by a variac and measured by the voltmeter V. However the same power pack is seriesed with the primary PP of a standard solenoid, tapping key T and ammeter A'. The secondary S' of solenoid is seriesed with the search coil S" and fluxmeter F, a moving coil ballistic galvanometer. The circuit with standard solenoid is used to calibrate the deflection of a galvanometer in terms of magnetic field. However Hall probe fluxmeter, which employs the Hall voltage developed in magnetic field for a definite current and a crystal of semi-conductor, may be used for measurement of magnetic field. The details of such measurements may be seen in Expt. A-1 and Expt. 14. The Gouy tube itself is used to determine the relative density ρ of the specimen.

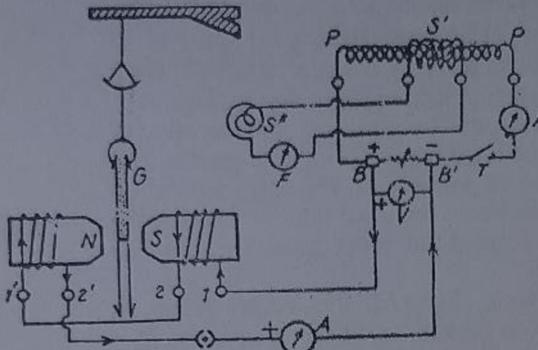


Fig. 15.1

Experimental Procedure. Set up the experiment as described above and ensure that each part is functioning properly. Suspend the empty Gouy tube with the arm of the balance; weigh it and record the reading. Keep the power pack off. Fill the half part of the tube with distilled water and weigh it. Find the weight difference of two readings. It gives the mass M of the water filling the half part of the tube. Empty the tube, dry it, refill it with the specimen and weigh it. Find the mass M' of the specimen filling the half tube. Divide M' by M to get the relative density of the specimen, *i.e.*,

$$\rho = M' / M \qquad \ldots(15.9)$$

Calibration of fluxmeter. Adjust the separation of the pole pieces for the tube and maintain it. As a first part calibrate the fluxmeter coil deflection to give directly the value H. For this switch off key, press T, adjust current I ampere to a low value in A, release T and note the deflection θ. Repeat for other increasing values of I and plot (I α θ) straight line passing through origin. Note effective area of search coil A', number of turns N per cm on primary PP, number of secondary turns N', area of cross section of secondary turn α. Record allied observations in tabular form and calculate constant (4π NN'α / 10 A') occurring in relation (15.3). Now keep T off, switch on key, pass a known current through the coils of electromagnet and note its value in ammeter A, keep the search coil S" within pole pieces centrally and with its face area normal to the lines of forces, remove it suddenly from within the pole pieces, note the deflection θ' of the fluxmeter coil, read current I' corresponding to θ' from (I α θ) plot and substitute I' in place of I in relation (15.3) and calculate the value of H. Repeat for other values of current readings given by ammeter A and calculate H for each reading of A. However a graph plotted between the readings of A and corresponding values of H, calibrate ammeter A readings to give value of H well within the pole-pieces for a particular separation of pole-pieces. The calibration changes with the separation of pole-pieces. The usual separation is about 1 cm. This also affords one to know the usual limit of H provided by the particular magnet. However calibrated Hall probe fluxmeters are also available.

Measurement of magnetic force. Suspend the empty tube as already described, weigh the tube, switch on key, adjust current in A to give maximum value of H and ensure that there is no change in the balance condition of the chemical balance. If there is any change, it is either due to improper setting of tube or its asymmetrical construction. Now fill the half part of the tube with the specimen (liquid, solution or powder). The solid specimen is taken in the form of a rod of uniform area of cross-section and length nearly equal to half the tube length (10-15 cm) and it is suspended to the arm of the balance with its lowest end occupying the position of central partition. Weigh the specimen, switch on key, adjust current in ammeter A to a value and note magnetic field H corresponding to it from the calibration curve, note whether the weight of the specimen has increased or decreased in the applied magnetic field, change weights on the other pan to get the balance and note the difference in the initial and final readigs as m, note the area of cross-section of the Gouy tube A as usual, tabulate readings systematically, substitute the values of g, m, A and H in proper units in relation (15.2) and calculate the value of K in C. G. S. units in order 10^{-6}. If weight in magnetic field increases the substance in paramagnetic and diamagnetic if there is decrease in the weight. Repeat for other values of H and obtain mean value of K. However a graph plotted between m and H^2 gives a straight line and the value of (m/H^2) may be calculated as its slope. Note the temperature of the specimen and convert it into absolute degrees. Express K in dynes. cm^{-2} $gauss^{-2}$ at a particular temperature. Calculate mass susceptibility by relation (15.4) and molar susceptibility by relation (15.5). If the substance is paramagnetic, then calculate Curie constant C by selation (15.6) and subsequently magnetic moment μ of the molecular magnet of the specimen and number of unpaired electrons n by relations (15.7) and (15.8) respectively. Tabulate readings and findings systematically and interpret them theoretically. In calculations the susceptibility of air has been ignored.

Record of Observations :

[A] Specifications of the specimen used :

(1) Name of the specimen......
(2) Molecular weight of the specimen M = ...
(3) Temperature of specimen = ...°C =...°K.

[B] Specifications of the Gouy tube used :

(1) Semilength of the tube = ... cm.
(2) Inner diameter of the tube = ...cm.
Radius r = ,..cm.
Area of cross-section $A = \pi r^2 = ...cm^2$
(3) Local value of $g = ...cm.sec^{-2}$.

[C] Specifications of standard solenoid and search coil or any other magnetic field measuring device.

(1) Number of primary turns per cm N = ...
(2) Number of secondary turns N' =...
(3) Mean diameter of secodnary =...cm
Radius = ...cm
Area of cross-section = $...cm^2$
(4) Mean area of search coil A' = $...cm^2$
(5) Constant $C = 4\pi NN'\alpha / 10A'$ = ...

Note. Use tables 2 and 3 of Expt. (14) as tables 1 and 2 to record observations to determine magnetic field H.

Table 3. **Measurement of ρ.**

S. No.	Wt. of empty tube (a)	Wt. of tube filled with distilled water (b)	Wt. of tube filled with specimen (c)	$\rho = \frac{c - a}{b - a}$
[illegible]	...gm	...gm.	...gm.	

Table 4. **Measurement of (m α H) and tabulation of m/H^2.**

S. No.	H	H^2	Difference in wt.			m/H^2	Remark
			wt. in H = 0	wt. in H	Difference m		
[illegible]	...G	...G^2	...gm	.. gm	...gm	...gm. G^{-2}	...

Note. m is usually of order of milli gm.

Substitute values in relations used as per description and calculate K, K', K", C, μ and n. Note down their standard values and calculate errors by using (E. 1) and (E. 3) of page 4. Now comment on experiment and note down sources of errors, precautions and findings.

Results :

Magnetic volume susceptibility $K \times 10^{-6}$	Mass susceptibility $K' = K/\rho$ $\times 10^{-6}$	Molar susceptibility $K'' = K' M$ $\times 10^{-6}$	Curie constant $C = K''T$	Magnetic moment $\mu = 2.8241 \sqrt{C}$	No. of unpaired electrons $\mu = \sqrt{n(n+2)}$
.....dynes. cm^{-2}. G^{-2}	......	......	......	...μ_B	......

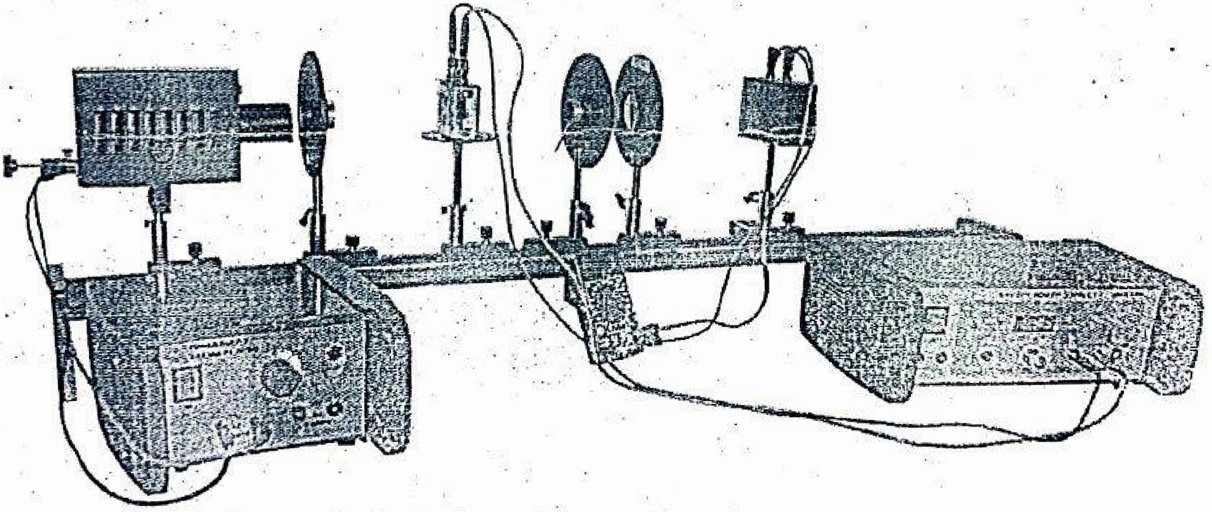
Note. Convert CGS units to MKS units, by using
10^5 dynes = 1 Newton
10^2 cm = 1 metre (1m)
10^4 G = 1 weber / metre^2 (1 W/m^2)
It gives : dynes. cm^{-2}. G^{-2} = $(Nm^2 / W^2) \times 10^5$.

Asish

INDOSAW
COMMITTED TO EXCELLENCE

Instruction Manual

KERR EFFECT
SK019



Note: Apply 3-4 kV at electrode for min. 2 hours to prepare the nitrobenzene for experiment.

OSAW INDUSTRIAL PRODUCTS PVT. LTD.

P.O. Box No. 42, OSAW Complex, Jagadhri Road
Ambala Cantt - 133001 (Haryana) INDIA
E-mail : deducation@indosaw.com
E-mail : qc1@indosaw.com

Phone : +91-171-2699347, 2699267
Fax : +91-171-2699102, 2699222
Website : www.Indosawedu.com
New Delhi, Phone : 011-46525029

An ISO 9001 :2008
Certified Company

OBJECTIVE: Demonstration of Kerr-Effect and determination of Kerr Constant using Nitrobenzene, an electro-optic substance.

APPARATUS:

S. No.	Item Name	Qty.
1.	Kerr Cell	1
2.	Prism Table	1
3.	Electrode Arrangement	1
4.	Halogen lamp, 12 V / 50 W	1
5.	Halogen lamp housing	1
6.	Monochromatic filter, blue (490nm)	1
7.	Lens in frame f = +100 mm	1
8.	Polarization filters	2
9.	Fixed Saddle	5
10.	Transverse saddle	1
11.	Optical Bench, 1 m	1
12.	Power Supply 2-12V, 5Amp for Halogen Lamp	1
13.	Power Supply 0-5kV, 2mA DC	1
14.	Silicon Photodetector	1
15.	Pair cables 100 cm, Red/Black	1
16.	Pair cables 100 cm, Yellow	1
17.	Digital multimeter	1
18.	Pair cables 50 cm, Red/Black	1

Note. Nitrobenzene not supplied with the setup, user to make own arrangement. Apply 3-4 kV at electrode terminals for 2 hours to prepare the nitrobenzene.

PRECAUTION :

1. Use a fume hood.
2. Avoid skin and eye contact.
3. Avoid inhalation or ingestion of the liquid.
4. Keep away from heat and naked flames.
5. Keep away from oxidizing materials.
6. Keep away from combustible substances.
7. Keep away from reducing agents.
8. Keep the container tightly sealed.
9. Wash hands throughly after handling.

WARNING!

- Handle the Kerr Cell very carefully.
- Do not increase high voltage power supply 0-5kV, 2mA for Kerr Cell beyond 4.5kV during experiment. This may damage the Kerr-Cell.

REMARKS:

- We recommend to use NICE make Nitrobenzene for better result (Assay (GLC) 99% min, Wt. per ml at 20°C: 1.200-1.204g, Freezing Point: 5-6°C, Boiling Range (95%): 208-212°C, Water: 0.5% max.)

PRINCIPAL:

Kerr Cell : It is a glass cell, containing two electrodes and filled with polar liquid like nitrobenzene. It is kept between two linear polarizers whose transmission axis are kept at ±45° to the applied electric field. With zero voltage across the plates, no light passes and the shutter is closed. The application of the modulating voltage generates an electric field under which the Kerr Cell act as a wave plate and thus opening the shutter.

INTRODUCTION:

John Kerr in 1875 discovered that if we place certain materials in a strong electric field, it becomes doubly refracting. Such an effect is named as Kerr electro-optic effect. Such an effect is limited to a region of very high electric field or for certain materials placed in small electric field. This effect is due to the rotation and reorientation of material's lattice at molecular level. Kerr-effect also takes place in a gas, liquid and solid state. Kerr coefficient of the material has been used to know the extent up to which Kerr effect quantitatively takes place. Kerr effect is used to study different properties of a material. The fast response of the molecular reorientation makes the Kerr electro-optic effect significant for use in a quick optical shutter or gate.

KERR ELECTRO-OPTIC EFFECT:

The Kerr electro-optic effect, or DC Kerr effect, is the special case in which the electric field is a slowly varying external field, for instance, a voltage applied by on electrodes across the material.

Under the influence of the applied field, the material becomes bi-refringent, with different indexes of refraction for light polarized parallel to and perpendicular to the applied field. The difference in index of refraction, Δn, is given by

$$n_e - n_o = \Delta n = \lambda K E^2 \qquad \text{.......................(1)}$$

Because normal refractive index of material without an electric field is modified by applying electric field in the parallel oscillation direction to the extraordinary refractive index n_e and in the perpendicular oscillation direction to the ordinary refractive index n_o. The two indices have the above relationship.
where λ is the wavelength of the light, K is the Kerr constant, and E is the amplitude of the electric field. This difference in index of refraction causes the material to act like a waveplate when light is incident on it in a direction perpendicular to the electric field. If the material is placed between two "crossed" (perpendicular) linear polarizers, no light will be transmitted when the electric field is turned off, while nearly all of the light will be transmitted for some optimum value of the electric field. Higher values of the Kerr constant allow complete transmission to be achieved with a smaller applied electric field.

Some polar liquids, such as nitrobenzene ($C_6H_5NO_2$) and nitrotoluene ($C_7H_7NO_2$) exhibit very large Kerr constants. A glass cell filled with one of these liquids is called a Kerr cell.

As we said earlier, when the electric field is on, the liquid becomes doubly refracting and the light is restored. With the cell oriented at 45°, the incident plane vibrations from the polarizer are broken up into two equal components parallel and perpendicular to the field,. These travel with different speeds, and hence a phase difference is introduced and the light emerges as elliptically polarized light. This phase difference between the two rays is given by

$$\varphi = \frac{2\pi}{\lambda}(\textit{path difference}) = \frac{2\pi}{\lambda}(\Delta n) \times \ell \qquad \text{.......................(2)}$$

$\because$ path in air = R . I X path in medium

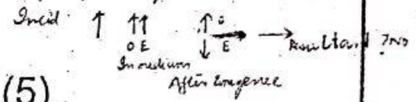
where ℓ is the length of the light pathin-electro-optic substance. It is basically equal to the length of each electrode.
Combining, equations (1) and (2), we obtain,

$$\Phi = 2\pi K E^2 \ell \quad \text{.......................(3)}$$

If, the voltage applied between the two plates of the electrodes is U and d is the separation between the two plates of the electrodes, then, substituting, this value for E in equation (3), we can obtain,

$$K = \frac{\Phi d^2}{2\pi U^2 \ell} \quad \text{.......................(4)}$$

Now, if the two rays (parallel and perpendicular to the electric field) are separated by a path distance of λ/2, then the phase difference between the two rays will be π because with the half wave voltage. Where the phase difference just reaches a half wave length (ie $\varphi = \pi$) the kerr cell behave like λ/2 plate i.e polarisation plane is turned by 90° so using eq^n.4.



$$K = \frac{d^2}{2U^2 \ell} \quad \text{.......................(5)}$$

In this case, the intensity of the light passing through the analyzer will be at maximum. If the light, emerging from analyzer, illuminates a photodiode, which is kept behind the analyzer, maximum voltage will be produced across the two terminals of the photodiode, for the above condition (Condition of maximum illumination). Let, the voltage required for this maximum illumination be V. That is, when U = V , then, . Substituting, U = V , then, , in equation (4), we can obtain,

$$K = \frac{d^2}{2V^2 \ell} \quad \text{.......................(6)}$$

The Voltage V is called the half-wave voltage.

As, we noted earlier, K is the Kerr constant for the medium. The unit of K is meterVolt^{-2}. The values of K depend on the medium and about 2.4×10^{-12} meterVoltfo^{-2} for nitrobenzene.

A Kerr cell with a transverse field can thus act as a switchable wave plate, rotating the plane of polarization of a wave travelling through it. In combination with polarizer, it can be used as a shutter or modulator.

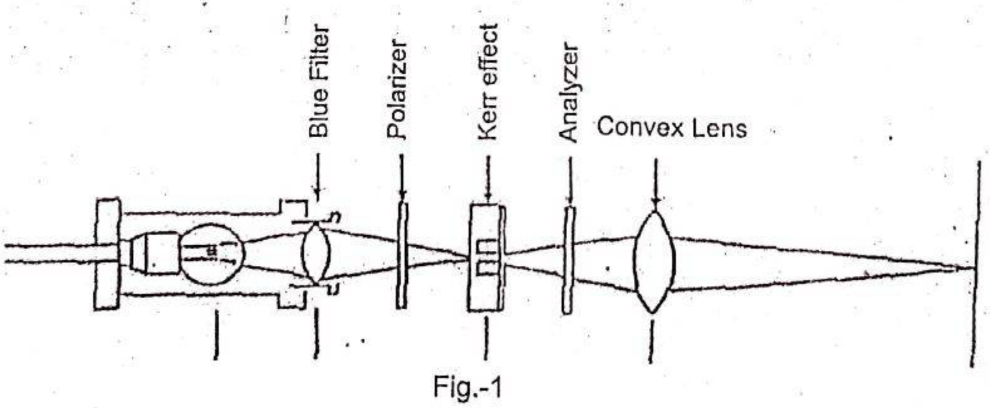


Fig.-1

EXPERIMENTAL SET-UP PROCEDURE

1. Place the optical bench on an experimental table and arrange the optical component as in fig.2

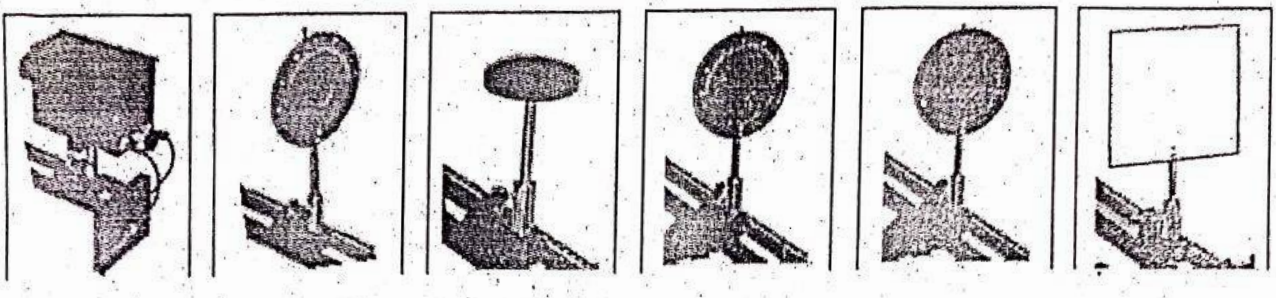


Fig.-2

2. Mount the Helogen Lamp, Polarizer (P1),Prism table ,analyzer(P2) convex lens on fixed saddle and Silicon Photodector on the transverse saddle as shown in Fig. 2.
3. Connect a digital multimeter in parallel across the two terminals of the digital Photodetector. Set the knob of the Multimeter at the 200 mili-Voltmeter range.
4. Apply 12 V D.C. to the lamp using a power supply(2-12 V, 5Amp AC/DC). 12v
5. Fix the analyzer and polarizer at 0°.
6. Focus the convex lens, so that to obtain a clear and bright spot of light on the Pin Hole of the Silicon Photo-detector. For this step, you might need to locate the image of the gap of the electrode with the help of a plane paper and ensure that the bright and focused image should enter the Pin Hole of the Silicon Photo-detector. Adjust the height and position of the photo-detector and transverse saddle accordingly. Also, you need to adjust the position of the convex lens as well.
7. Note : Ensure the light should pass through the central portion of each optical element. Also the image of the gap between the electrodes must be brought into the focus, not any other part. Success of the experiment depends on the alignment of each and every optical component. So try to align the central portion of each optical element along the same horizontal axis as far as possible.
8. Now, rotate the analyzer through 90°. In this position polarizing filters P1 and P2 are crossed so that no light is seen on the Photo-detector.
9. Remove the Electrodes from the Kerr Cell as shown in Fig. 3.
10. Fill the Kerr Cell with Nitrobenzene so that electrodes are dipped into it as shown in Fig. 4.
11. Place the Kerr Cell containing Nitrobenzene as Kerr medium on the prism table and connect the leads of the Kerr Cell to a high voltage power supply (0 - 5 kV, 2mA, DC).

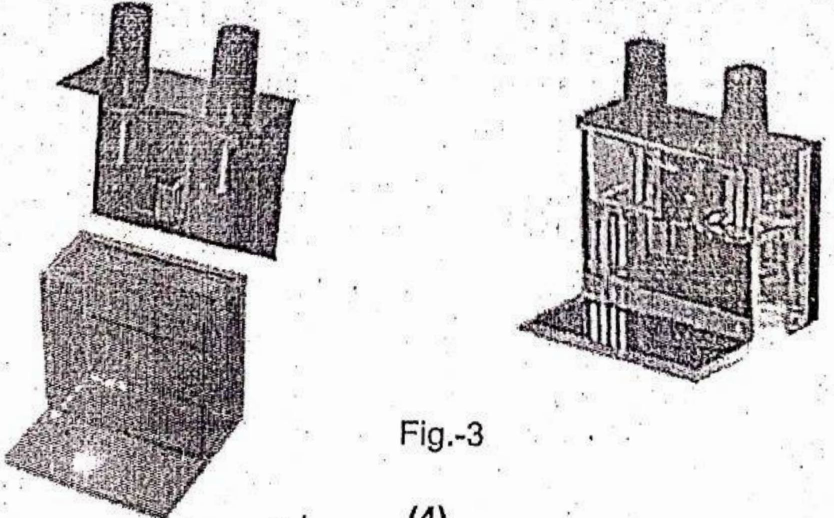


Fig.-3

12. Now locate the positive and negative plates of the electrode and note the direction of the electric field.
13. Now, align the optical axis of polarizer at an angle + 45° with respect to the direction of the electric field.
14. Now, align the optical axis of analyzer at an angle - 45° with respect to the direction of the electric field. The angular scale is not printed in this direction. The alignment at - 45° is made possible by rotating the analyzer and by observing the minimum intensity simultaneously. This can be done by holding a plain paper over the surface of the photodiode.
15. Now increase the voltage of the High Voltage Power Supply gradually from 0 V to 4 kV in steps of 0.2 kV and note down the corresponding voltage obtained across the two terminals of the Si-Photodetector.

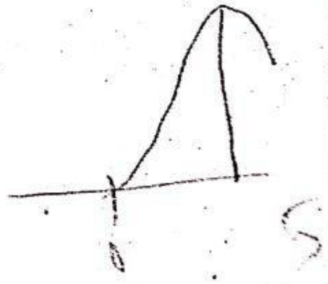
Note : Rotate the knob of the High Voltage power Supply very slowly. Don't rotate it fast. If rotated in a faster rate, the power supply would stop working. If it happens so, then minimize the rotating knob, then press the reset button inwards and then switch off the power supply. Then again switch on the power supply.

16. Voltage at first starts to drop for 30-60 seconds, then it will increase with the increment of the applied voltage (or Electric Field).
17. At a sufficient high voltage (applied across the electrodes) (say U), the voltage obtained in the multimeter will become maximum. Beyond this high voltage (applied across the electrodes), the voltage obtained in the multimeter (connected across the two terminals of the Si-Photodetector) will start decreasing. This high voltage V' is the half-wave voltage U.
18. Calculate the Kerr Constant from equation (5). Take l = 2 cm and d = 1.2 mm for the set-up.

$$K=\frac{d^2}{2U^2\ell} \qquad \text{mean} = \ell = 2\text{cm}$$
$$d = 1.2\text{mm}$$

Observation : $U = 4000$Volt
$K = 2.2 \times 10^{-12}\ \text{mv}^{-2}$

VIVA-VOCE QUESTIONS



- What type of fluid should be used as dielectric medium in this experiment?
- Name the liquid that should be preferred to be used as the Kerr-medium?
- what do you mean by birefringence?
- What is Kerr electro-optic effect?
- Explain the phenomenon of double refraction?
- Is the Kerr effect limited to only very high electric field?
- Is the Kerr effect material dependent?
- Does the Kerr effect takes place in all media i.e. solid, liquid and gas?
- How does polarization of dielectric takes place?
- Can you perform this experiment if provided with a dielectric of small dipole moment?
- Does the dielectric behaves as a wave plate?
- Can you use polar liquids like nitrotoluene or nitrobenzene as a dielectric medium in your experiment?
- What is a wave plate?
- Does the dielectric medium behave as a quarter wave or half wave plate?
- Why should one prefer a dielectric material of high value of the Kerr constant?
- Can you use Kerr cell to modulate light?
- Do Pockel's cells also need a very high voltage?
- What are the disadvantages of Kerr cell ?
- Can you use transparent crystal fro Kerr Modulation despite of their smaller Kerr constants?
- What is the difference between Kerr electro optic effect i.e. DC Kerr-effect and optical Kerr effect i.e. AC Kerr-effect?
- Can a Kerr cell be used as a shutter or modulator?
- Does the value of Kerr constant depend upon he medium?
- Which has higher value of Kerr constant, water or nitrobenzene?
- What makes Kerr cell important to be used as a shutter?

(1)

ULTRASONIC INTERFEROMETER

Date :- 21-6-2001

Object :-

Measurement of 'velocity' and 'compressibility' in a liquid or mixture (Water + Methyl Alcohol) at various concentrations of Methyl Alcohol by Ultrasonic Wave Propagation through the mixture using Ultrasonic Interferometer at room temperature.

Theory :-

* The velocity 'v' of the Ultrasonic (U.S) wave in a liquid or mixture is given by ,

$$V = n\lambda \qquad \text{.............(1)}$$

Where, n = frequency of U.S. wave
= frequency of crystal transducer which produces U.S. wave(which is filled and supplied).
λ = Wave-length of U.S. wave to be determined experimentally . (Its value depends on the nature of liquid used in the cell).

And compressibility of the liquid or mixture is given by ,

$$\beta s = 1/v^2\rho \qquad \text{................(2)}$$

where, v = U.S. velocity of the liquid
ρ = density of the liquid *

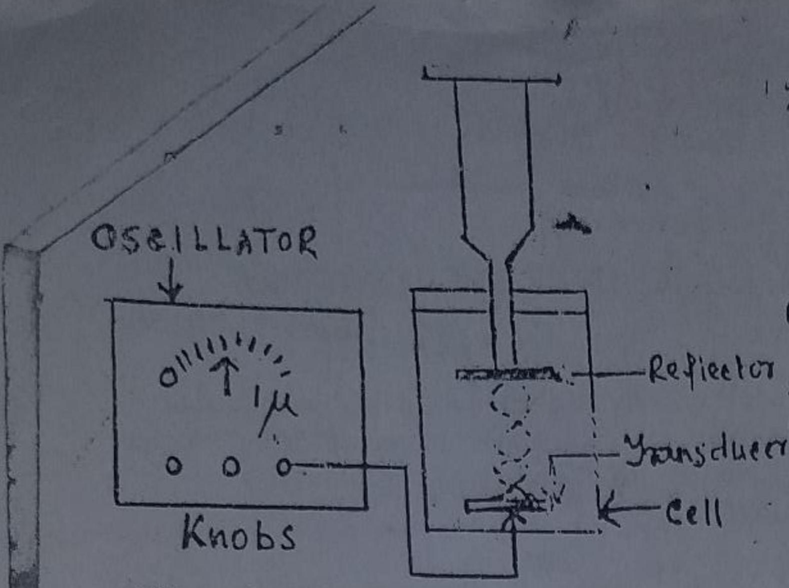
Use approximately 0%, 10%, 20%, 30%, 40%, 50% , 60% , 70% of mixture of Methyl Alcohol in distilled water and determine U.S. wavelength 'λ' and density 'ρ' at each concentration (0% mixture means pure water) .

To measure wavelength 'λ' :-

(U.S Interferometer consists of a transducer crystal at the bottom of the Cell which is driven by a Crystal Controlled Oscillator of fixed frequency . U.S. wave is transmitted to the liquid in contact with the transducer and is reflected from a metal plate placed at some distances away from the transducer in the liquid and this reflection can be moved up and down by a michrometer and its position can be read from the michrometer It has got two vernier scale and reading can be taken upto 0.001 mm. The reflected U.S. wave is received also by the same transducer and a meter indicates the position of reflector at node or antinode of stationary waves formed in the liquid 'Cell' due to transmitted and reflected waves .)

(When the reflector is at antinodes , water deflections becomes minimum. (Adjust the two knobs to have a difference of reading of about 10 divisions between maximum & minimum deflections). So, if the reflector is moved and set at two consecutive maxima, the difference of michrometer readings at these positions gives the value of λ/2 .) *

Gradually move the reflector from the middle (appx.)position to upward and take readings at sixth maxima . So, the difference in michrometer readings 'd' of 1st & 6th maxima will give you value for $5 \times \lambda/2 = d$. So, λ can be found out .



(1) Use maximum water deflection, 10 to 20 div. from minimum position using Sensitivity Control.
(2) By zero control bring the needle to 5 or 7 div. from zero at the minimum readings.
(1) &(2) refers to meter deflection when reflector is moved.

This method is more accurate than making readings at maxima. Take such 5-7 set of readings, setting the reflector at 11th, 16th maxm. etc. while moving the reflector upwards. Take mean.

Find mean d and then λ, and find 'v' (equ.1). Measure density of the liquid by a 15cc. Sp.gr.bottle and then find compressibility (equ.2). Change the liquid to different concentrations and repeat.

While making measurement with michrometer, use no. of complete rotation method or use linear scale method as is advantageous to you.

(Avoid backlash error. Readings for 'd' should be taken so cautiously that the set of readings for 'd' should not change in the second place of decimal when expressed in mm.)

TABLE :-

To prepare solution of different concentration :
(Assume no limitation of volume on mixing alcohol with water)
Room temperature = °C

$C_2 = \frac{C_1 x}{(x+y)^{-1}}$

$(C_2 - C_1)x + 6$

Sl.No.	Volume of Stock solution x cc.	Initial Concentration C_1%	Volume of Water added y c.c.	Final Contration $C_2=C_1x/(x+y)$%
1	15	100	7	68.1
2	15			58.0
3	15	68'1	6	48.64
4	15	48'64	9	30.4

100·11

$C_2 = \frac{C_1 x}{x+y} \Rightarrow C_2 x + C_2 y = C_1 x$

$\frac{10}{60} x + 2$

$\boxed{90 \cdot 1}$

$\frac{(C_1 - C_2) x}{C_2}$

14×60

$\frac{60 + 40 - 90}{50\ 40}$

$= 100 \left(\frac{30}{70}\right) \times 70$

6

$5 = \frac{600}{70}$

$\frac{10}{50} \times 12$

$\frac{100 - 90}{90}$

$\frac{10}{5} = 2$

y

$\frac{20}{40}$

To determine velocity :-

L.C = ………mm. V.C.= …………mm. Frequency = 2x10^6 Hz

Table :

Sl. No.	Conc. of Soln. %	Linear Scale Read-ing. mm.	Circular Scale Read-ing. mm.	Vernier Scale Reading mm.	Total Reading mm.	Linear Shift 'd' mm.	Mean 'd' mm	$\lambda = 2d/n$ (n=5) mm.	Velocity $V = n\lambda$ m/s
1	zero								
6							8.705	1.4825	(14825 × 2)
11									
16									
11									
6									
1									

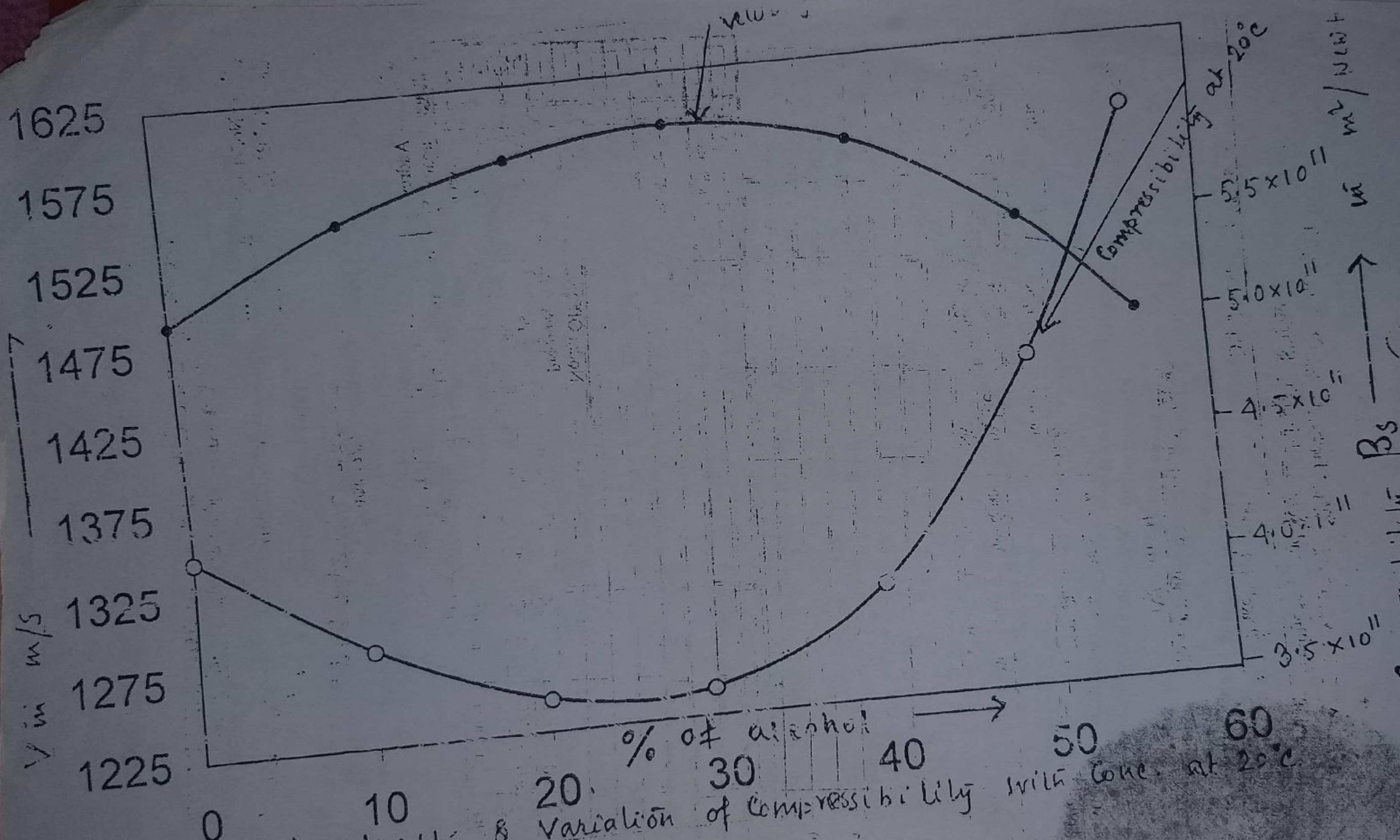
Table For Density :- Room Temperature = °C

Conc. Of Soln.	Wt. Of empty Sp.Gr. Bottle W_1gm.	Wt. Of distilled water filled Sp.Gr. Bottle W_2gm.	Wt. Of sp.gr. bottle filled with soln. W_3gm.	Sp. Gr. $\rho = \frac{W_3 - W_1}{W_2 - W_1}$	Velocity V m/s	Compressibility $\beta s = 1/\rho v^2$
.0%						
68%	8.93	25.1506	28.7236	0.9105	1398.0	5.62x10
48.64%						

DISCUSSION : Try to explain why velocity is nonlinear with Concentration ? What physical process has been involved To make it so ?

Ref :

Richardson *Ultrasonics*
Meson - *Sound*
Nozdev - *Use of Ultrasonics in Mod-Physics.*



Variation of velocity & Variation of compressibility with conc. at 20°C

CHAPTER 12

ULTRASONICS

12-1. Introductory. The entire spectrum of acoustic energy is divided into four parts, namely, (*i*) infrasound or infrasonics, (*ii*) audible sound or sonics, (*iii*) ultrasound or ultrasonics and (*iv*) hypersound or hypersonics. The frequency ranges are taken approximately as follows :

(*i*) Infrasonics : Frequency f less than 10 cps.
(*ii*) Sonics : Frequency range 10 to 20,000 cps.
(*iii*) Ultrasonics : Frequency range 2.10^4 to 10^9 cps.
(*iv*) Hypersonics : Frequency above 10^9 cps.

Thus ultrasonics means the study of elastic waves covering the frequency range 2.10^4 to 10^9 cps. The terms 'supersonic' and 'subsonic' are used now-a-days to qualify the speeds of fast moving objects (such as projectiles, jets, aircrafts, spacecrafts, etc.), the former meaning 'greater than' and the latter 'less than' the speed of sound. 'Supersonics' now stands for the general subject covering phenomena associated with speeds greater than that of sound. Shock waves belong to this field.

Infrasonic, ultrasonic or hypersonic vibration do not produce the sensation of sound in the ear.

Earlier, we have stated that elastic waves may be of various kinds, namely, longitudinal (Sec. 4-10 and 8-10), extensional (Sec. 8-2), transverse or shear (Sec. 6-10 and 8-10), flexural (Sec. 8-6), torsional (Sec. 8-9). Besides, there may be surface waves (the so-called Rayleigh waves), which are propagated along the surface of a medium. These we have not discussed.

Any mechanical system capable of vibrating within the ultrasonic frequency range in any of the above manners constitutes a source of ultrasound. When these vibrations are transferred to a suitable medium we get ultrasonic waves in the medium. As in the sonic range, the production of ultrasonic waves in a medium requires three agencies, namely, (*i*) a source of energy, (*ii*) a system, called a *transducer*, which receives and transfers this energy while vibrating in the ultrasonic range, and (*iii*) the medium to which the ultrasonic vibrations are transferred from the transducer.

The energy supplied to the transducer may be electrical or mechanical.

The following are the generally used types of transducers :

A. Electrically excited :

Piezoelectric transducers ;

Electrostrictive transducers ;
Magnetostrictive transducers ;
Electrodynamic transducers ;
Electrostatic transducers ;
Spark transducers.

B. Mechanically excited :

In these types, the pressure or speed of the fluid receiving the energy is modulated at high frequency by one of the following devices :

Fixed mechanical elements ;
Moving mechanical elements.

The most commonly used types of transducers are the piezoelectric, electrostrictive and magnetostrictive transducers. We shall discuss only these three types.

To avoid confusion, we may briefly note here the meanings of magnetostriction, piezoelectricity and electrostriction.

Magnetostriction relates to the production of various strains in a ferromagnetic material under the action of a magnetic field. These include (*i*) elongation or contraction of a rod when magnetized (Joule effect), (*ii*) change in magnetization of a rod under longitudinal stress (Villari effect or inverse Joule effect), (*iii*) twisting of a rod carrying an electric current when subjected to a magnetic field (Wiedemann effect), and (*iv*) tendency of a bent ferromagnetic rod to straighten in a longitudinal magnetic field (Guillemin effect). The Joule effect is concerned in ultrasonic generation and its inverse effect (Villari effect) in ultrasonic detection.

Piezoelectricity and *electrostriction* both refer to the appearance of mechanical strain (x) under the action of an electric field (E). The relation may be written as

$$x = aE + bE^2 + \cdots\cdots\cdots$$

Piezoelectricity is the first-order effect ($x \propto E$), and *electrostriction is the second-order effect* ($x \propto E^2$). (Strictly speaking, piezoelectricity includes all odd powers of E, and electrostriction all even powers. The coefficients of the higher powers are ordinarily negligible). Crystals such as quartz, tourmaline, lithium sulphate and ammonium di-hydrogen phosphate (ADP) exhibit strong piezoelectric behaviour. Electrostriction is strong in ferroelectric crystals such as Rochelle salt, barium titanate ($BaTiO_3$), etc. All ferroelectric crystals are also piezoelectric.

When mechanical strain is produced on the application of an electric field to a crystal, the phenomenon is called the *inverse* *piezoelectric effect*. The appearance of electric charges on faces of crystals subjected to mechanical stress is known as the *direct piezoelectric effect*. The former is used in the generation, and the latter in the detection of ultrasonic waves.

In utilising electrostriction of ferroelectric ceramic materials, like barium titanate, the specimen is initially polarised electrically. Application of an alternating electric field to it produces an alternating mechanical strain of the same frequency. The inverse effect is utilized for detection.

12-2. Application of magnetostriction. When a rod or tube of ferromagnetic material is magnetized parallel to its length, it undergoes a small change in length, which is about a few parts in a million and may be an increase or decrease depending on the material. On the other hand, if a stress alters the length of a ferromagnetic specimen, it is magnetised longitudinally. This is the inverse effect.

The strain (i.e., change in length per unit length of the specimen) is a function of the intensity of magnetization. For flux densities well below saturation, the strain is practically proportional to the *square* of the flux density. So, we may write strain $= \delta L/L = KB^2$ where K is a constant for a given material and B is the flux density. For nickel and some of its alloys (such as invar, nichrome, monel*), K is large and negative. For annealed nickel, $K = -1{\cdot}0 \times 10^{-4}$ upto 0·5 weber. Fe and Co are not used as K changes sign above a certain field. Magnetostriction curves for Fe, Co and Ni are shown in Fig. 12.1. In many applications ferrites are now replacing nickel.

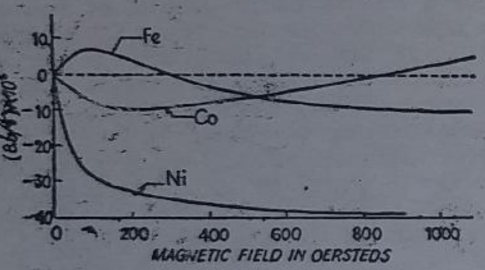


Fig. 12.1

In applying magnetostriction for producing high frequency waves, a rod of nickel, or some other suitable material, is placed in a solenoid through which a high frequency alternating current is passed. The varying magnetization of the rod causes variations in its length with a frequency twice that of the alternating current, as the change in length is independent of the direction of magnetization. The two frequencies can be made the same by superposing the a.c. on a steady current, or by polarizing the rod by keeping it in a permanent magnetic field. Under given conditions the polarizing field has an optimum value. The amplitude of vibration of the rod becomes a maximum when resonance occurs, i.e., when the frequency of the a.c. equals that of the natural longitudinal vibration of the rod. The vibrating rod excites longitudinal high frequency waves in the medium in which it is placed.

Frequencies upto 60 kc/sec can be attained in this way. The length of a nickel rod which vibrates longitudinally in the fundamental mode with this frequency when fixed at one end is about 2 cm. In short rods, it is difficult to get the fundamental. If harmonics are used, there is considerable loss of energy, and the output is small. For this reason, application of magnetostriction in the ultrasonic range is limited to about 60 kc/sec. At 20-30 kc, the efficiency is high. At the fundamental frequency, the maximum amplitude is about 10^{-3} times the length. The associated stress is very high, being over 200 atmospheres.

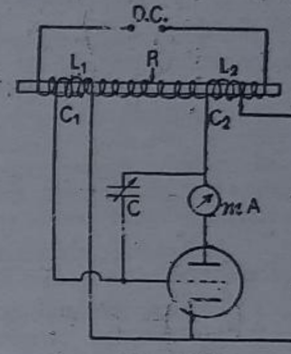


Fig. 12.2

12-3. Magnetostriction oscillator. Fig. 12.2 shows a simple circuit for producing ultrasonic vibrations by utilizing magnetostriction. A nickel rod R is clamped in the middle and the two sections (L_1 and L_2) of the rod are surrounded by coils C_1 and C_2 connected to the grid and anode circuits respectively. Another coil wound round the rod carries a steady current and polarizes the rod. Tuning is effected by the variable condenser C.

The action is as follows. Suppose application of the anode voltage causes such a current to flow through C_2 as would cause the specimen to lengthen. This change in length causes, by inverse effect, a change in flux through C_1, which induces an emf in it. If C_1 is correctly connected to the grid this emf will be in such a direction as will raise the potential of the grid. This increases the anode current further and maintains the oscillations.

Magnetostriction oscillators are used extensively in industry where high power is needed. It is superior to crystal oscillators

---

*An alloy of Cu, Ni and Fe.

(Sec. 12-6) in that large amplitudes offer no risk of cracking. But the frequency is low.

Application to sonar. The high stresses that are developed in a magnetostrictive oscillator show that such oscillators can be used as powerful sound sources under water. Sound navigation and ranging (SONAR) is the most important phase of underwater acoustics. Its development has been made possible by the use of magnetostriction oscillators. One such oscillator-detector is described below.

A number of nickel tubes (*N*; Fig. 12.3) attached to a plate (*P*) forces the plate to oscillate by the magnetostrictive stresses generated in the tubes when alternating currents flow in the coils (*C*) around the tubes. Each tube has a length equal to one-fourth of the wavelength in nickel for the frequency to be transmitted. Hundreds of such tubes may be employed, one end of each tube being free and the other being imbedded in one side of a circular steel plate. The plate has such dimensions that the resonant frequency of the entire system is near that of the tubes alone. The currents through the coils are in phase. Polarizing fields are commonly supplied by permanent magnets (*M*) mounted inside the watertight housing (*H*) containing the tubes. The alternating forces exerted on the plate by the reaction to the stresses in the nickel tubes are transmitted by the plate into the water with which it is in contact.

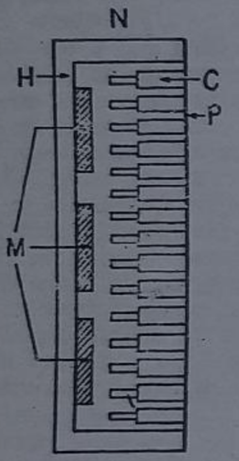


Fig. 12.3

Because of the reversibility of magnetostriction effect, the same oscillator can be used as a receiver. Sound waves impinging on the plate will set it into vibration and correspondingly set up stresses and strains in the tubes. As a result, the magnetization changes and alternating voltages are set up in the surrounding coils. These are amplified and made to operate a meter or recorder. The sensitivity is however limited to a narrow band of frequencies around the resonant frequency of the plate-tube system. The Q-value, defining sharpness of resonance, is about 50.

12-4. Application of piezoelectricity. When a plate is cut in some particular way from a *single crystal* of piezoelectric material, such as quartz, Rochelle salt, ADP, etc., it is found that a compression of the plate causes its faces to become charged with opposite kinds of electricity. On stretching the plate, the sign of the change is reversed. The converse behaviour is seen when a properly cut piezoelectric crystal is placed in an alternating

electric field, it contracts and expands periodically and sets up mechanical vibrations in any acoustical medium in which it may be placed. The frequency is in the ultrasonic range. The amplitude of vibration is usually very small; but if the applied frequency is equal to one of the natural frequencies of the crystal, resonance occurs and the amplitude increased considerably.

Man-made ceramics of barium titanate, lead titanate zirconate solid solutions, etc., show similar behaviour after they have been placed initially in a strong electric field for a few minutes.

12-5. Crystal cuts. The inverse piezoelectric effect, i.e., elongation and contraction of a crystal on application of an electric field is utilized for the generation of ultrasonic waves. The direct piezoelectric effect, i.e., generation of an electric field on the application of mechanical stress, is utilized for the detection of sonic and ultrasonic waves. For maximum efficiency, it is necessary in either case that a change of one kind (electrical or mechanical) be accompanied by a maximum change in the other. Technically speaking the coupling between the electrical polarization and the mechanical strain should be the strongest possible. This can be achieved only if the crystal is cut in some particular way. For different kinds of crystals the cuts are different. For the same kind of crystal there may be more than one kind of cut for reasons other than that of strongest coupling. Some of the more widely used cuts are discussed below. Note that the crystals used must be single crystals. Polycrystalline material is no good, except where ceramics are used.

Quartz crystal. A single crystal of quartz is a hexagonal prism (Fig. 12.4) bounded by two six sided pyramids at the two ends. The long axis of the crystal is the *optic axis* and is called the *z*-axis. Let a hexagonal slice be cut off from the crystal by two planes perpendicular to the *z*-axis. A line perpendicular to the *z*-axis, which joins the opposite angles of the hexagon gives the direction of the *electric or x-axis*. Any axis perpendicular both to the *x*- and *z*-axes is the *mechanical* or *y-axis*. It will be

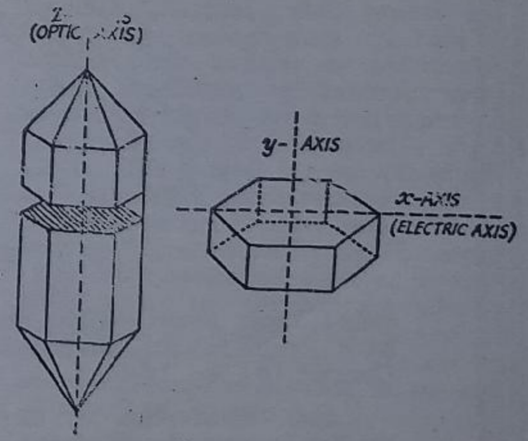


Fig. 12.4

seen that the y-axis is perpendicular to any opposite pair of the six faces of the crystal slab.

A quartz plate to be used for producing high frequency oscillations may be cut from the mother crystal in various ways. Thus the two largest faces of the crystal may be normal to the x-axis or to the y-axis (Fig. 12.5). The former is called an X-cut crystal, and the latter a Y-cut crystal. For production and detection of ultrasonic waves, the X-cut crystal is most commonly used. When a quartz crystal is used as a frequency stabiliser with a valve oscillator, the cuts are more complicated. These cuts go by such names as AT-cut, BT-cut, etc.

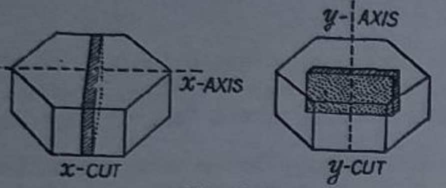


Fig. 12.5

Frequency of X-cut crystals has a small negative temperature coefficient. Y-cut crystals have a similar positive coefficient. Other cuts are designed to have a practically zero temperature coefficient at the working temperature and avoidance of undesirable resonances between different modes of vibration.

The cuts for crystals of Rochelle salt and ADP are shown in Figs. 12.6(a) and (b) respectively. The plates so obtained are called *shear plates.* They are used mostly in microphones and have been further discussed under crystal microphones in Chapter 14 [Sec. 14-4(3)].

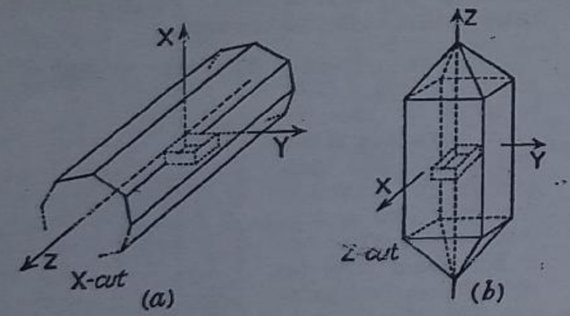


Fig. 12.6

12-6. Generation of ultrasonic waves by quartz. When an X-cut quartz crystal plate is placed in an electric field parallel to its x-axis, the plate will expand along the y-axis and contract along the x-axis or show the reverse behaviour according to the direction of the field. If the electric field is alternating, mechanical vibrations will be set up along the x- as well as the y-axis. The vibrational mode along the x-axis (which is in the direction of thickness) is called *thickness vibration*, and that along the y-axis, *lenght vibration*. The amplitude of vibration becomes large as the frequency of the alternating field approaches any of the natural frequencies of the plate for either mode of vibration.

The natural frequency of vibration of the plate is determined by its dimension (l) parallel to the direction of vibration. Thickness vibrations have higher frequencies while length vibrations have lower frequencies. In the fundamental mode of vibration, the wavelength in the crystal $\lambda = 2l$. The velocity of compressional waves in the crystal is $c = \sqrt{Y/\rho}$ where Y is Young's modulus in the direction of vibration and ρ the density of the crystal. This makes the frequency about $272/l$ kc/s for length vibrations and $287/l$ for thickness vibrations when l is in cm. Length vibrations in quartz (or other piezoelectric crystals) have been utilized for producing ultrasonic vibrations in liquids at frequencies ranging from 50 kc/s to several hundred kc/s. Thickness vibrations are suitable for frequencies in the megacycle range. The radiating surface is considerably greater in thickness vibrations than in length vibrations. Hence the electro-acoustic efficiency is also relatively high in thickness vibration. For laboratory purposes the thickness mode is most commonly used for generating ultrasonic waves in gases, liquids and solids. Besides, the radiating area being large compared with the wavelength in a thickness mode, the radiated ultrasonic beam will have small angular divergence.

The quartz oscillator. Eletronic circuits are used for applying the necessary alternating voltage to a quartz crystal to cause it to vibrate in a natural mode. A thin film of metal is deposited on each face of the crystal for connecting electrodes.

Electrically, vibrating quartz crystal is equivalent to a resonant circuit consisting of a capacitance. C_1 (Fig. 12.7) shunted by an LCR branch. L of the branch is the electrical equivalent of the crystal mass that is effective in the vibration, C represents the elasticity of the crystal and is the electrical equivalent of the effective mechanical compliance, while R is the electrical equivalent of the resistance offered to mechanical vibration by friction. C_1 is the electrostatic capacitance between the crystal

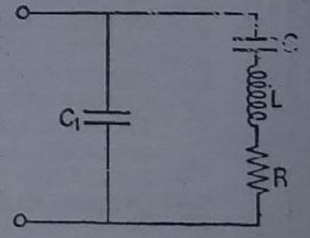


Fig. 12.7

electrodes when the crystal is not vibrating. The values of *LCR* depend upon the dimensions of the crystal. If l, w and t respectively denote the length, width and thickness of the crystal in cm, we have the following relations :

$$C = 0.0029\, lw/t \ \mu\mu f$$

$$C_1 = 0.40\, lw/t \ \mu\mu f$$

$$L = 118 t^3/lw \text{ henrys (for thickness vibration)}$$

$$= 118 wt/l \text{ henrys (for width vibration).}$$

Because the inductance of the crystal is large compared to its resistance, the crystal represents a high-Q* tank circuit. Hence crystals can be used instead of conventional tank circuits for determining the operating frequency of an oscillator.

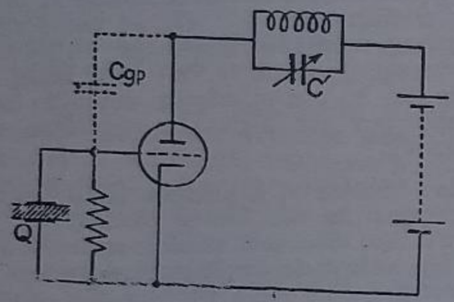


Fig. 12.8 (*a*)

The circuit of Fig. 12.7 has two resonant frequencies, f_r and f_a, given by

$$2\pi f_r L = 1/2\pi f_r C$$

and $$1/2\pi f_a C_1 = (2\pi f_a L - 1/2\pi f_a C),$$

f_r is the series resonance frequency of the *LCR* branch and offers low impedance to the external terminals f_a is the parallel resonance frequency of the crystal system, in which the inductive reactance of the *LCR* branch is equal to the capacitive reactance of C_1. It offers a high impedance to the external terminals $f_a > f_r$, while $f_a - f_1$ is about 1% of f_a.

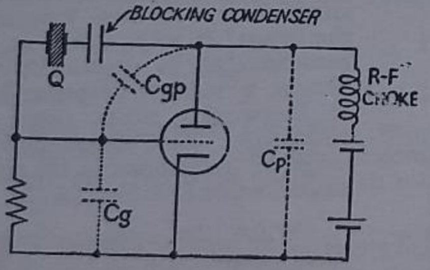


Fig. 12.8 (*b*)

The essential characters of the two most widely used oscillator circuits are shown in Figs. 12.8(*a*) and 12.8(*b*). Fig. (*a*) is known as the Miller cicruit and Fig. (*b*) as the Pierce circuit.

---

* Q, which is defined as 2π times the ratio of the energy stored in the cricuit to the energy lost per cycle is ordinarily greater then 20,000 and may be ten times or even greater.

The former can give a higher power output and is relatively free of harmonics. For these reasons it is more advantageous for ultrasonic work. The latter has great frequency stability* and is more used for controlling the frequency of valve oscillators.

The Miller circuit corresponds to a tuned-grid tuned-plate arrangement as may be seen by replacing the crystal by its equivalent electrical circuit. The coupling between the anode and grid circuits is secured through inter-electrode capacitance. The plate resonant circuit is tuned to a frequency slightly higher than the resonant frequency of the desired crystal mode. The amplitude of oscillation is determined by the amount of inductive reactance in the plate circuit.

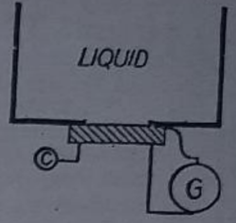


Fig. 12.9

For generating ultrasonic waves in a liquid, the crystal (*C*) is placed relative to the liquid as shown in Fig. 12.9. *G* in the figure represents the rest of the electronic circuit. Because of the large impedance mismatch, the face in contact with air radiates very little energy.

When it is desired to produce a strongly directed ultrasonic beam, the radiating area must be large compared with the square of the radiated wave length. For quartz in thickness vibration this condition is generally satisfied as the frequency is in the megacycle range. For length vibration, it is not so as crystals of natural quartz cannot be had in large enough sizes. In such a case, a large number of individual quartz oscillators are mounted in a *mosaic* pattern and are driven in phase. One such design is illustrated in Fig. 12.10. The bars Q are the individual half-wavelength quartz vibrators. One end of each is imbedded in a rubber backing (*R*) attached to the housing (*H*). This design being meant for use under water, the vibrators are imbedded in oil. Their ends in contract with the oil radiate the sound. The oil is sealed off from the adjacent water by a sound transparent window (*W*) made of rho-c rubber.

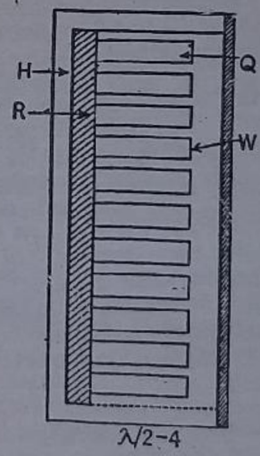


Fig. 12.10

---

* The Pierce circuit is equivalent to a Colpitts circuit, which has the best frequency stability of all basic oscillator circuits. The Pierce circuit does not require tuning, and will operate when crystals of different frequencies are substituted in the circuit.

If D is the diameter of the radiating surface of a source of ultrasonic sound and λ the wavelength radiated, the beam spreads out into a cone of semi-angle $\theta = \sin^{-1}(1{\cdot}22\lambda/D)$. For a sound radiation of 40 kc in water, λ is about 3·5 cm. If $D = 30$ cm, θ will be about 8°.

12-7. Comparative properties of different piezoelectric materials. In order to be suitable for use as an ultrasonic generator or detector, a piezoelectric material should have some desirable properties. The chief amongst them are (*i*) a workable value of the *strain constant*, that is, the ratio between the mechanical strain and the voltage gradient, (*ii*) mechanical rigidity, (*iii*) insensitivity of physical properties to changes of temperature and other environmental conditions, (*iv*) purity, (*v*) availability, (*vi*) cost, etc. These requirements heavily restrict our choice, which is now practically limited to quartz and Rochelle salt among naturally occurring crystals. Search for a wider variety of useful material has led us to man-made crystals of *ADP* and lithium sulphate and to ceramics of barium titanate, lead titanate, lead zirconate, lead niobate, etc. The search is still continuing. As large natural crystals are rare, the crystals are now being prepared in a pure condition from melts or solution. As the titanates and zirconates cannot be prepared except in the form of very small crystals, they are made into ceramics and can be given any shape and size, which is an advantage. The ceramic preparation is placed in a strong electric field (of about 40 to 60 kv per cm) for a few minutes. This direction marks the electric axis.

For longitudinal vibration, the strain constant for an X-cut quartz crystal is $2{\cdot}3 \times 10^{-10}$ cm/volt. For Rochelle salt in the most favourable cut (45° X-cut ; see Sec. 14-6) the value is 275×10^{10} cm/volt, for ADP (45° Z-cut) it is 24×10^{-10} cm/volt, and for barium titanate, 56×10^{-10} cm/volt. The chemical and physical stability of quartz, its high mechanical rigidity, low temperature effect and internal friction make it the material of choice as ultrasonic generator in spite of the low value of its strain constant. Barium titanate is a less expensive alternative to quartz, and has a higher acoustical output for a given electrical input. It can be used for low frequency high power applications where quartz is unsuitable.

The electrical properties of Rochelle salt change rapidly with temperature in the neighbourhood of the room temperature. Low humidity dehydrates the crystal and high humidity dissolves it. ADP and lithium sulphate are soluble in water. All these three crystals require protective coatings. Lithium sulphate responds under a uniform volume strain, which other crystals do not. This property makes it possible to use lithium sulphate crystals for detection of sound under water (See Sec. 14-12).

With improvement in the technique of preparation of $BaTiO_3$ and other ferroelectric ceramics, they can now be made in necessary sizes, large and small, and given any shape. These ceramic crystals are replacing natural or other man-made crystals and magnetostrictive materials in many applications in the field of ultrasonics, both in research and in industry.

12-8. Ultrasonic receivers Because of the reversibility of the piezoelectric effect, a quartz oscillator will also serve as a good detector for the frequency it radiates. It can be used over a band of frequencies in the neighbourhood of its resonance frequency, particularly in water where its Q value is low, being of the order of 10. We may recall Eq. 3-18.1, which tells us that the band width around the resonant frequency f_0 for which the response is greater than $\frac{1}{2}$ is f_0/Q. So, an oscillator with $f_0 = 40$ kcs can be effectively used over the range $40{,}000 \pm 2{,}000$ kcs if $Q = 10$. By contrast, Q in air is very high, being of the order of 20,000. So in air, its use practically would be limited to the resonant frequency but for high gain amplifiers, which extend the range considerably.

The principle of action of a piezoelectric detector is simple. The pressure changes in the waves incident on the receiver diaphragm throws it into vibration, which is strongest at resonance. The piezoelectric elements undergo alternating stresses as a result, and alternating charges, and hence voltages, are developed at the opposite ends of the electric axis. These voltages are properly amplified and made to operate a meter or recorder. Magnetostrictive receivers can be used in the same way.

With the development of high gain amplifiers it has been possible to use piezoelectric receivers at frequencies well away from their resonant frequencies. The voltage developed across the crystal is very small in such cases, and well away from resonance it is practically constant for a given excess pressure. Having a receiver response independent of frequency, as happens at frequencies much lower than resonance, is in a sense an advantage. Thus piezoelectric receivers can be used over a wide-range of frequencies in the sonic and ultrasonic ranges with proper amplification (See Sec. 14-12).

When the lateral dimensions of the receiving element are small compared with the wavelength in the adjacent medium, the response is practically the same for all directions of incidence, *i.e.*, it is non-directional. When large, it becomes directional as in the transmitter.

Analysis shows that the response of a crystal receiver is inversely proportional to the thickness l_z of the crystal in the z-direction. For crystals of the same size cut from different materials in the best way, sensitivity decreases in the order Rochelle salt (45° X-cut), barium titanate, ADP, quartz.

Magnetostrictive receivers can also be used in the same way below the resonant frequency.

A cylindrical ceramic type of ultrasonic receiver has been discussed under hydrophones (Sec. 14-12). The hot-wire microphone (Sec. 14-8) has been used upto 100 kc/s in fluids.

12-9. Ultrasonic absorption and dispersion. Propagation of ultrasonic waves in a medium is characterised by absorption, which is strong in many cases, and by dispersion (i.e., change of velocity with wavelength). These features are not perceptible in the sonic region. But since the nature of the waves is the same, the same law of propagation should apply to both. This means that the mechanism of sound wave propagation should also include appropriate mechanisms for absorption. Dispersion follows as a consequence of absorption.

Attempts to incorporate absorption mechanisms in the propagation of compressional waves are old. The first attempt was made by Stokes, who considered viscosity of the medium as the physical property responsible for absorption. This was followed by Kirchhoff, who took thermal conductivity into account.

The absorption coefficient α of a plane compressional wave is defined by

$$p = p_0 e^{-\alpha x}$$

where p and p_0 are excess pressures in a plane wave at a distance x apart. Assuming that α in a gas is made up of the absorption α_v due to viscosity and α_h due to heat conduction, we get, following Stokes and Kirchhoff,

$$\alpha = \alpha_v + \alpha_h = \frac{8\pi^2 \eta f^2}{3\rho c^3} + \frac{K}{\rho C_v}\left(1 - \frac{1}{\gamma}\right)\frac{2\pi^2 f^2}{c^3}$$

where η = coefficient of viscosity, f = frequency, c = wave velocity, ρ = density, K = thermal conductivity, C_v = specific heat at constant volume, γ = ratio of specific heat at constant pressure to that at constant volume.

In gases, α_h is about $\frac{1}{3}\alpha_v$, whereas in liquids α_h is negligible. Absorption estimated on the above basis is known as *classical absorption.*

While the results are in fair agreement in monatomic gases, large differences are noticeable in polyatomic gases. Hence some other absorption mechanism must be considered. This was provided by what we now call relaxation absorption.

Relaxation absorption. This relates to energy losses due to exchanges between internal and external molecular degrees of freedom. Energy takes a finite time to pass from an external to an internal degree of freedom, and vice versa. At low frequencies this time is negligible compared with the time period of the sound waves. So, energy is taken from and returned to the sound wave with negligible phase lag. At higher frequencies, this lag is no longer negligible. The peak pressure is therefore reduced, and absorption occurs.

When a molecular quantity changes rapidly with time we define a time τ, called the *relaxation time*, which represents the time that some suitable quantity associated with the change takes in falling to $1/e$ of its initial value. The corresponding frequency is called *relaxation frequency.*

The absorption is a maximum around the relaxation frequency. At still higher frequencies, the energy exchanges do not find enough time to take place, and absorption decreases.

In the case of monatomic geses, relaxation absorption is absent as there are no internal degrees of freedom. Experimental results broadly agree with classical absorption.

Both classical and relaxational absorption can take place in diatomic gases. Presence of impurities modifies the relaxation frequency.

Polyatomic gases have more pronounced relaxational effects and the relaxation frequencies are high. There will be a relaxation frequency for each mode of vibration. CO_2 exhibits a major absorption peak at 20 kc, which corresponds to a deformation mode of vibration.

In most gases, equilibrium between translational and rotational energies is reached repidly. The vibrational modes are responsible for relaxation absorption.

Absorption in liquids. Except for a few monatomic liquids and highly viscous liquids, the absorption in liquids is much greater than classical absorption. In associated liquids like water and alcohol, the absorption is 2-4 times the classical absorption. *Structural relaxation* is thought to be responsible for the excess absorption. Many unassociated liquids has absorption 100 or 1000 times stronger than classical absorption. This has not been satisfactorily explained.

Absorption in solids. Absorption in solids may occur from a larger variety of causes. Some of these are

(*i*) Scattering by the minute crystals (grains) which make up the polycrystalline solid.

(*ii*) Transfer of heat across the individual grains.

(*iii*) Thermal conductivity.

(*iv*) Structural properties.

(*v*) Ferromagnetic and ferroelectric properties.

(*vi*) Transfer of acoustic energy to free electrons in metals at low temperatures.

Because of these complicating effects a general theory of propagation of compressional waves in the matter could not be satisfactorily derived. Effects of individual absorption mechanism can be separately considered and the conclusions tested against observation where possible.

These discussions show that in ultrasonic measurements determination of wavelength velocity and absorption are of prime importance. A simple method for doing so is discussed in the following section.

Apart from relaxation mechanisms which help in understanding vibration processes of complex molecules even in the infra-red region, study of ultrasonics throw great light on the elastic properties of solids and liquids.

Under the action of these waves a volume element is cyclically strained. Its mechanical stiffness and energy loss can be measured. Variations of these quantities can be obtained as a function of environment and frequency. Information obtained can then be correlated with the physical processes involved.

12-10. Ultrasonic interferometer : Measurement of wavelength, velocity and absorption. Recent developments in the production of ultrasonic vibration of *accurately known frequency* by piezoelectric crystals and magnetostrictive rods have made the method of stationary waves a method of precision for the determination of velocity of sound in gases and liquids.

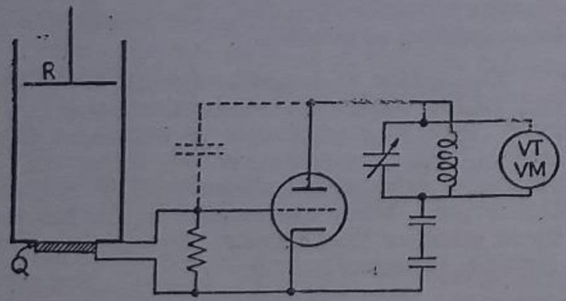


Fig. 12.11 (*a*)

The device known as the ultrasonic interferometer was first used by Pierce (1925). He used plane waves in a cavity, usually cylindrical, and the source was a vibrating quartz crystal though magnetostrictive rods were also used. There are two main forms, single crystal and double crystal instruments. The former uses the reaction of a standing wave system on the source crystal. Standing waves are formed by a reflector at the other end of the cavity opposite the source.

A single crystal instrument is represented in Fig. 12.11 (*a*). A piezoelectric oscillator, such as quartz crystal (*Q*), with fundamental frequency in the region where the measurement is to be made is mounted in front of a smooth reflector (*R*). The two may be contained in a wider vessel filled with the medium as shown. *Q* is maintained in vibration by an electronic circuit. The sound waves are practically plane. These are reflected by *R*, which must be accurately aligned for the purpose, so that stationary waves are formed between *Q* and *R*. *R* can be moved to-and-fro by an accurately cut screw. The reflected waves falling on *Q* help or oppose the vibrations of *Q*. This causes the readings of the valve-tube voltmeter (*VTVM*) connected across the inductance in the plate circuit to fluctuate in accordance with the phase of arrival of the reflected waves. Alternatively, a milliammeter may be used in the plate circuit.

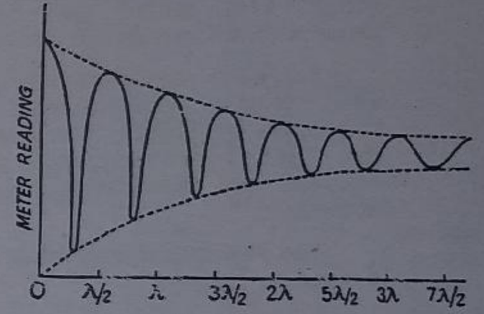


Fig. 12.11 (*b*)

The experiment consists in moving *R* parallel to itself and plotting the *VTVM* reading against the position of *R*. The reading passes through maxima and minima as shown in Fig. 12.11(b). The distance between two successive maxima or minima is $\lambda/2$. Under suitable conditions a few hundred maxima or minima can be located with precision. Thus a precision determination of λ can be made. This combined with a knowledge of the vibration frequency of the crystal, which again can be known with a high degree of accuracy, gives the value of the velocity of sound in the medium between *Q* and *R*. The medium may be a liquid or a gas. In liquids, the minima are more sharply defined than maxima, while in gases the reverse holds.

In a gas, the maximum current occurs when the reactive effect of the gas is zero at exact resonance, and the resistive effect is a maximum. In liquids, the minimum current occurs when the reactive effect is zero between resonance positions and the resistive effect is smallest. At high gas pressures there will be a transition between the two cases.

The difference arises from the fact that the radiation impedance of the medium, c, is much larger in liquids than in gases.

There are general precautions to be taken while using an ultrasonic interferometer.

(*a*) The amplitude of vibration of the crystal must not be too large. This will produce heating of the medium near the crystal.

(*b*) A quartz crystal has many resonance frequencies. The selected frequency must be well removed from neighbouring resonant frequencies.

(*c*) The crystal and reflector surfaces should be exactly parallel. The parallelism should be correct to within about 3×10^{-5} cm.

(*d*) The waves should be plane waves. This requires that the diameter of the crystal be large compared with the wavelength.

(*e*) The circuit must have extreme electrical stability. Any drift in frequency should be no more than 2 cycles in 2 megacycles during the period of measurement.

(*f*) For consistent values errors caused by diffraction due to finite size of source, excitation of other modes of vibration of the crystal, coherent radial reflections, and reflection of the primary beam from the walls of the container must be eliminated.

In low absorbing liquids measurements of wavelength at frequencies of the order of 1 Mc may be made with an accuracy of 1 part in 30,000. In high absorbing liquids it is 1 part in 5,000.

Absorption is determined by measuring ratios of maximum and minimum amplitudes.

The interferometer can be used over the range 0·3 to 80 Mc. A pulse technique can extend the measurements to 200 Mc. At the low end, reverberation method can be used down to 0·02 Mc.

12-10-1. Sonic velocity from ultrasonic measurement. When there is absorption in a medium, the wave velocity changes. So sound propagation in a medium exhibits dispersion in the neighbourhood of an absorption region. On both sides of the absorption peak, the wave velocity reaches a limiting value which is lower on the low frequency side (Fig. 12.12). This has been experimentally confirmed, the key experiment in this regard being the dispersion and absorption in carbon dioxide. Small amplitude ultrasonic velocity at low frequencies is identifiable with small amplitude sonic velocity as absorption regions are high up the frequency scale.

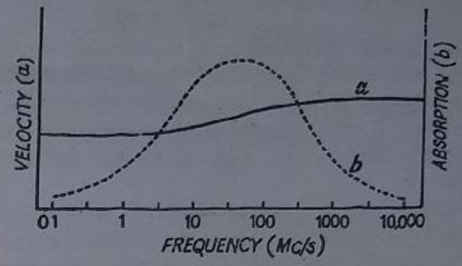


Fig. 12.12

12-11. Debye-Sears optical effect in ultrasonics. Debye and Sears discovered that alternate compressions and rarefactions caused by a sound wave in a liquid effectively produced a diffraction grating for light. This has provided a method for measuring ultrasonic wavelengths, hence velocities, and also absorption coefficients. One such method is illustrated in Fig. 12.13. The sound beam is produced by a suitable transducer (*C*), usually an X-cut quartz crystal, and is generally absorbed at the far end of the cell by some absorber (*A*) to eliminate standing waves. Light from a monochromatic source passes through a slit and then traverses the ultrasonic cell (*UC*) as a parallel beam. The image of the slit is focused on a photographic plate (*P*) along with the various diffracted orders.

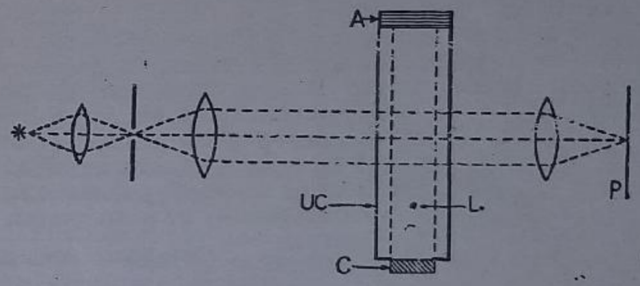


Fig. 12.13

According to Raman's theory, the diffraction angles θ, which can be determined experimentally, are given by

$$\lambda_s \sin \theta = n\lambda$$

where λ_s is the wavelength of ultrasonic waves and λ, that of light, n being a positive integer specifying the order of diffraction.

Absorption may be measured by replacing the photographic plate with a photometer and measuring the intensity of one of the diffracted orders as the position along the ultrasonic beam is varied.

When white light is used, a colour picture of the sound field is obtained in which areas of the same colour represent corresponding regions in the liquid having the same sound intensity.

Velocities can be determined to within 0·1%. In recent years, such optical methods have been used to study the distortion of waves caused by very high amplitudes. Both running and standing waves can be used.

12-12. Some effects and uses of ultrasonic waves.

(i) **Mechanical, chemical and biological effects** are produced in many substances by exposure to strong beams of ultrasonic vibration. For example, particles of colloidal material in liquids are shattered and form extremely fine emulsions. Polymerized molecules disintegrate and the chain of starch molecules splits into several fragments under the action of ultrasonic waves. Smoke is coagulated, and the large particles so formed cannot remain suspended in air. In this way smoke and dust particles can be removed from air and other gases. Many micro-organisms, and even tadpoles, can be killed by these waves. Sterilising equipment using ultrasonic waves has been devised. Milk can be freed from bacteria by such equipment.

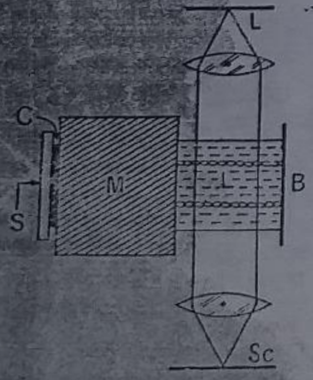


Fig. 12.14

(ii) **Flaw testing.** The Debye-Sears optical effect has been used for detecting flaws and inhomogeneities in solid materials. Fig. 12.14 shows an arrangement due to Sokoloff. *S* is an ultrasonic quartz oscillator and *M* the solid material under test. Good transmission of energy is assured by putting some oil between the surfaces of the two. In contact with the other side of *M* is a liquid held in a container *B*. A narrow beam of monochromatic light passes through the liquid at right angles to the ultrasonic beam. Spectra are formed on a screen *Sc*. The sample is moved slowly along.. If the material is homogeneous, the spectral pattern will remain unchanged. If it has flaws the intensity and sharpness of the spectral lines will change. In this way internal defects in opaque solids can be discovered.

Pulse method. The pulse method is, however, more commonly used for locating flaws in solid specimens. Short pulses of ultrasonic waves, each pulse containing an equal number of waves, are propagated through the material at regular intervals, and are picked up by a suitable receiver. If the frequency is 1 Mc pulses may be of 5 micro-second duration, and there may be 250 such pulses per sec.

Piezoelectric transmitters and receivers are used. Emission of a pulse applies at the same time a signal to the Y-plates of a cathode ray oscilloscope. The X plates are connected to a linear time base. As the pulse reaches the receiver, it induces a voltage across the crystal receiver. After necessary amplification and rectification, the voltage is applied to the Y-plates. Thus two vertical traces appear on the screen. Their distance of separation, as measured by the time base, represents the time of travel of the pulse. When the frequency of the time base is the same as the pulse repetition frequency the pattern appears stationary.

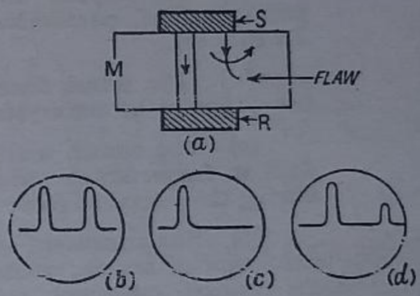


Fig. 12.15

The source (*S*) and the receiver (*R*) are placed parallel to each other at the opposite ends of the specimen (*M* ; Fig. 12.15*a*). Figures 12.15 *b*, *c* and *d* respectively represent the pattern to be seen on the oscilloscope screen when there is no flaw present (*b*), when there is a large flaw (*c*), and when the flaw is small (*d*).

When the transmitter is also made to serve as the receiver, we may have only one transducer in place of two. This is practised in the *pulse-echo method*. The sound pulses are reflected back to the transmitter, which now serves as receiver, from the far boundary of the specimen or from a flaw.

(iii) **Heating effect** of the waves is considerable. A rod dipped in a liquid through which an ultrasonic beam is passing becomes so hot that it cannot be held in the hand. The heat is caused by friction between the vibrating rod and the skin of the fingers. The heating may provide an alternative to the present methods of diathermy.