Doppler free spectroscopy of Rubidium and vapor cell interferometer

Vidhya S

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Certificate of Examination

This is to certify that the dissertation titled **Doppler free Spectroscopy of Rubidium and vapor cell interferometer** submitted by **Vidhya S** (Reg. No. MS13135) for the partial fulfillment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. Mandip Singh   Dr. Samir Kumar Biswas   Dr. Jasjeet Bagla

(Supervisor)

Dated: April 20, 2018

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Mandip Singh at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Vidhya S
(Candidate)

Dated: April 20, 2018

Dr. Mandip Singh
(Supervisor)

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Notation

ν_0	Resonance frequency
ν_L	Laser frequency
h	Plank's constant
$FWHM$	Full width half maximum
Rb	Rubidium atom
I_s	Saturation Intensity
L	Total angular momentum
S	Spin angular momentum
J	Total angular momentum
K	Kinetic energy
V	Potential enrgy
H_{so}	Hamiltonian of spin-orbit interaction
I	Nuclear angular momentum
H_{hf}	Hamiltonian of hyperfine splitting
ϕ	Phase
t	Thickness of glass plate
λ	Wavelength of beam
n	Refractive Index
ϵ	Dilectric constant
$ECDL$	Extrnal Cavity diode laser
PD	Photo detector
BS	Beam splitter
PBS	Polarizing Beam splitter
BS	Beam splitter
$\frac{\lambda}{2}$	Half wave plate
BS	Beam splitter
M	Mirror
D	Detectorr

Abstract

Doppler-free saturation spectroscopy is a technique used for the precise determination of Hyperfine spectrum of atoms without Doppler broadening. Throughout this work measured the Doppler-free hyperfine spectrum of two isotopes(^{85}Rb and ^{87}Rb) of Rubidium atom and observed the power broadening of spectra.Then we incoporated a Mach-Zehnder interferometer in this spectroscopy setup to measure the pump light induced phase shift in the Rubidium vapor cell.

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Chapter 1

Introduction

1.1   Absorption spectra and Doppler broadening

When atoms interact with electromagnetic radiation, it either absorbs or emits certain frequencies of radiation. This frequency of absorption or transmission is called as the resonance frequenc y of the atom, and it depends upon the energy difference of atomic state. For instance, consider a two-level system of an atom with ground and excited state energies are E_1 andE_2 respectively. Then the resonance frequency is,

$$\nu_0 = \frac{E_2 - E_1}{h} \tag{1.1}$$

where h is the Plank's constant. Even in the absence of an electromagnetic field, the excited state decays to the ground state by the spontaneous emission. In this spontaneous emission, photons are emitted in all direction with an energy spectrum having mean energy and a full width half maximum (FWHM) ΔE, which given by the Heisenberg's uncertainty principle,

$$\Delta E \Delta t = h. \tag{1.2}$$

Here, Δt is mean lifetime.The transition rate of atoms is defined as, $\Gamma = 1/\Delta t$. In the presence of external electromagnetic waves, stimulated transition rate depends upon the intensity of the field and is equal to non zero only when the laser frequency is near or equal to the resonance frequency. Stimulated emission photons also have Lorentzian energy spectra with an FWHM depended on the intensity of the field.

The intensity of a laser beam which propagated through the vapor cell has measured using a photodetector as the frequency is tuned through resonance frequency. As the laser beam passes through the cell, the number density of atoms in the ground and excited state get affected by the stimulated emission, and absorption and more importantly doppler shift caused by the thermal motion of atoms affected the energy spectrum of atom leads to further broadening of spectra called the Doppler broadening. In detail, atoms in vapor cell move in the random direction with each velocity component have the Maxwellian distribution of values. So due to this random motion, atomic spectral lines are said to be doppler broadened because the transition frequency is depending upon the velocity of the atom. That is if an atom is moving towards or away from the laser source, the atoms see either blueshifted or redshifted radiation. Only the atoms with zero velocity absorb the radiation at resonance frequency without any shift, and for those atoms which moving towards the laser the frequency gets blueshifted so frequency less than resonance frequency have to provide to get absorbed by the resonance frequency. Similarly, if an atom is receding away from the laser frequency, the atomic frequency get redshifted and laser frequency greater the than resonance frequency must be provided for the laser to get absorbed. Quantitatively, atoms with zero kinetic energy absorb the laser at the resonance frequency of ν_0 and if atoms moving with velocity v parrellel to the direction of the laser beam, then in the rest frame of laser atoms absorbs the laser with laser frequency ν_L, where ν_L is,

$$\nu_L = \nu_0(1 + v/c), \tag{1.3}$$

c is the speed of light. So the laser frequency has blue shifted from ν_0 to ν_L, and ν_L is greater than ν_0. Similarly if the atom is receding from the laser, the laser frequency has red shifted from ν_0 to ν_L

$$\nu_L = \nu_0(1 - v/c), \tag{1.4}$$

and the atoms absorbs the laser beam at the frequency less than the resonance frequency of the atom. So set of atoms with different velocities absorbs a broad range of frequencies and results in broadening of absorption spectra. Normally atoms in thermal motion have Maxwellian distribution of velocity and the probability of finding atoms which have velocity between V and $V + dv$ is,

$$P(V)dV = (\frac{M}{2\pi kT})^{1/2} exp(-\frac{MV^2}{2kT})dV \tag{1.5}$$

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where M is the mass of the atom, k is the Boltzmann constant and T is the temperature and the FWHM of Doppler broadened spectrum is

$$\Delta \nu_{1/2} = 2\frac{\nu_0}{c}(\frac{2KT}{M}ln2)^{1/2} \tag{1.6}$$

1.2 Doppler free saturation absorption spectroscopy

Saturation absorption spectroscopy is a technique which aims to produce Doppler-free absorption spectra of atoms .

The laser from an external cavity diode laser source splits into three beams consist of two less intense probe beam of the same frequency and same intensity, which parallelly propagates through the vapor cell in the same direction and one high intense pump beam, which counter-propagate to the probe beam and overlap with one of the probe beam. The overlapping probe beam is called as the first probe beam. Since they are overlapping inside the cell, they interact with the same set of atoms. The Doppler shift caused by the pump is opposite to the shift caused by the probe beam since they are counter-propagating. That is if an atom was moving with velocity v, the Doppler shifted the frequency of the probe beam is $\nu_0(1 + v/c)$ and of the pump beam is $\nu_0(1 - v/c)$, where ν_0 is the resonance frequency. So the same atoms interact with the pump and probe beam at different frequencies, and the absorption of the probe beam is not affected by the absorption of the pump beam. But if atoms are stationary that is if their kinetic energy is zero, then both beams interact with the same atom simultaneously. Then due to the high photon flux of pump beam, the absorption rate is very high, and it excites most of the atoms from the ground state to excited state and eventually to the ground state by the spontaneous emission. So high intense pump beam depletes the ground state population, as a result when we monitor the absorption spectra of the probe beam, small peaks start to appear corresponding to resonance frequency of transitions, these small peaks are called as the lam dip. In the absence of the pump beam, spectrum detected is the traditional Doppler-broadened absorption spectra, but when the pump beam is turned on, the absorption spectra is the Doppler-broadened spectra with lamb dips at resonance frequencies of the atomic transitions. The width of lamp dip is very much less than the Doppler width. Even though the absorption spectra of first probe beam contains lab dips, the second probe beam's absorption spectra don't have any lamb dips. So now it is easy to resolve the absorption peaks without the Doppler broadening, by

subtracting the absorption spectra of first probe beam from the second probe beam, that is why it is called the Doppler-free spectroscopy. Once the pump beam intensity is higher than the saturation intensity(I_s), which is the intensity at which excited and the ground state has equal population, power broadening of absorption spectra occurs. Natural linewidth of the spectrum is due to the spontaneous emission of atoms, but if the field has very high intensity, stimulated emission dominates the spontaneous emission and causes shortening of excited state's natural life time, which leads to the broadening of peaks by the uncertainty principle. So as the laser intensity increases, the rate of induced emission increases and results in further broadening. A Quantity saturation parameter s is defined as the ratio of the stimulated to the spontaneous transition rate, and the corresponding intensity is the saturation intensity I_s, is the photon flux required to achieve the ratio. So the intensity of pump and probe beam must always be less than the saturation intensity to avoid the power broadening.

1.2.1   Multi level atoms

So far considered the case of the only two-level system, but it cannot apply to real atoms, which consist of multiple ground and excited state. So in the case of multiple level atom additional feature called cross-over resonance and optical pumping has to be considered. Cross-over resonance is the additional peaks appears because several upper or lower levels are close enough in energy that their Doppler-broadened profiles overlap. Optical pumping happens when atoms in the excited state spontaneously decay to more than one ground state results in the depletion of the state which can enhance or diminish absorption peaks.

Crossover peaks appear exactly at the midway frequency of two transitions from a common ground state and different excited state. For instance, consider the situation of having two excited states and a common ground state with the resonance frequency of ν_1 and ν_2. In the presence of the pump beam absorption spectra gives two lamb dips at frequency ν_1 and ν_2. In addition to that, there is a cross-over resonance peak at a frequency of $\frac{\nu_1+\nu_2}{2}$, because pump beam and probe beam interact with the different set of atoms which have the same velocity but in the opposite direction. So due to the opposite Doppler shift, the pump beam in resonance with the one transition and t the same time probe beam is in resonance with the other transition. In detail, consider atoms which have velocity $+/-V_1$ and $+/-V_2$ and the V_1 velocity red shifted to ν_v1 resonance frequency by the pump beam and $-V_2$ blue shifted to ν_1 frequency by the probe beam similarly for the ν_2 transition. So technically like the

zero atoms, pump and probe beam make same transition and depletion of ground state population by the pump beam happen. Quantitatively, the probe beam doppler shifted to ν_1 frequency by the +V atoms, $\nu_1 = \nu_L(1 + V/c)$ and doppler shifted to ν_2 transition by the V atoms, $\nu_2 = \nu_L(1 - V/c)$. Solving for the laser frequency gives $\nu_L = \frac{\nu_1 + \nu_2}{2}$, the crossover frequency.

Optical pumping happens when one atoms in excited state can decay to more than one ground state when the energy separation of lower levels are much more than the Doppler width. Even when the atom is on resonant with only one of the lower level, the chances of decaying to the other lower level is high. Once the atom decays to the non-resonant level, atom no longer interacts with the laser, and the atom said to be 'shelved.' Further, it cannot participate in the absorption. So optical pumping can deplete the population of resonant lower level which in turn affects the size of absorption peaks.

1.3 Atomic structure and energy levels of Rubidium(Rb).

The atomic number of Rb is 37 and the electronic configuration of the ground state is $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^{10}, 4s^2, 4p^6, 5s^1$. The outermost shell or valence shell contains only one electron, so the spectrum resembles with the Hydrogen atom spectra. The next possible atomic transition is from 5s to 5p, which doesnt affect the remaining electrons in the inner shells. Rb in its natural condition exist in the form of two isotopes, ^{85}Rb(72%) and ^{87}Rb(28%).

1.3.1 Fine structure

Fine structure energy level arises due to the energy difference in the Coulomb and spin-orbit interaction. The Coulomb interaction is because of the usual electrostatic potential energy between the electrons and between the electrons and nucleus. The spin-orbit interaction appears because of the orientation energy caused by the electron's magnetic dipole moment μ in the internal magnetic field B of atoms, which is represented as $\mu.B$. The Russell-Saunders or L-S coupling scheme provides an appropriate description of the strength and form of the fine splitting of energy levels. Angular momentum quantum numbers L, S, J, have introduced by the L-S coupling method. The magnitude of total angular momentum is described by the Quantum

number L that is, L is the sum of the electron's angular momentum $L = \Sigma_i l_i$, where l_i is the angular momentum of electrons. Whereas the quantum number S represents the magnitude of the total electronic spin angular momentum that is the sum of the spin angular momentum, $S = \Sigma_i s_i$, where s_i is the spin angular momentum of electrons. The third quantum number J represents the magnitude of total electronic angular momentum, means the sum of the total orbital and total spin angular momentum, which is given as $J = L + S$. The magnitudes of these quantum numbers are $J = \hbar\sqrt{j(j+1)}$, $L = \hbar\sqrt{l(l+1)}$ and $S = \hbar\sqrt{s(s+1)}$. Each energy level in the hyperfine splitting denoted by the term symbol, $^{2S+1}L_J$, where the term $2S+1$ is called as the multiplicity. L denotes S,P,D... corresponding to L =0,1,2,.. The total angular momentum can take value from $|L - S|$ to $L + S$. For any filled orbital the sum of orbital and spin angular momentum is zero. So since Rb atom contains only one electron in the unfilled valence orbital, the values of L and S depends only on the valence electron. The lower level of Rb is 5s, so L= 0, S= 1/2 and the multiplicity is 2, doublet. The total angular momentum J can take only one value of 1/2 then the term symbol is $^2S_{1/2}$. The next possible atomic subshell is 5p, so L=1, S=1/2, and J can take the values of 1/2 and 3/2, and the appropriate term symbols are $^2P_{1/2}$ and $^2P_{3/2}$.

The nonrelativistic Hamiltonian of the atom having one electron with the fine splitting of energy is,

$$H = K + V + H_{so}. \tag{1.7}$$

The first term K of the Hamiltonian is the kinetic energy of the electron which is given as,

$$K = \frac{p^2}{2m}$$

here p is the momentum of electron mass m. The second term represents coulomb interaction energy of the single electron with the other electrons and with the nucleus, which is represented as,

$$V = -\frac{Ze^2}{4\pi\epsilon_0 r}$$

where Z is the atomic number of the atom, e is the electronic charge and r gives the distance between the electrons. The K+V term causes for the energy splitting between 5s and 5p. Finally the third term H_{so}, of the Hamiltonian describes the spin-orbit interaction,

$$H_{so} = \zeta(r)\mathsf{L}.\mathsf{S}. \tag{1.8}$$

The magnitude of $L.S = (J^2 - L^2 - S^2)/2$, so rewriting H_{so} as

$$H_{so} = \zeta(r)\frac{\hbar^2}{2}[j(j+1) - l(l+1) - s(s+1)]. \tag{1.9}$$

The fine splitting of $5^2S_{1/2}$ to $^2P_{1/2}$ is in the wavelength of 794.764nm and the transition between these two level is called the D_1 transition. The wavelength of transition between the energy levels of $5^2S_{1/2}$ and $5^2P_{3/2}$ is 780.023nm, and this transition is called as the D_2 transition.

1.3.2 Hyperfine splitting

In addition to the fine splitting of energy level, there is finer energy level called hyperfine energy level arises due to the energy difference in the orientation energy of nuclear magnetic dipole moment in the presence of the magnetic field of the atom. Since nuclear magnetic momentum is proportional to the spin angular momentum of the nucleus, the magnitude of the nuclear angular momentum is represented by the quantum number I. The hyperfine energy level depends upon the total angular momentum that is the sum of the nuclear spin magnetic momentum and electronic angular momentum, so the quantum number representing hyperfine energy level is $\mathbf{F}$, where

$$\mathbf{F} = \mathbf{J} + \mathbf{I} \tag{1.10}$$

and $\mathbf{J}$ is total electron angular momentum and $\mathbf{I}$ is nuclear spin angular momentum. The allowed values of $\mathbf{F}$ ranges from $|J - I|$ to $J+I$. Since nuclear magnetic moment is much smaller than the electronic, magnetic moment,t the hyperfine splitting appears to be smaller than the fine splitting. The allowed values of quantum number $\mathbf{I}$ vary with different isotopes since it depends on the nuclear structure, so two isotopes of Rb have different I value. The ^{85} Rb isotope has I value of 5/2 and ^{87} Rb has 3/2. So when considering the number of hyperfine energy levels of Rb, the ground state $^2S_{1/2}$ and one of the excited state $^2P_{1/2}$ contains two energy levels F=I-1/2, I+ 1/2 and the other excited state $^2P_{3/2}$. contains four hyperfine levels which are F = I-3/2, I-1/2, I+1/2, I+3/2. the selection rule for the dipole transitions are, $\Delta F = 0, \pm 1$ (not 0 to 0) $\Delta J = 0, \pm 1$ and $\Delta S = 0$

Now the Hamiltonian of atom contains an extra term H_{hf} because of the hyperfine splitting, which is represented as,

$$H_{hf} = \alpha\mathbf{J.I} + \frac{\beta}{2I(2I-1)J(2J-1)}[3(\mathbf{I.J})^2 + \frac{3}{2}(\mathbf{I.J}) - I(I+1)J(J+1)]. \quad (1.11)$$

Here α is magnetic hyperfine constant, it has unit of energy and β is electric quadrapole interaction constant. Solving for the value of $\mathbf{J.I}$ gives

$$\begin{aligned} \mathbf{J.I} &= (\mathbf{F}^2 - \mathbf{J}^2 - \mathbf{I}^2)/2 \\ &= [F(F+1) - J(J+1) - I(I+1)]/2. \quad (1.12) \\ &= C/2 \end{aligned}$$

where C represents the dimensonless magnitude F(F+1) - J(J+1) - I(I+1). So replacing the $\mathbf{I.F}$ in the Hamiltonian and including fine enrgy terms, gives Casmir Energy formula for enrgy values of hyperfine levels, $E_{J,F}$

$$\begin{aligned} E_{J,F} &= E_J + E_{hf} \\ &= E_J + \alpha\frac{C}{2} + \beta\frac{3C^2/4 + 3C/4 - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}. \quad (1.13) \end{aligned}$$

From Eq.(1.13), we will get frequency of the different hyperfine level by dividing the equation with Plank's constant,

$$\nu_{J,F} = \nu_J + A\frac{C}{2} + \frac{[\frac{3}{4}C(C+1) - I(I+1)J(J+1)]}{2I(2I-1)J(2J-1)}, \quad (1.14)$$

where $A = \alpha/\hbar$ and $B = \beta/\hbar$, and both have unit of Hertz. The detailed values of constant A and B for various hyperfine transition for the two isotopes is given below in the table1.1

$A_{5^2S_{1/2}}$	$h \cdot 1.0119108130(20)$ GHz		$A_{5^2S_{1/2}}$	$h \cdot 3.41734130545215(5)$GHz
$A_{5^2P_{1/2}}$	$h \cdot 120.527(56)$ MHz		$A_{5^2P_{1/2}}$	$h \cdot 408.328(15))$ MHz
$A_{5^2P_{3/2}}$	$h \cdot 25.0020(99)$ MHz		$A_{5^2P_{3/2}}$	$h \cdot 84.7185(20)$ MHz
$A_{5^2P_{3/2}}$	$h \cdot 25.790(93)$ MHz		$A_{5^2P_{3/2}}$	$h \cdot 84.7185(20)$ MHz

(a) The values of A and B for the isotope ^{85}Rb (b) The values of A and B for the isotope ^{87}Rb

Table 1.1: Values of magnetic dipole constant and quadrapole constant for various hyperfine enrgy level of two isotopes of Rb

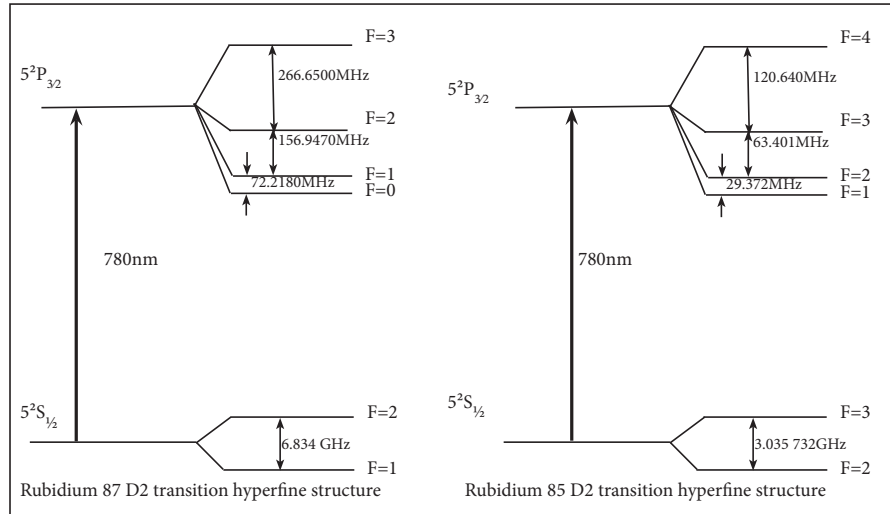The hyperfine energy level diagramme of the two isotopes is given below in the fig1.1

Figure 1.1: The Hyperfine energy level digramme of ^{87}Rb and ^{85}Rb

1.4 Mach Zehnder interferometer with Rb cell as phase shifter

1.4.1 Mach Zehnder interferometer

Mach interferometer is a device which produces interference by the division of the amplitude of light. A light beam from the laser first split into two beams by a 50/50 beamsplitter. Then this reflected and transmitted beams allowed to travel through different paths to the photodetector. Before striking the detector, these two beams get combined by another 50/50 beam splitter and overlaps over some distance. The path difference between the two paths results in interference of two beams. There is a phase shift of π caused by the beam splitter, but since both the beams are passing through the same beam splitter, there is no phase difference by the beam splitter. Moreover, a glass plate is used in one arm of the interferometer to produce a phase difference. By rotating a glass plate of thickness t by an angle θ changes the thickness

of the glass plate which in tur causes a phase shift, ϕ,

$$\phi = \frac{2\pi}{\lambda} t'(n-1). \tag{1.15}$$

Where t' is the changed thickness

$$t' = \frac{t}{cos(\theta)} \tag{1.16}$$

and n is the refractive index of the glass which is 1.5. The change in phase with respect to the change in the angle is

$$\frac{d\phi}{d\theta} = \frac{2\pi}{\lambda} t \mathrm{cosec}\theta \tan\theta(n-1) \tag{1.17}$$

The electric field of light which passes through the arm does not contain glass plate is E_1,

$$= E_0 \exp{-i(kz - wt)}, \tag{1.18}$$

where E_0 is the amplitude of the wave. The electri field of the wave passes through the arm conytain glass plate is E_2,

$$E_2 = E_0 \exp{-i(kz - wt - \phi)}. \tag{1.19}$$

. Then the Intensity of light strikes at the photodetector is,

$$I = I_0(1 + \cos\Delta\phi),$$
$$= 2I_0 \cos^2\frac{\Delta\phi}{2}. \tag{1.20}$$

Chapter 2

Experimental setup

In this chapter discussing the deetails of the experimental setup used for the spectroscopy and interferometer experiment. In addition to that short description of instrumenst used also included.

2.1 Instrumentation

In addition to the common physical laboratory instruments like the digital oscilloscope, more advanced instruments and components are required to carry out this experiment. The brief description of some of them is given below.

1. **External cavity diode laser**

   The external cavity diode laser(ECDL) is the main part of the experimental setup. The Littman-Metcalf configuration of ECDL consists of a diffraction grating and lens with the diode laser. The light from the diode laser passes through the lens to form a collimated beam. Then this beam directed to a diffraction grating, in this the zeroth order diffracted beam come out as output and the first order diffracted beam is reflected to mirror. The beam again reflected by the beam and strikes on the diffracting from which it directs to the diode laser. So the mirror and the diffraction grating is responsible for the laser action. By applying the voltage the position of mirror changes which in turn causes to change the length of the cavity. So this provides the tuning of the laser over a wide range of frequencies.

   The wavelength required for the experiment is 780nm, that is the transition wavelength required for the D2 transition of Rb atoms. The frequency of the

laser depends mainly on Temperature, Current and the position of the grating. The frequency and temperature together constitute the coarse tuning of frequency. They set the frequency over which the diode laser performs. Once the appropriate range set, the frequency can be continuously tuned by changing the position and orientation of grating; this is the fine-tuning of the laser diode. The Piezoelectric transducer(PZT) has used for accomplishing the fine-tuning of the laser. The PZT is located below of the grating mount of diode laser and it gets expands with the change in Voltage. Since the number of wavelength in the laser cavity is constant, the wavelength or frequency can change with changing the cavity length. But if the cavity length change goes too far, the mode hope occurs, that is the number of half-wavelength changes by one or two in the cavity that is there is switching from one longitudinal mode to another mode. This switching also results in fluctuating the intensity slightly which in turn cause to increase of relative intensity noise. This mode hope can be avoided by optimizing the laser temperature and laser current accurately.

2. **Photodetector**

The detector used for the experiment is photodiodes, two photodetectors are used for two probe beams, and detected photons are converted into electrons which in turn measured as a voltage by either by passing through a current amplifier or sending to the ground through a resistor. In addition to that, both photodiodes are placed in one box with a circuit providing two probe beam signal as well as a difference signal between two probe beam. When the laser is tuned to resonance, the photons get absorbed by the atoms and the intensity of light coming to the photodetector get reduced. Even though the intensity of beam gets to the PD is reduced because of absorption still, there is a high intensity of beam which saturates the photodetector means the number of electrons detects higher than the rate of the electron to photon conversion, which results in unconverting of many electrons and then undetecting the electrons. So the intensity of beam should not be very much higher such that it does not saturate the photodetector.

3. **Beam splitter**

Beam splitters are optical devices which used to splits single beam of the laser into two beams of different intensity. The type of beam splitter used in this experiment is cubic beam splitter which made of two glass prism glued together. When the beam is passing through the beam splitter, some of it gets reflected

one direction, and some of it gets transmitted. Mainly there are two types of the beam splitter; they are polarizing beam splitter(PBS) and non-polarizing beam splitter(BS). In non-polarizing splitter, the intensity of reflected and transmitted beams have specific R/T ratio. Particularly a 50/50 beam splitter, splits single beam to two beams of equal intensity in different direction means the beam gets partially reflected and partially transmitted by the beam splitter. On the other hand, the polarizing beam splitter, the reflection, and transmission depend upon the polarization of beam, that is it designed to reflect S polarized and transmits P polarized beam. So the intensity of reflected and transmitted beams can be controlled by using a waveplate together with the beam splitter. The waveplates are used to change the polarization of beams passing through it, particularly the half-wave plate changes the direction of the linear polarized beam. So by combining the waveplate and polarizing beam splitter, the intensity of reflected and the transmitted beam can change, and the high intense pump beam and less intense probe beam can make this way.

2.2   Producing hyperfine spectrum

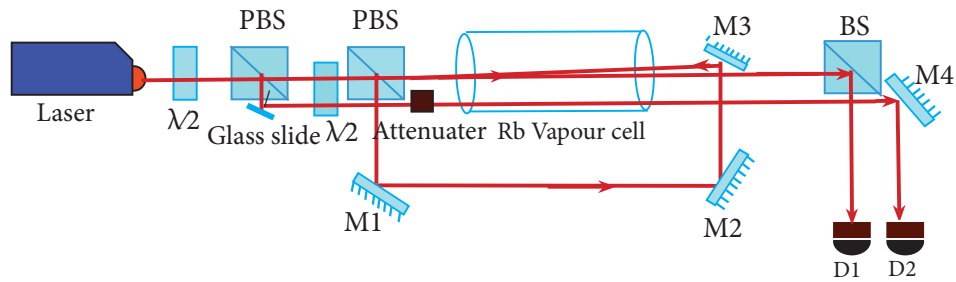The setup for producing the hyperfine spectrum of Rb is shown in fig 2.1

Figure 2.1: The experimental setup for producing hyperfine spectrum Rb atoms.

The beam from a 780 nm diode laser first splits to two probe beams using a polarization beam splitter(PBS), a half wave plate($\lambda/2$) used in front of this PBS to

control the intensity of both beams. The intensity of beams should not be higher than the saturation intensity(I_s), here for Rb $_s$ is 1.6mW/cm^2. So using wave plate the intensity of transmitted beam can be made to be lesser than the reflected beam, the transmitted beam is the first probe beam which overlaps with the pump, and the reflected beam is the second probe beam or the reference beam. Two probe beam must be in parallel direction when passing through the vapor cell for that, a glass plate used to reflect the reference beam and made it parallel to the first beam. When the beam passes through the glass plate, it also transmits and reflects the laser, but the intensities are not same. So the high intense transmitted beam from the glass plate has blocked using a beam tumbler, and an attenuator has used for reducing the intensity and make it equal to the power of the first probe beam. The first probe beam again splits to two, the probe and the pump beam and intensity of pump beam made to be higher than the probe by rotating the half wave plate put in front of the PBS. The reflected pump beam struck to mirrorM1 and directed to mirrorM2; then upon reflecting by the mirrorM3, it passes through the vapor cell. Vapor cell is a glass cell contains Rb in the natural condition with two isotopes ^{87}Rb and ^{85}Rb. Then all the three beams allowed to pass through the Rb vapor cell, in which two probes propagate parallel to each other and pump beam propagates and overlapping to the first probe beam. The vapor cell has tilted by some angle to avoid the back reflection of beams inside the vapor cell. Then both the probe beam is detected using the photodetector, in which a 50/50 beam splitter used to reflect the probe beam to the detector and the reference beam struck to the mirror M4 and reflected directly to the detector. The detector then connected to the oscilloscope to monitor the absorption spectrum.

Once the beams are correctly aligned, the frequency of the laser has to be tuned to the resonance frequency of atoms. At first, coarse tuning of the laser has been done by setting the current and temperature of laser suitably without any mode hopping, and the temperature values are 23.1^{0}C and the current is 1315mA. Then change the grating of laser diode till the fluorescence is visible inside the cell through the IR viewer. Initially, blocked the pump beam, and not allowing to pass through the vapor cell and expected to get a doppler broadened spectra with two broadened absorption dip of two isotopes in the oscilloscope. Once the pump beam is unblocked, it overlapped with the probe beam and expected to get small peaks in the Doppler-broadened absorption dip corresponding to the hyperfine transition of atoms when monitoring the first probe beam in the oscilloscope. Now to resolve the hyperfine peaks from

the Doppler-broadened background uses the second probe beam in which the oscilloscope connects to the circuit providing the difference in the two probe beams. It gives substracted spectra of two probe beam which doesn't have any doppler broadening background, only the hyperfine peaks. So by a proper aligning and tuning of laser beams, the hyperfine spectra of two isotopes of Rb atoms with crossover resonance peaks expected to get.

2.3 Mach-Zehnder interferometer with phase shifter based on Rb vapor cell

The setup for measuring the interference signal from a Mach Zehnder interferometer with doppler free absorption spectroscopy is given below in the fig 2.2
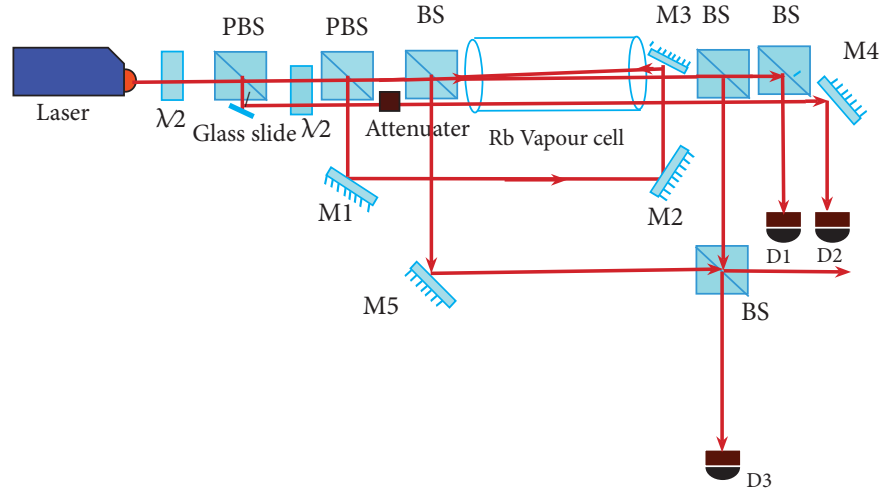
Figure 2.2: The experimental setup to measure light-induced phase shift

A beam splitter has placed before the vapor cell to split the probe beam into two beams. The reflected beam strikes to the mirror M5 and propagates in parallel to the transmitted beam from the beam splitter. An attenuator has placed in the path to make both beams of the same intensity. Again a 50/50 beam splitter has used for splitting the probe beam which passes through the Rb cell. The transmitted beam directed to a photodetector to measure the absorption spectrum. A 50/50 beam splitter has used for recombining two reflected beams, and they allowed to overlap over 1 meter before striking the photodetector. The photodetector has connected to

the oscilloscope to visualize interferometric signal.

After this to check whether the interferometer is working or not, we removed the Rb cell and blocked the Pump beam. The Mach Zehnder interferometer setup is shown in fig 2.3
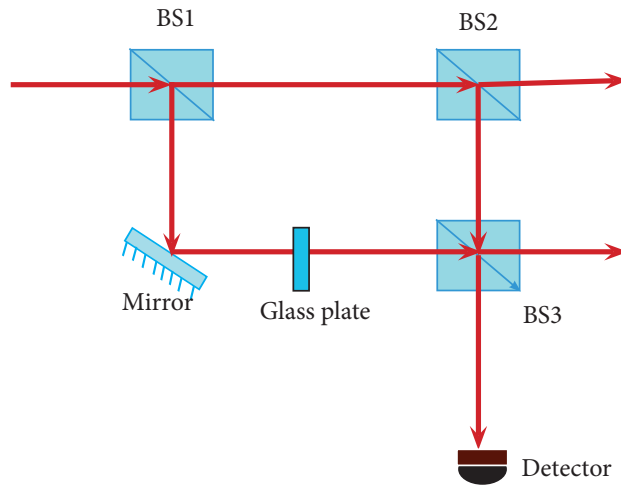
Figure 2.3: The Mach Zehnder interferometer setup with varying phase shift

Then placed a thin glass plate of thickness 't' to the lower path of the interferometer. This glass plate was placed in a rotating ground state. So as rotating the glass plate by some angle θ there will be a phase shift corresponding to the change in path length due to the change in thickness of the glass plate. By properly optimizing the position of two overlapping beams and intensity of beams shows an interferometric signal with maximum visibility.

Chapter 3

Result and analysis

3.1   Hyperfine spectrum of Rb

At first, produced the standard absorption spectra of Rb by passing only probe beam through the vapor cell and the pump beam is blocked. The result obtained is shown in fig 3.1 The two large dip in the spectrum is the absorption dip of two isotopes ^{87}Rb and ^{85}Rb.
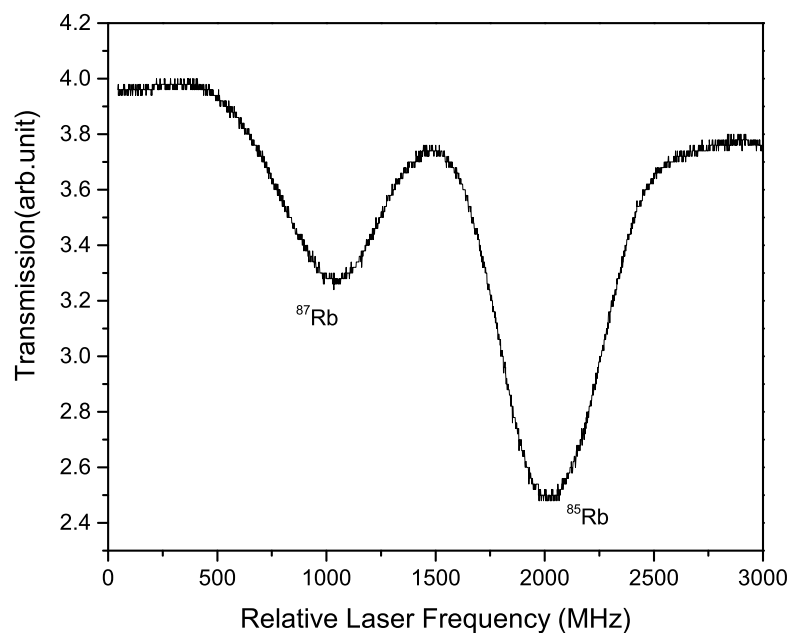

Figure 3.1: Absorption spectrum of Rb without pump beam

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The corresponding absorption taking place is the absorption from the ground state of $5^2S_{1/2}$ F=2 to excited states of$5^2P_{3/2}$ for ^{85}Rb and from the ground state of $5^2S_{1/2}$ F=3 to excited state of $5^2P_{3/2}$ for ^{87}Rb. The complete spectrum of the ground state would have a fourth peak further to the right corresponding to the F = 1 energy level of 87Rb; this was apparently out of the range of our scan. It is clearly shown in the spectra that absorption of ^{85}Rb is more deeper than ^{87}Rb, this is because ^{85}Rb is more in proportion() than ^{87}Rb in the natural condition of Rb and also the energy difference between the hyperfine level of ^{85}Rb is higher than ^{87}Rb.

Now unblocked the pump beam and allowed to overlap with the probe beam in the vapor cell. So pump beam saturates the ground state, and lamb dips appear.The absorption spectrum with the pump beam is shown in fig 3.2
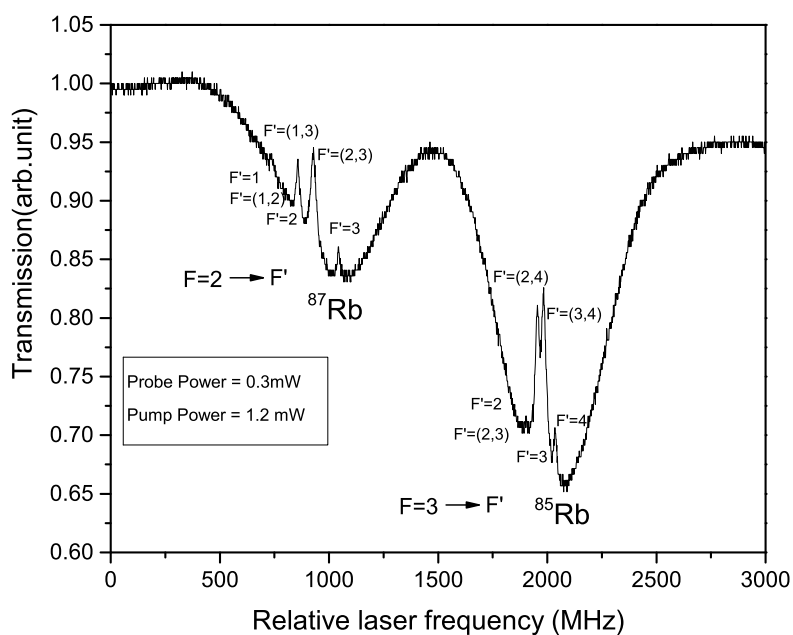

Figure 3.2: Absorption spectrum of Rb with the pump. The small peaks are hyperfine peaks corresponding to the transition.

The spectrum shows the lamb dips corresponding to the hyperfine transitions with the Doppler broadening. The crossover resonance peaks are also visible in the spectra. The intensity of probe and pump used are 0.3mW and 1.2 mW respectively.

Now the absorption spectra from bothof the probe beams are subtracted to remove Doppler broadened background. This results are shown below.
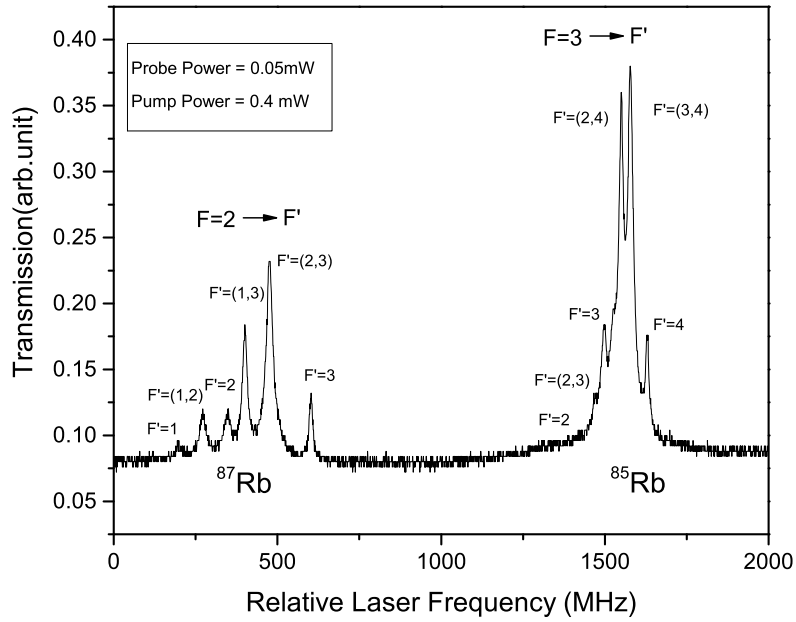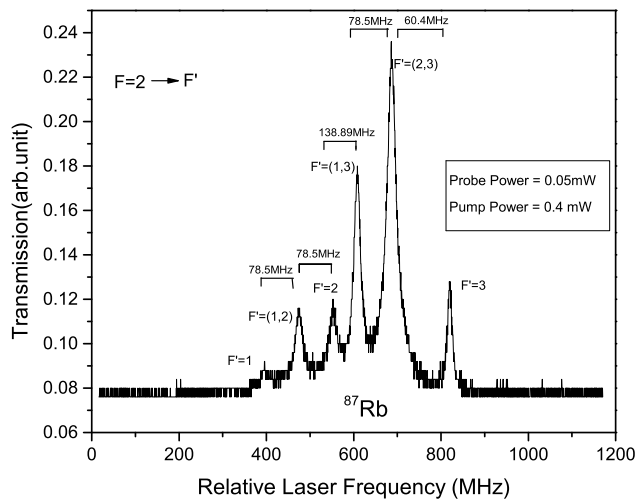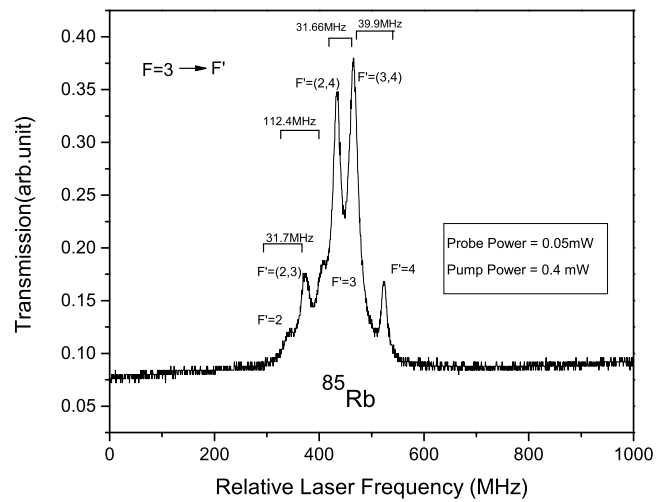
Figure 3.3: Absorption spectrum of Rb with the pump. The small peaks are hyperfine peaks corresponding to the transition.

(a) Hyperfine spectrum of isotope ^{87}Rb

(b) Hyperfine spectrum of isotope ^{85}Rb

The fig3.3 shows the doppler free hyperfine spectra of both the isotope. The intensity of pump and probe are 0.4mW and 0.05mW respectively. Fig 3.3(a) shows

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spectrum of only ^{87}Rb. It is shown that there are six hyperfine peaks and three of them are crossover resonance peaks. The ground state of the absorption is F=2, then by the selection rule of the dipole transition, the allowed transition to the excited levels are F' = 1,2,3. There are crossover resonance because these energy levels are so close in energy and have a common ground state of F=2. The crossover resonance in the spectrum are exactly midway of the transition F'=(1,2), F'=(1,3) and F'=(2,3). The corresponding frequency difference calculated from the eq 1.14 is also shown in the spectra.The fig 3.3(b) hyperfine transition of ^{85}Rb, there are also six hyperfine peaks including the crossover. Here the ground state is F=3, so allowed transitions are F'=2,3,4. The crossover resonance is between the transition of F'=(2,3), F'=(2,4) and F'=(3,4). The thing worth to note here is that the crossover resonance peaks are always larger than the normal hyperfine transition peaks for both of the isotope, this is because the density of atoms participates in the crossover transitions are higher than those in the normal transitions.

The power broadening of Rb spectra also checked. Now the intensities of both the beam have increased to the values higher than the saturation intensity of Rb. The intensity values are 1.5mW for the probe beam and 3.2mW for the pump beam. The broadening of spectra is shown in the below figures.
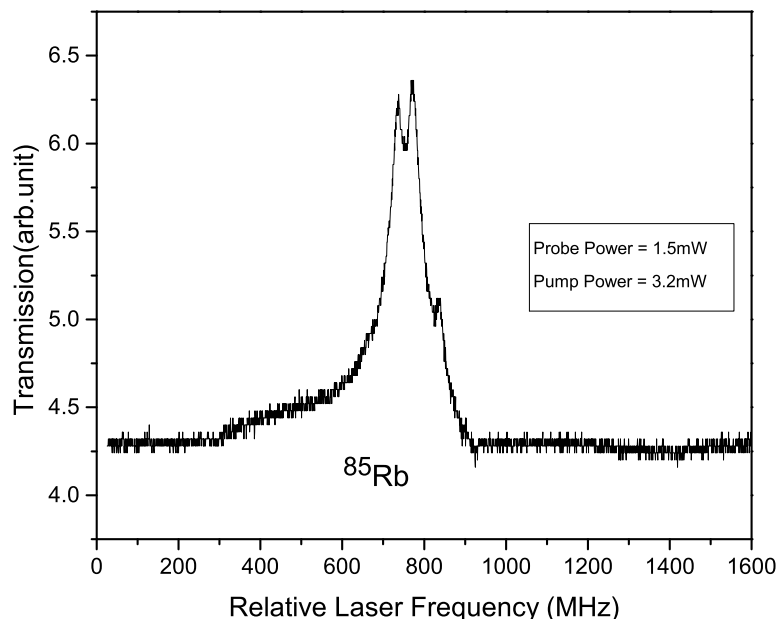

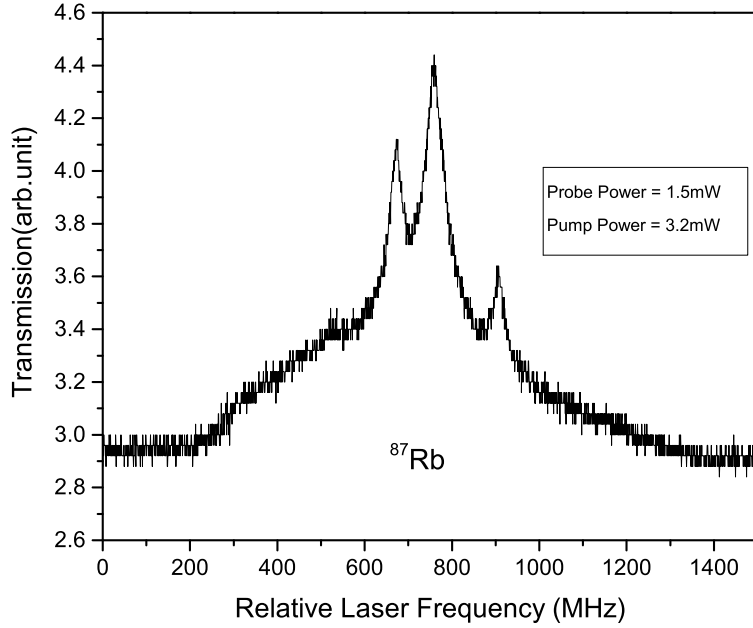Figure 3.5: The power broadening of the absorption spectra of ^{85}Rb

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Figure 3.6: The power broadening of the absorption spectra of ^{87}Rb

3.2 Interefernce from the Mach interferometer

As we rotates a phase shift has produced due to the change in the pathlength. The oscilloscope showed the interference oscillations and then optimized the system to get maximum visibility. From the oscilloscope signal calculated the visibility of the interferometric signal and the maximum visibility obtained is 75%. Then note down the change in intensity with change in θ of 0.1^0. Calculated the phase difference for the change in angle using the equation (1.17) snd plotted phase shift v/s Intensity. The fig 3.7 shows the plot obtained when plotting the phase difference v/s Intensity.
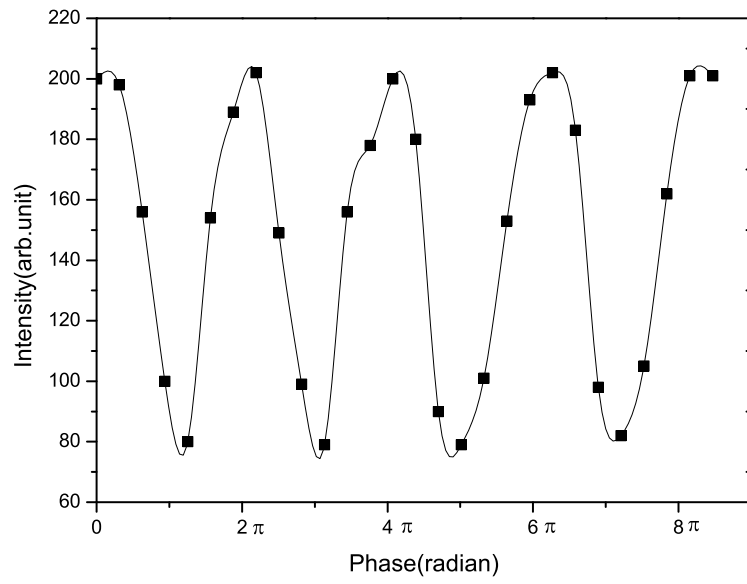
Figure 3.7: Interference signal from the Mach Zehnder interferometer.

The plot shows the expected cos-wave signal with variation in phase shift. So we can conclude that our Interferometer is working properly.

Chapter 4

Conclusion

Throughout this thesis work, Doppler-free Saturation absorption spectroscopy of Rb atoms has reported. At first, produced the Doppler-free hyperfine spectrum of isotopes ^{85}Rb and ^{87}Rb for the hyperfine transitions of F=3 to F' and F=2 to F' respectively. In addition to this, we observed the power broadening of the hyperfine spectra, when providing beam intensity higher than the saturation intensity of Rb.

Then we incoporated a Mach-Zehnder interferometer in this spectroscopy setup, in a way that the Rb vapor cell placed in one arm of the interferometer. To check whether the interferometer is working properly, put a thin glass plate in one arm of the interferometer and produced the interference signal without the Rb cell and pump beam. Then we concluded that our interferometer is working correctly with visibility of 75%.

In the future, we place the Rb cell in the interferometer and measures the light-induced phase shift in the interferometer because of the pump beam

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