Chapter 4

Quantum Interference in Atomic Ensemble and its Applications

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4.1 Introduction

In this information age, precise and accurate time keeping device are in much demand for a wide range of applications like global positioning system, secure communication, financial transaction or in advance physics experiments. Thus, the technology evolution of time keeping is in continuous progress starting form pendulum to quartz to atomic clocks. The atomic frequency standard-based time keeping devices like atomic clock are in much demand for its accuracy and compactness. There is also a considerable interest in the development of highly sensitive magnetometer for a variety of applications like biomedical, geo-magnetic field mapping, underground and underwater surveys to stellar and interstellar field mappings. The highly sensitive atomic magnetometer has unique advantages due to their operation near room temperature and compactness.

4.2 Revolution in Time Keeping

All time keeping devices are based on the measurement of a periodic event repeated at a constant rate [34]. The device which exhibit a periodic motion with the help of an energy

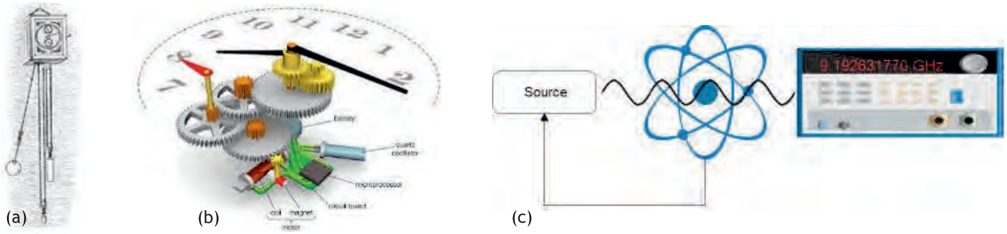

Figure 4.1: Development of Atomic Clock: (a) Pendulum Clock [32], (b) Quartz Clock [33], and (c) Schematic of Atomic Clock.

source is called an oscillator. The rate at which the oscillator shows a periodic motion is basically defined as time.

Early age oscillators

The very early source of time standard was the natural oscillator viz the Earth's rotation on its own axis. Thus, the basic unit of time, second was defined as the fraction of the solar day (1/86400). But scientists soon realised that the time based on natural oscillator are less accurate as the length of the solar day fluctuates large according to the seasonal changes. Thus, soon mechanical (Pendulum Clock) and electrical oscillator (Quartz Clock) took over the natural oscillator as time standard [34, 35]. In 1969, Christian Huygens invented the mechanical clock inspired by the investigations of pendulum by Galilieo Galilie around 1602. He took the advantage of harmonic motion exhibited by the pendulum to designed the time keeping standard. Due to the harmonic motion, the pendulum swings back and forth around its equilibrium position at a particular rate. The period with which it exhibits oscillation is given by

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{4.1}$$

where L is the length of the pendulum rod and g is the acceleration due to gravity. The major source of error in these types of clocks is thermal expansion. As the pendulum rod is made of metal, it becomes very much prone to the surrounding temperature. A slight increase in temperature causes the pendulum rod to expand, thereby increasing the clock period. Thus, the accuracy of these types clocks is typically one minute per day.

In 1927, Quartz clock were first developed by Warren Marrison and J. W. Horton to improve the time keeping performance beyond the mechanical clock. These clocks were based on the piezoelectric property of the crystal. In a suitable electronic circuit, the interaction of mechanical stress and electric field causes the crystal to vibrate and generate electrical signal at a particular frequency. This frequency is used as a time for crystal-based clocks. The major drawback of crystal-based clock is the ageing effect in addition to the other detrimental factor like crystal size, shape and crystal plane. So, typically, the accuracy of these clocks is ±0.2 seconds per day.

Atomic oscillator

Lord Kelvin in 1879, first suggested the possibility of an atomic clock based atomic oscillator using atomic transitions [36–38]. In 1949, the US National Bureau of Standards (now NIST) developed the first atomic clock based on the Ammonia absorption line at 23870.1 MHz. The accuracy of the Ammonia [39, 40] based atomic clock is less than that of the quartz clock but it demonstrated the concept required for the development of the atomic frequency standard.

An atomic clock utilizes the characteristic frequency of an atomic system as a frequency standard. The characteristic frequency of an atomic oscillator is defined as $\nu_0 = \frac{E_2 - E_1}{\hbar}$, where E_1 and E_2 are the energy levels of the system. These frequencies are stable over space and time. Thus, atoms behave like a stable "pendulum" to reproduce a constant period of oscillations and forms the basis of atomic clocks.

Before the pre-atomic era, the second was defined by dividing the astronomical event such as a solar day or a year. But the definition of second was redefined after the development of atomic clock as the duration of 9,192,631,770 periods of the radiation corresponding Cesium-133 atom resonance frequency [41–43].

Alkali atoms as oscillator

Though for redefining time, Cesium atoms was used but in actual practice various alkali atoms such as H, Rb, Cs can be used for the development of an atomic clock [34, 43, 44]. Due to the presence of a single electron in its valence shell, these atoms have a simple energy spectrum, long lived ground states, and can be easily coupled to light in the visible or in near infrared region by a low-cost semiconductor laser. In addition to this, spin angular momentum of atomic nucleus and the valence electron of alkali atoms provides a relatively large hyperfine splitting (∼1-10 GHz) required for frequency references. Further, all alkali atoms are non-poisonous, non-radioactive (expect Francium) and are readily available.

Principle of atomic clock

The traditional frequency reference standard uses a vapor cell placed in a microwave cavity. The microwave field in the cavity was generated by a local oscillator (generally quartz crystal oscillator), a less accurate frequency reference. Its frequency drift is continuously corrected by monitoring the response of the atomic system to an additional light field passing through it. The atoms in the vapor cell were illuminated by a suitable source to prepares the atoms in one of the two hyperfine ground states through optical pumping. The atomic absorption after optical pumping were found to be less when compared with the absorption due to thermal distribution of the atoms in the hyperfine states. As the RF field generated from the local oscillator is tuned near the atomic resonance, the population imbalance created due to optical pumping gets redistributed. This results in the increase in the atomic absorption and is detected by measuring the photodiode voltage. The change in the transmitted optical power as a function of microwave frequency is used to lock the local oscillator. The local oscillator synchronized with the atomic transition is called an atomic clock.

CPT based atomic clock

Traditional atomic clock uses microwave cavity [45] that limits the size of the device. In addition, the higher power requirement is a drawback for its compact operation. These shortcomings are overcome by using Coherent population trapping (CPT) technique, by which the device size can be miniaturized to chip scale [45–47]. The CPT based atomic clock does not require any microwave cavity, has very low power requirement, and has a stability comparable to that of conventional microwave cavity-based clocks. CPT is a quantum interference phenomenon realized by simultaneously coupling the two exciting pathways with a common energy level. The probability amplitudes of the two competing excitation pathways are superimposed resulting in the generation of constructive or destructive interference. As a result, the eigenstates of the system changes leading to the formation of dark and bright states responsible for the generation of the ultranarrow resonances. These ultra-narrow resonances do not require any microwave cavity, thereby offering miniaturization. In CPT, a local oscillator is used to drive a RF source to modulate the injection current of the laser generate a sidebands. The simultaneous coupling of the two ground state hyperfine level of the alkali atoms to a common excited state by the sidebands leads to the generation of ultranarrow resonances. These resonances were observed only when the frequency difference between the two side bands exactly matches with the frequency difference between the two hyperfine ground levels(commonly known as two photon resonance condition). This resonances occurs at a frequency defined as second and are very stable and thus used to lock the local oscillator to act as atomic clock.

4.3 Revolution in Magnetometer

The magnetic field carries important information about its sources. Thus, its measurement provides a probe to the characteristic the source. The improvement in the magnetic field measurement is in continuous progress from hall probe, fluxgate, SQUIDs to atomic magnetometer [48].

Fluxgate magnetometer

Fluxgate magnetometer are very rugged and compact, capable of measuring magnetic field in one direction only [49]. Due to its compactness, these types of magnetometer are used for many portable applications. The working principle of the fluxgate magnetometers is based on the saturation of the magnetic core. Basically, it consists of highly permeable ferromagnetic core surrounded by a primary and secondary coil. Due to the application of an alternating current in the primary coil, magnetic field is induced in the secondary coil. As long as the ambient magnetic field is absent, the voltage across the two coils is zero as equal amount of oppositely directed current flows in the two coils. Due to the presence of external magnetic field, the ferromagnetic core gets easily saturated in the direction of the field while less saturated in the opposite direction resulting in the difference in the current in the primary and secondary coils. This difference in current develops some voltage across them depending upon the strength of the external field. Generally, these devices are used to measure the Earth's magnetic field. As the inductive property of the pick coils are utilized, it is less effective for low frequency applications. It is hard to realize sensitivity below nT range. Thus, for low frequency applications and high sensitive measurements like biomedical applications, SQUIDs or atomic magnetometer are more suitable.

Superconducting quantum interference devices (SQUIDs)

As the name describes, SQUIDs utilize the superconducting property of the material to construct the device [50]. These devices are capable of measuring magnetic field in the low frequency regime. It consists of a superconducting ring with one or two Josephson junctions. The tunnelling of electron through these junctions, exhibit quantum interference depending upon the strength of the magnetic field within the loop. The voltage across the junction measure the magnitude of the magnetic field. Though these types of devices are used to measure very low magnetic field with high sensitivity but have a portability issue due to the need of cryogen to reach the superconducting state. The highly sensitive, near room temperature, compact atomic magnetometers provides an alternate method for both high and low frequency regime.

CPT based atomic magnetometer

A compact atomic magnetometer based on CPT utilizes the non-degenerate Zeeman states of the system [51]. For a small ambient magnetic field, the CPT signal get splits (field insensitive and field sensitive signal). The atomic clock utilizes the field insensitive transition as its frequency reference while the difference between the field insensitive and field sensitive transition is used to measure the magnetic field. As atomic magnetometer based on CPT requires a continuous scanning of RF field across the CPT state, the measurements are not user friendly. The contradictory requirement of the CPT based atomic clock and magnetometer forbids their simultaneous operation.

Progresses in the laboratory

In the laboratory, the protocol have been developed for the operation of a compact dual atomic device (DAD) based on CPT and Polarization rotation. It offers the realisation of atomic frequency standard and atomic magnetometer simultaneously. Here, the occurrence of a magic frequency provides a way for self-correction of an atomic clock. It has a unique advantage for situation where master clock signal is not available for correction of the atomic clock like isolated military facility, deep space navigation etc. The physics and technology associated with the operation of a single beam three axis polarimetric based atomic magnetometer has been invented in this laboratory. It uses non-linear magneto-optic effect (NMOE) and polarization self-rotation (PSR) as the degenerate CPT condition is realized at zero magnetic field.

Apart from technology aspect, the research program addresses the various aspects of quantum interference effects. It includes Coherent Population trapping, Nonlinear magneto-optic effect, polarization self-rotation and their interplay zero magnetic field. It provides a very rich system as multiple coherently couple excitation dictates the dynamics of the overall process. The effect of frequency modulated linearly polarized light on Hanle configuration brings out interesting physical processes. Single and multi-photon processes associated with a narrow band frequency comb (NBFC), generated by the frequency modulation of the light field have been studied. It provides platform to witness the distinct characteristic of on-/off-resonant dichroism and birefringence.

4.4 Physical Processes

The physical processes like coherent population trapping, Non-linear magneto-optic rotation, polarization self-rotation, and narrow bandwidth frequency comb are described as follows:

4.4.1 Coherent population trapping

The phenomenon of CPT comes in to action as two phase locked laser field simultaneously couple the two-different state to a common excited state [52]. The population in the ground level gets coherently trapped and is immune to excitation. This leads to enhance transmission only when the frequency difference of the two-laser field becomes equal to the ground state energy difference i.e. near Raman resonance. When a bi-chromatic field couples the two-ground state simultaneously to the common excited state as shown in Fig. 4.2, the bare atomic states are no longer are the eigenstates of the system. Under two-photon Raman resonance condition, the new eigenstates of the system changes to dark and bright states as

$$|Bright\rangle = |C\rangle = \frac{\Omega_1}{\sqrt{\Omega_1^2+\Omega_2^2}}|1\rangle + \frac{\Omega_2}{\sqrt{\Omega_1^2+\Omega_2^2}}|2\rangle \tag{4.2}$$

$$|Dark\rangle = |NC\rangle = \frac{\Omega_2}{\sqrt{\Omega_1^2+\Omega_2^2}}|1\rangle - \frac{\Omega_1}{\sqrt{\Omega_1^2+\Omega_2^2}}|2\rangle \tag{4.3}$$

The dark state is the dipole forbidden state while the bright state couples to the excited state. Thus, over a period of time all the population of the system gets optically pumped to the dark states and gets trapped. This phenomenon is known as coherent population trapping. The absorption and dispersion for single photon and two photon resonance for three level atomic system is shown in Figs. 4.3 and 4.4 respectively. The absorption profile shows enhance transmission whose width is independent of excited state lifetime and can be made extremely narrow if the transition between the lower states are dipole forbidden. Such ultra-narrow resonance generated by the CPT states are used for atomic frequency references and atomic magnetometer.

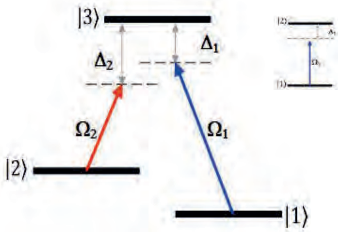

Figure 4.2: Three level atomic system coupled to bichromatic field.

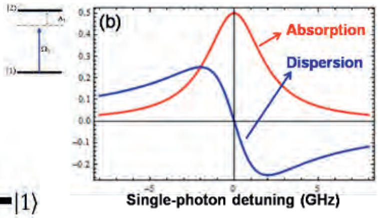

Figure 4.3: Absorption and dispersion near single photon resonance.

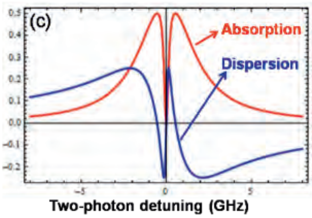

Figure 4.4: Absorption and dispersion near two-photon resonance.

4.4.2 Nonlinear magneto-optic effect and polarization self rotation

The NMOE is a process which arises due to the bipolar nature of the linearly polarized light [53–55]. In laser atom interaction process, when the right and left circularly polarized light component of a linearly polarized light couples the Zeeman nondegenerate atomic sample to a common excited state, the different coupling strength of the σ_+ and σ_- accumulates differential phase shift between the two orthogonal circular components (known as circular birefringence). The mechanism of differential phase shift of σ_+ and σ_- components presence of a non-zero magnetic field is known as nonlinear magneto optic effect. Polarization Self Rotation is a phenomenon which arises when the slightly imbalanced light interacts with an isotropic medium to induces dichroism and birefringence. Depending upon the transition strength, the slightly imbalanced light produces population imbalance among the Zeeman sub states through differential optical pumping mechanism. Thus the σ_+ and σ_- light interacting with the medium experiences different refractive index, resulting in a net phase shift between the two, thereby exhibit PSR. The enhancement of polarization rotation occurs near two photon Raman resonance conditions. The dual atomic device is based on the enhancement of the polarization rotation near two photon resonance condition. The Coherent population trapping signal is used to for atomic clock while the polarization rotation is used to measure the amplitude and direction of the magnetic field.

4.4.3 Narrow band frequency comb (NBFC)

The conventional way of generating a frequency comb (defined as a series of coherently evenly spaced discrete spectral lines) is realized by a mode locked pulse laser [56–58]. However, modulation of the laser frequency using external modulators also produce a frequency comb. The frequency comb generated by current modulation of the laser diode have been studied. It generates equally spaced spectral lights in the frequency domain having much smaller bandwidth compared to the conventional frequency comb. The frequency comb produced by the continuous wave laser by frequency modulation technique is termed as Narrow Band Frequency Comb (NBFC). It provides a complimentary technique for the study of interaction of the frequency comb with an atomic ensemble.

4.5 Experimental Set-up for Atomic Devices

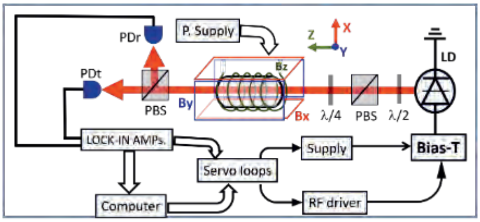

Figure 4.5: Experimental Set-up for CPT based atomic device, DAD and Self-corrected atomic clock.

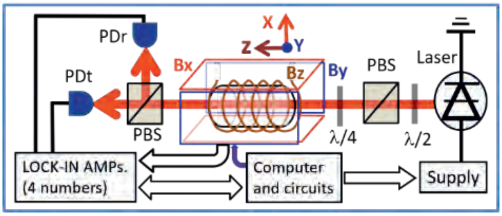

Figure 4.6: Experimental Set-up for Three axis magnetometer and NBFC experiment.

Figures 4.5 & 4.6 show the experimental set-up for the various type of atomic devices with slight modification according to the requirement of the experiment. In Fig. 4.5, the injection current of the VCSEL is modulated with a desired frequency to generate the bichromatic field required to couple the two-ground state of Rubidium atoms. A part of the beam is used to generate the error signal required to lock the laser at desired frequency. Half wave plate, polarizing beam splitter cube and quarter wave plate are used to control the intensity and polarization of the light as per requirement. Naturally abundant Rubidium atomic sample is placed in a magnetic and temperature-controlled environment. The Rubidium atoms are accompanied by suitable buffer gas or placed in anti-relaxation coated glass cell to overcome the transit time broadening. Two sets of rectangular coils and a solenoidal coil are used for controlling the magnetic field in transverse and along the laser propagation direction respectively. The detection PBS is used according to the need of the experiment. The reflected and transmitted signal of the PBS are phase sensitively detected with respect to the modulation applied to the RF frequency. This type of experimental setup is used for CPT based atomic device, dual purpose atomic device and for self-corrected atomic clock. Fig. 4.6 is used for single beam three axis atomic magnetometer and for NBFC experiment. The laser current is modulated at desired frequency to interact the Rubidium atomic sample in Hanle configuration. The atomic sample is placed in temperature and magnetic field-controlled environment and PBS and Quarter wave plate is used to change the polarization of the light according to the requirement. Small modulation is applied to the coils which are used to control the magnetic field along and in transverse to the laser propagation direction respectively. The transmitted signal of the detection PBS is demodulated with respect to the modulation of the laser to lock the laser at the desired frequency. While the reflected signal is demodulated with respect to the modulation given in the three-orthogonal signal and are termed as MMx, MMy and MMz signal. These signals are measured by scanning the longitudinal magnetic field and are used to measure magnetic field in the respective direction.

A compact experimental set-up was developed by replicating the laboratory set-up (Figs. 4.7 & 4.8). It comprise of a physics package and an electronic control unit having dimension of 21 cm × 8.5 cm × 8.5 cm and 30 cm × 20 cm × 11 cm respectively. The device is powered by a bench top power supply giving ±15 V DC with a current capacity of 2 Amp. Quantum interference signal was successfully generated among Zeeman sub-state belonging to different hyperfine state as well same hyperfine state in this compact version. The two-photon transmission and polarization rotation signal were successfully acquired. The magnetic coils were spectroscopically calibrated using quantum interference signal. In the magnetometry measurement, the sensitivity was measured to be ∼10 $\mathrm{pT/Hz^{-1/2}}$@10 Hz. The measurement involves probing of the Zeeman sub-state originating from the same hyperfine level. The device was operated in a feedback control of the bias magnetic field to improve dynamic range. The illustrated compact experimental set-up provides an economical package to carry out various kind of experiment at post graduate and pre-doctoral level. It can be instrumental for students to learn various laser spectroscopic and measurement techniques. The various learning tool includes, absorption spectroscopy, frequency-modulation spectroscopy, narrow band frequency comb spectroscopy, polarization spectroscopy, laser frequency stabilization, Quantum interference, atomic clock, magnetometer and dual atomic device.

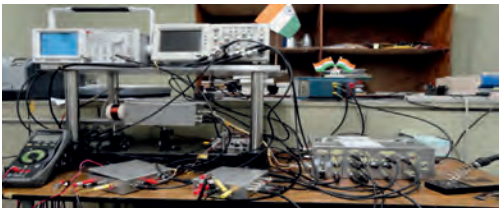

Figure 4.7: A table-top economical set-up for improving quality of education.

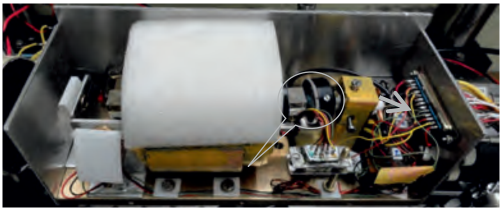

Figure 4.8: The physical enclosure of the set-up.

4.6 Atomic Devices Based on Quantum Interference

The atomic devices based on quantum interference operates near room temperature and evade the use of microwave cavity. Thus, the overall size of the device can be made very compact leading to a wide sphere of applications in fields such as biomedical, defence and space.

4.6.1 CPT based atomic devices

Conventional type atomic device based on CPT requires two phase locked laser field to couple the two-hyperfine ground state to the common excited state. The desired bichromatic field can be conveniently generated by frequency modulation of the laser at a sub-harmonic of the ^{85}Rb hyperfine splitting. The bichromatic field is tuned to the D1 (D2) line of the Rubidium at 795 (780) nm. The hyperfine levels split into 2F+1 Zeeman sub-states in presence of a finite magnetic field (Fig. 4.9). So, when two photon Raman condition satisfies, five CPT resonances are obtained as shown in Fig. 4.10. For the realisation of only CPT signal, either a linearly or circularly polarized light is used without a detection PBS in the experimental set-up (Fig. 4.5). The transmitted signal is measured phase sensitively by scanning the RF frequency across the two photon resonance. The observed CPT signal (Fig. 4.10) is used for atomic frequency reference and magnetic field measurement. The CPT resonance marked as “c” in Fig. 4.10 is used for atomic frequency standard as the resonance arises from the coupling of the field insensitive transition (mf = 0, mf = 0) to the excited state (mf = +1) for circularly polarized light as shown in Fig. 4.9. While the resonance marked at “e” is sensitive to the external magnetic field. So, the separation between the resonance at “c” and “e” is used to measure the magnetic field by scanning the RF field. Here, a continuous calibration of RF is required for magnetic field measurement. The same device cannot operate as atomic clock and magnetometer simultaneously. The invented dual purpose atomic device circumvents this limitation and offers additional scope of operation [59, 60].

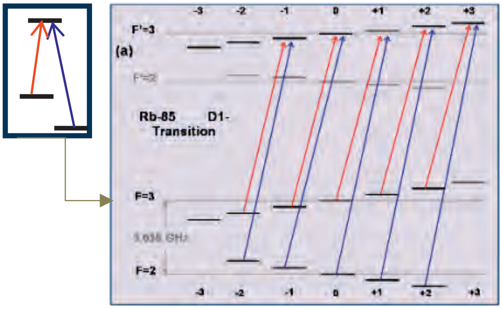

Figure 4.9: Zeeman states of the Rb-85 atoms in presence of a magnetic field. The Two-photon resonance can be satisfied at five different RF frequencies.

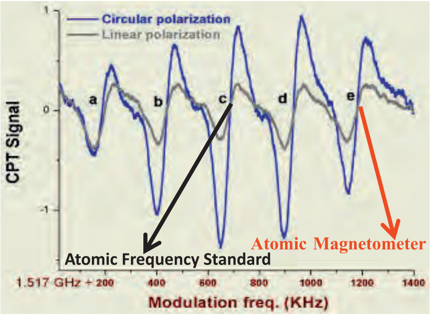

Figure 4.10: Experimentally observed splitting in the CPT signal in presence of a magnetic field. The position "a" is insensitive magnetic field and used as reference for atomic clock.

4.6.2 Dual atomic device

The dual atomic device is a hybrid device which realizes both atomic frequency reference and magnetic field measurement simultaneously [59, 60]. It utilizes the enhanced transmission (CPT) and polarization rotation signal (PR signal) near two photon resonance condition for the realisation of atomic clock and atomic magnetometer. The slightly imbalanced light (elliptically polarized light) and a detection PBS were used in the experiment (Fig. 4.5) for the realisation of the dual atomic device. The transmitted (CPT) and reflected (PR) signal of the detection PBS were used for atomic frequency reference and for magnetic field measurement respectively. In a low field regime, where the separation of the resonances is smaller than the width of the CPT resonances, all the five resonances convolute to a single profile for both transmitted and reflected signal as shown in Fig. 4.11. The operation of DAD depends on the response of the CPT and PR signal with the magnetic field. As shown in Fig. 4.12, the convoluted CPT is immune to small value of the magnetic field where as the PR signal is sensitive to the field. It provides a way to measure magnetic field and frequency standard simultaneously without any scanning RF field. The zero crossing of the

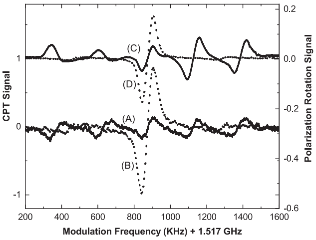

Figure 4.11: High field and low field regime CPT (lower) and PR signals (upper). The dotted signals for CPT and PR are the convoluted CPT and convoluted PR signals respectively.

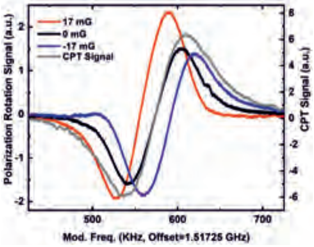

Figure 4.12: Convoluted CPT and Polarization rotation (PR) signals. The PR signal is very sensitive to magnetic field in contrast to the immunity of the transmitted CPT signal.

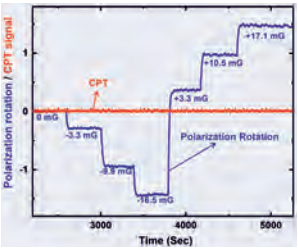

Figure 4.13: Operation of DAD. The RF is locked to the transmitted signal (red) and constitutes the atomic clock; whereas the reflected signal (blue) is used for magnetic field measurement.

convoluted CPT signal was used to generate the error signal for VCO stabilization using the servo loop (shown as red line written as CPT in Fig. 4.13) and is used a frequency reference. The magnitude and direction of the external magnetic field was reflected in the PR signal as shown in Fig. 4.13.

4.6.3 Magic frequency based self corrected atomic clock

The sensitivity and stability of dual atomic device highly depends upon the width of the CPT (narrower is the CPT better is the device). Use of buffer gas filled atomic sample is one of the way to reduce the width of CPT. It was observed that in presence of buffer gas, the convoluted CPT signal also become sensitive to the magnetic field as in Fig. 4.14, which limits the device to be used as atomic frequency references. Thus, a synthesised signal is generated by summing the convoluted PR (with proper gain factor) with the convoluted CPT. It was found that synthesised signal for different magnetic field has a common frequency which is independent of magnetic field and is named as magic frequency [61] (Fig. 4.15). The RF was stabilised at the magic frequency for the operation of the atomic clock, under which the PR signal gives the magnetic field. Apart from dual operation, the magnetic field measurement by this method does not require regular calibration as it is done in situ. This is a significant advancement in the CPT based magnetometry without compromising the sensitivity of the device. In fact, the sensitivity is expected to be better as magnetic field is measured using polarization rotation signal which carries limited laser intensity noise. This magic frequency-based DAD has an additional advantage over conventional atomic clock as the former doesn't require any master clock for its correction due to external perturbation. Hence the magic frequency based atomic clock is also known as self-corrected atomic clock. This type of atomic clock can be operated by applying a small magnetic field modulation along the laser propagation direction. As long as the RF is locked at the magic frequency, the synthesised signal remains unaffected by the small applied magnetic modulation. If the RF frequency drifts away from the magic frequency due to some external perturbation, the synthesised signal starts oscillating at the modulation frequency. These oscillations can be detected and corrected using a closed loop operation, thus bypassing the need of master clock signal for regular correction of the atomic clock.

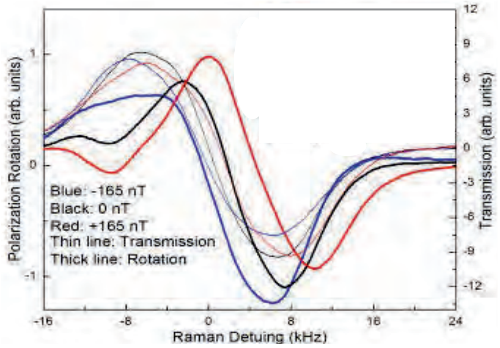

Figure 4.14: Dependence of convoluted CPT and PR signals with magnetic field.

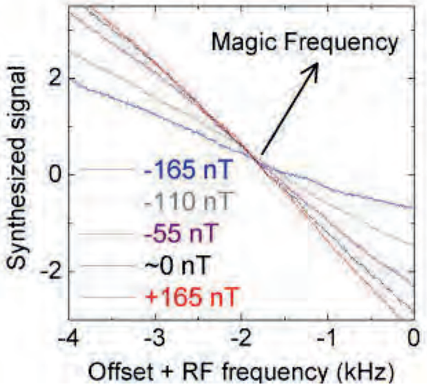

Figure 4.15: Synthesized signals for various magnetic fields.

4.6.4 Single beam three-axis atomic magnetometer

All the atomic magnetometer explained so far are based on the quantum interference between the two-dipole forbidden hyperfine ground state. These types of magnetometer can measure magnetic field in only one direction. Three-axis magnetic field measurement by such magnetometer is yet to be demonstrated. A compact vector magnetometer which can measure magnetic field in three orthogonal direction [62–66] has been developed. Here single beam which establishes the quantum interference in degenerate two level atomic systems (DTLSs) is used. In order to make the device compact, only single elliptically polarised light in the experiment (Fig. 4.6) was used. The right and left component of the elliptically polarised were used to establish the quantum interference required for the operation of magnetometer. The transmitted part of the detection PBS is used to stabilises the laser frequency at the desired transition. Further the reflected signal of the detection PBS was phase sensitively detected with respect to the modulation applied to the three sets of orthogonal magnetic field. The demodulated reflected signal with respect to x, y and z direction modulation is termed as MMx, MMy and MMz respectively. These signals are used for magnetic field measurement in three orthogonal direction as shown in Fig. 4.16. The general condition for establishing a three-axis magnetometer is found out to be $\frac{\partial MMu}{\partial Bu} > \frac{\partial MMu}{\partial Bu'}$, where u, u' = x, y, z and $u \neq u'$. The sensitivity of the magnetometer is measured to be $<$ 20 pT Hz$^{-1/2}$@200 mHz. The cross talk between the various direction was probed using Lissajous plot [41]. The different phase shift of the signal to magnetic field direction provides an additional handle for discriminating the magnetic field orientation.

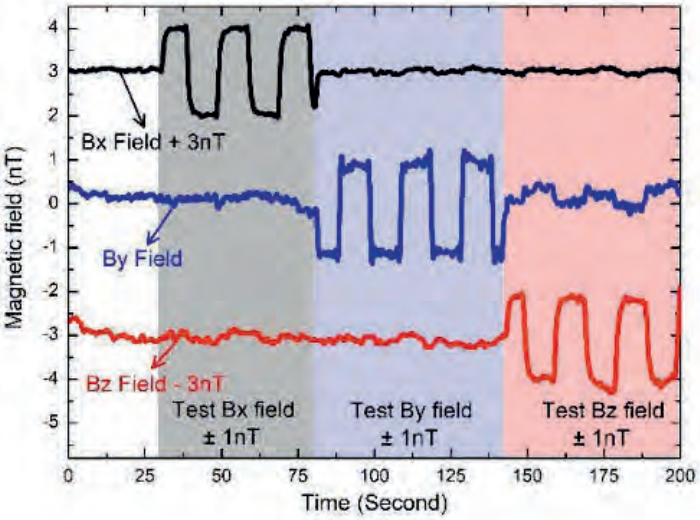

Figure 4.16: The MMR signals for sequential change in applied DC magnetic field by ±1 nT along x, y, and z directions. The hollow circles are experimental data.

4.7 Atomic Response due to Narrow Band Frequency Comb

In the experimental setup (Fig. 4.6), the current of the laser was modulated to generate the NBFC [58, 67] which is made to interact with the atomic sample in Hanle experimental configuration. The reflected signal of the PBS was demodulated with respect to the modulation applied to the scanning magnetic field. The observed magnetic resonance split for a linearly and elliptically polarized light but exhibit a single profile for circularly polarized as shown in Fig. 4.17. The left and right circularly components of the frequency modulated linearly (elliptically) polarized light undergoes quantum interference during the atomic excitation. The temporal oscillations in the atomic polarization sue to the use of frequency modulated light has been reported in earlier literature. However, the experimental observation reveals the establishment of steady state atomic polarization that gets enhanced whenever the Larmor frequency of the system approaches a multiple of the modulation frequency (as Raman resonance condition only satisfies at the harmonics of the modulation frequency). This leads to apparent splitting of the magnetic resonance. It is consistently shown in Fig. 4.17, where the split components are separated by half of the modulation frequency with the central component lying at zero-magnetic field. The presence or absence of the odd split components as shown in Fig. 4.18 can be explained by considering the interaction of teeth components of the NBFC with the atomic level. The modulation parameters (ω_m and A_m) dictates the narrow band frequency comb spectrum. The separation and amplitude of NBFC teeth are decided by the first kind Bessel function properties ($J_n(I_m)$). The amplitude of the nth teeth is $\propto |J_{-n}(I_m)|^2$ and the phase relation between the two consecutive teeth is given by $J_{-n}(I_m) = (-1)^2 J_n(I_m)$, where n and I_m is the order and modulation index of the Bessel function. The separation between the teeth component is equal to the modulation frequency (ω_m) and the extent of NBFC is proportional to A_m. Practically, the Doppler profile having a width $\cong 450$ MHz consists of large number of frequency teeth components for the applied modulation parameters ($\omega_m = 12$ kHz and $A_m = 1.62$ GHz). However, only a fraction of the NBFC spectrum (GHz) as shown in Fig. 4.19A. Depending upon the value of Δ (frequency difference between the central component of the NBFC and the atomic resonance), only a specific part of NBFC is in resonance. Fig. 4.19A shows the relative phase and amplitude of the frequency components depending upon the detuning region, $\Delta = 0$, $\Delta < 0$ and $\Delta > 0$. For $\Delta = 0$ region, when compared for three consecutive frequency components, first and third components are always in opposite phase while for the region $\Delta > 0$ and $\Delta < 0$, the first and third frequency components are in same phase irrespective of the phase of second component. Therefore, the various phase combinations for any three consecutive frequency components for $\Delta = 0$ region is $(-,+,+)$, $(+,+,-)$, $(-,-,+)$, $(+,-,-)$. Similarly, for $\Delta > 0$ and $\Delta < 0$ region, the phase are in the form of $(+,+,+)$, $(-,-,-)$, $(-,+,-)$, $(+,-,+)$. These two classes of frequency components when interacted with the simplified three level atomic system (Fig. 4.19B) shows contrasting quantum interference effect at $\Omega_L = \pm\frac{\omega_m}{2}$. As

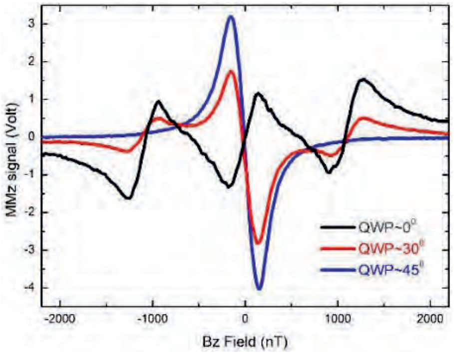

Figure 4.17: Polarization dependence of the MMz signal. Splitting occurs only for linearly polarized light.

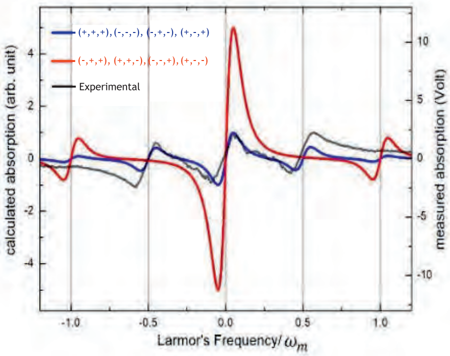

Figure 4.18: Dependency of split components for different phase relation combination of teeth.

for $\Delta = 0$ region, the two side teeth component with respect to the central component are in opposite phase, the quantum interference gets destroyed and hence the odd split components are absent for resonant case. Quantum interference assisted absorption, birefringent, dichroism and optical pumping is controlled by input field ellipticity. The enhancement of optical activity for elliptically polarized light is observed as its population imbalances between the relevant ground Zeeman level due to optical pumping.

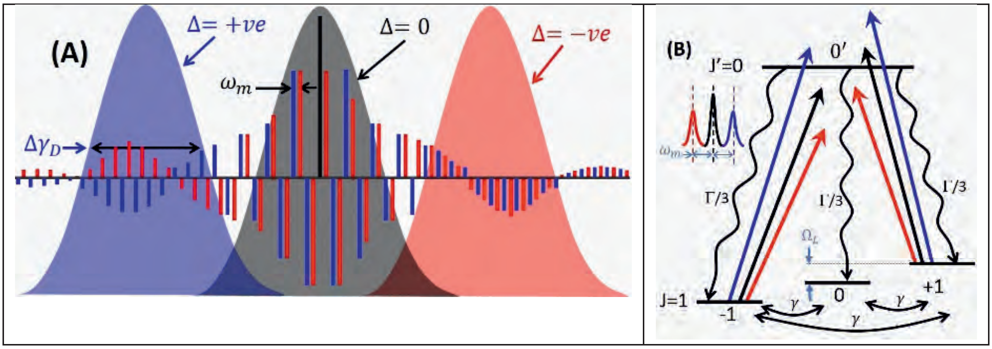

Figure 4.19: A: Representation of Doppler profile in the NBFC spectrum for different detuning (Δ). The central (black), odd (red) and even (blue) teeth are shown. The up/down direction of teeth from the baseline represents its phase. B: A trichromatic field separated by ω_m couples $J = 1 \rightarrow J' = 0$. At multiple Ω_L, different sets of light exhibit quantum interference.

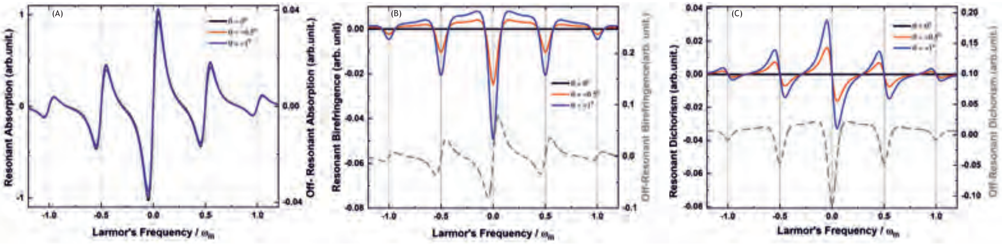

Figure 4.20: (A) Absorption, (B) Birefringence, (C) Dichroism for different ellipticity of the light field. The solid and dotted lines represent resonant and off-resonant behaviours respectively.

For a slight ellipticity change, absorption signal has no significant change both on- and off-resonant cases as shown in Fig. 4.20A. The resonant and off-resonant birefringence for circularly polarized light has distinct features. Also, birefringence signal for resonant linearly polarized light is absent as shown in Fig. 4.20B. However, the response is sensitive at $\Omega_L = 0, \pm\frac{\omega_m}{2}, \pm\omega_m$ for small change in ellipticity. The amplitude of the dip structure increases with the ellipticity due optical pumping and Zeeman coherences. For off-resonant light field, the dispersive line shapes at the harmonics modulation frequency were observed. These resonances are insensitive to the change in ellipticity parameter like amplitude and polarity. Similarly, for pure linearly polarized light resonant dichroism were absent as shown in Fig. 4.20C. The dispersive line shape at the harmonics of the modulation frequency for on resonant light field were observed which increases its amplitude with the small change in ellipticity. The dip structure, insensitive to change in amplitude or polarity of the ellipticity were observed for off-resonant case. The calculated spectra suitably explain the experimentally observed optical activity.

4.8 Conclusions

The operating principles of atomic devices, namely atomic clock and atomic magnetometer based on quantum interference effect were described. The dual purpose atomic device has added advantages over the conventional CPT based atomic devices. The difficulties in the operation of the DAD for narrower resonance width was further overcome by the realization of a magic frequency based self-corrected atomic clock. The development of a single beam three-axis vector atomic magnetometer has promising prospect as the whole device (physics package and electronic control) can be made very compact. This magnetometry geometry is suitable for further expansion to an array of detector for spatially resolved magnetic field imaging and/or high sensitive gradient field measurement. The complex interaction of NBFC with an atomic system is investigated. It provides a microscopic picture of the underlying physical processes. The splitting and position of the magnetic resonance and their dependencies on the relative phase of the field components were explained. The dependency of birefringence, dichroism, quantum interference assisted enhanced transmission with the small change in ellipticity studied. The NBFC can provide complementary information to the conventional frequency comb spectroscopy. The precise control of the atomic dynamics and simultaneous reading using laser light are the basis of the fundamental studies and their technological application, as described in this chapter.