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Summer Internship Project
Final Report

ATOM BASED ELECTRIC FIELD SENSING

Submitted by

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Laxmi Prasoon Barik

ATOM BASED ELECTRIC FIELD SENSING

1 Abstract

Electric field sensing is a growing area for research. Need for highly sensitive and accurate sensors has brought atom-based sensors. Atom based sensors use the properties of atoms for measurement and detection of electric fields. Rubidium or Cesium atoms are used as vapor cells which act as medium for laser interaction. The phenomena of Electromagnetically Induced Transparency (EIT), which is a quantum interference phenomena where two beams destructively interfere, is used along with a homodyne detection method for accurate sensing. The challenges in making such sensors are mentioned. Current applications are also mentioned along with future expectations.

2 Introduction

Electric field sensing has very widespread use. It is used in weather, electronic devices, environmental and astronomical sciences. The accuracy of conventional antennas has increased over time. However conventional measurement techniques use probes made up of metals and metal transmission lines that disturb the targeted electromagnetic field. This poses a limit to the precision of electric field sensing. There can be large perturbations depending on the geometry. Electric fields of $1mVcm^{-1}$ can be determined with a sensitivity of $\sim 1mVcm^{-1}Hz^{-1/2}$ at an accuracy of $\sim 10\%$ Using a homodyne detection method, a sensitivity of $3\mu V cm^{-1} Hz^{-1/2}$ at an accuracy of $\sim 1\%$ for electric fields $\sim 1\mu V cm^{-1}$ has been demonstrated.[1]

Apart from conventional method, there are two approaches for electric field sensing:

- Use of ultracold atoms such as Magneto Optical Traps (MOTs)
- Use of Rydberg atoms

Here, latter has been used to describe sensing.
Highly excited atoms in a vapor cell (Rydberg atoms) can be used as a solution for highly accurate electric field sensing over the Radio Frequency-Far Infrared (RF-FI) spectrum. It can be measured very accurately with modern laser spectroscopy. By using Rydberg atoms, which are highly sensitive to electric field and depend on transition dipole moment, RF-FI, one can detect small changes in properties such as transmission or absorption of any electromagnetic field through a medium. The medium is atoms of cesium or rubidium contained in vapor cell. Rydberg atom Electromagnetically Induced Transparency (EIT) can be used as a probe and as an atomic standard for the electric field.

A Rydberg atom is a specific atom with at least one electron in a highly excited state and has a principal quantum number n greater than 20. A Rydberg atom's large electric dipole moment causes it to couple strongly to a weak electric field, which can be utilised to detect electric fields. When an electric field is applied, the Rydberg atom couples to the external field through its large electric dipole moment, causing the Rydberg atom's state to change. The population of each energy level changes when the atomic energy levels change. This change in the atomic state is monitored using EIT.

3 Theory

3.1 RYDBERG ATOM BASED ELECTROMETRY

The basic principle that is used in Rydberg atom based electrometry is the interaction between Rydberg atoms and the electric field i.e. When Rydberg atoms are exposed to an electric field, it experiences a Stark shift which causes shifts in energy levels. These shifts can be measured by monitoring the atom's fluorescence or absorption spectra. This process is enhanced by EIT, which uses the phenomena of quantum interference. This spectroscopic technique makes direct optical probing of high energy Rydberg states possible such that one can measure the effect of a field on a photo detector. There has been a growing use of Rydberg atoms for the measurement and detection of radio-frequency (RF) fields (from MHz-THz).[2-6] Initial applications of this technique focused around the direct measurement of RF field strength, but the high sensitivity and extremely large frequency range of this technique extended their application to more general quantum sensors. Various aspects can be measured using different methods.

RF field strength metrology uses the relation between Autler-Townes splitting (Δf)[7-8] and strength of applied electric field i.e.

$$\Delta f = \frac{\mu}{h}|E|$$

Voltage metrology uses the relation between Stark shift of the EIT peak and electric field amplitude i.e.

$$\Delta_f = -\frac{\alpha}{2}|E|$$

Where Δ_f is the Stark shift of the EIT peak and α is the polarizability of the atom.[9] DC Stark shifts of Rydberg atoms rely on the large Rydberg atom polarizability while resonant AC Stark shifts depend on the large transition dipole moments between energetically nearby states.
RF power metrology uses the relation between power and electric field i.e.

$$P = E_0^2 \frac{ab}{4} \sqrt{\frac{\epsilon_0}{\mu_0}} \sqrt{1 - (\frac{c}{2af})^2}$$

Where E_0 is the amplitude of the electric field at the center of the waveguide, a and b are the width and height of the waveguide cross-section, f is the RF frequency, ϵ_0 and μ_0 are the permittivity and permeability of free space, respectively and c is the speed of light in vacuum.[10]

3.2 ELECTROMAGNETICALLY INDUCED TRANSPARENCY

EIT is a technique for making an otherwise optically thick medium transparent to a laser radiation. Using EIT, Rydberg atom based RF sensing in room temperature can be achieved. EIT occurs when a probe laser, tuned to a ground state transition, and coupling laser, tuned to a Rydberg transition state are incident on a glass cell filled with Rubidium or Cesium atoms. The phenomenon arises from the quantum interference effect, where the transition amplitudes of different pathways destructively interfere. In a typically EIT setup, three energy levels are involved;

1. Ground state

2. Meta-stable state

3. Excited state

There are three canonical types for three-level atomic systems, 1 ;

1. Vee (V)
2. Ladder
3. Lambda (Λ)

Here, the lambda type system is used to explain the phenomena of EIT.

Among the three states, transition between two states is dipole allowed and one is prohibited. For the lambda type system, transition between state $|1\rangle$ to $|3\rangle$ and $|2\rangle$ to $|3\rangle$ are dipole allowed and transition between $|1\rangle$ to $|2\rangle$ is dipole forbidden.

When a weak probe laser beam is incident on the atomic medium, it interacts with the atoms and can be absorbed or scattered. When two laser beams are interacting one can write the free Hamiltonian (H_0) as;

$$H_0 = \hbar\omega_0|3\rangle\langle 3| + \hbar\frac{\delta}{2}(|2\rangle\langle 2| - |1\rangle\langle 1|)$$

Where $\omega_0 \pm \frac{\delta}{2}$ are resonance optical frequencies of the atom.

The interaction Hamiltonian, treated classically, can be written as;

$$H_I = -\hbar\Omega_P e^{-i\Delta_1 t}|3\rangle\langle 1| - \hbar\Omega_C e^{-i\Delta_2 t}|3\rangle\langle 2|$$

Where Ω_P and Ω_C are probe and rabi frequencies. However, when a strong coupling laser beam is applied simultaneously, it modifies the energy level of atoms creating two new energy states. The Hamiltonian can be solved and we get two orthogonal states;

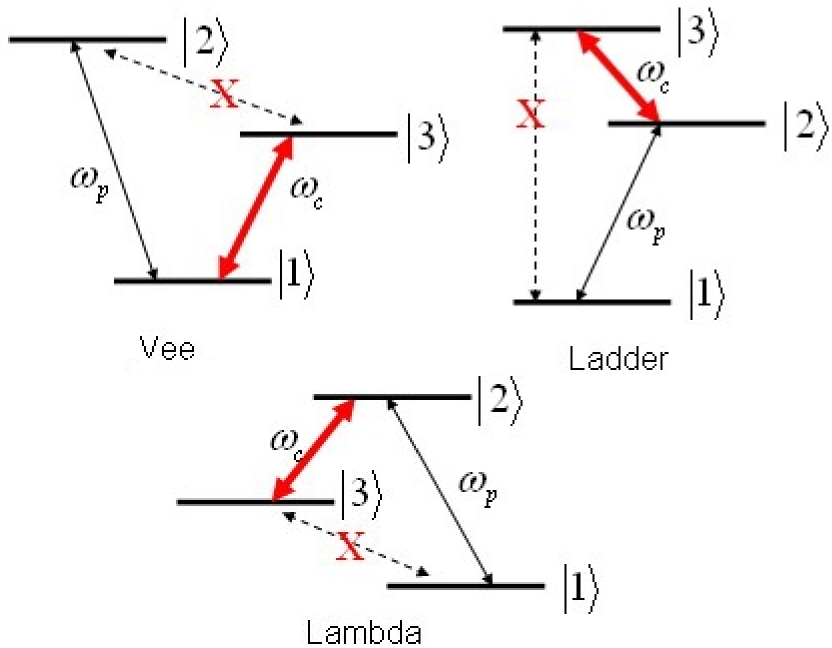

Figure 1: EIT level schemes can be sorted into three categories; Vee ladder and lambda.

1. Bright state
$$|B\rangle = \frac{\Omega_C^*}{\Omega_R^*}|1\rangle + \frac{\Omega_P^*}{\Omega_R^*}|2\rangle$$

2. Dark state
$$|D\rangle = \frac{\Omega_C}{\Omega_R}|1\rangle - \frac{\Omega_P}{\Omega_R}|2\rangle$$

Where $\Omega_R = \sqrt{(|\Omega_P|^2 + |\Omega_C|^2)}$ is the resultant Rabi frequency.

If the atom is in the dark state, the probability to be excited to the upper state becomes zero. The atomic population is trapped in the lower levels and there is no absorption even in the presence of the field, 2. Thus atoms become transparent to the incident field even in the presence of resonant transition. These two energy states are such that the absorption of the probe beam is cancelled out thus creating a narrow transparency window. This can be observed as the narrow transmission peak of the probe laser.

The process of EIT can be divided into two steps.

1. Creation of dressed states
2. Interference between the decay pathways to these states.

Destructive interference between probe absorption amplitude due to the two dressed states leads to EIT.

4 Methodology

The incident RF–FI electric field causes a splitting of the EIT transmission peaks, $\Delta\nu$, and/or a change in the amplitude of

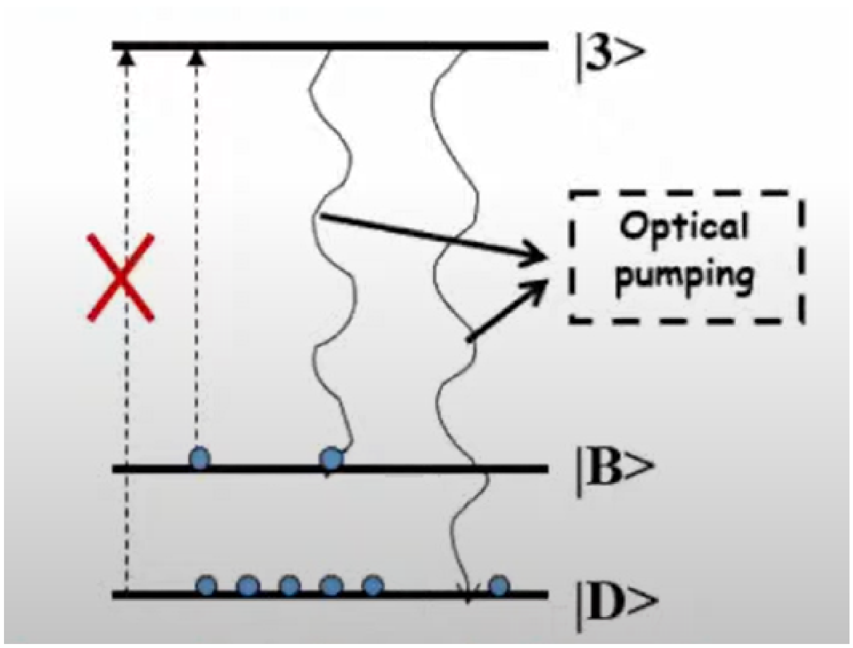

Figure 2: Transitions after dressing of dark and bright state

the EIT transmission that is ideally proportional to the RF–FI electric field amplitude, E, and depends only on the transition dipole moment, μ_{RF-FI}, of the Rydberg atom transition and Planck's constant, h,

$$E \propto h \frac{\Delta\nu}{\mu_{RF-FI}}$$

If the parameters such as laser intensities and cell temperature are controlled, the effect of the electric field on EIT can be calculated since the Rydberg atom properties are well known. Haoquan Fan et al[1] improved the measurement using a homodyne detection method and detected the electric field of $\sim 1\mu V cm^{-1}$ with sensitivity of $\sim 3\mu V cm^{-1} Hz^{-1/2}$. The accuracy is limited by the uncertainty in the transition dipole moments. Many other approaches have also been developed and their minimum detection range and sensitivity are superior to currently used methods. [11,12]

4.1 MEASUREMENT OF ELECTRIC FIELD

The RF-FI electric field measurement in [1] depends on resonant transitions and the associated large transition dipole moment between neighbouring Rydberg states. The electric field coupling between two close lying Ryberg states can be large when the electric field is weak.

$$\Omega_{RF-FI} = \vec{E}\frac{\mu_{R\vec{F}-FI}}{\hbar}$$

Coupling,Ω_{RF-FI} , causes the transition to split in the Autler-Townes limit in proportion to Ω_{RF-FI}. If we can use the sub-Doppler method for detecting the splitting in transition, electric field amplitude can be observed spectroscopically using current frequency stabilized diode lasers and room temperature vapor cells. Vapor cell is a dielectric medium which contains sample of atoms in a gas phase (Usually ^{87}Rb or ^{133}Cs).

The basic notion is detecting how electric field affects the optical transitions of alkali atoms.The probe and coupling fields create a quantum interference in the atom where absorption of the probe beam interferes destructively with the process of probe absorption and coherent excitation and de-excitation by the coupling beam. If the coupling beam is strong enough in this first order picture then these two amplitudes have similar magnitude but opposite sign, so absorption of the probe field is significantly reduced on resonance. A spectrally narrow transmission window can be created in a normally absorbing material. If an electric field is resonant with another transition, figures 4 and 5, it can

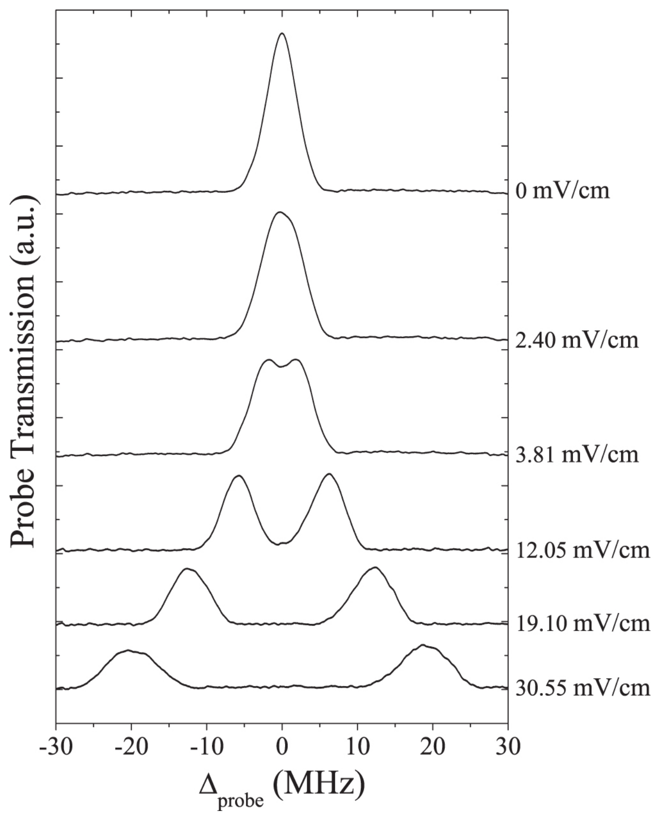

Figure 3: Experimental probe transmission spectral lineshapes for different RF–FI electric field amplitudes for ^{87}Rb at a frequency of 14.233 GHz.

change the interference in the atom to induce a narrow absorption feature or split the transmission line-shape that is observed as a function of probe laser frequency, 3.[1]

4 (a) shows a typical excitation scheme for Rydberg atom-based electrometry for Cs.The lower panel of 4 (b)shows the absorption spectrum obtained by tuning the probe laser across the D2 transition with no coupling laser or resonant RF–FI electric field present. The middle panel shows how the spectrum changes with a resonant coupling laser and no resonant RF–FI electric field. The plot shows an EIT probe transmission dip in

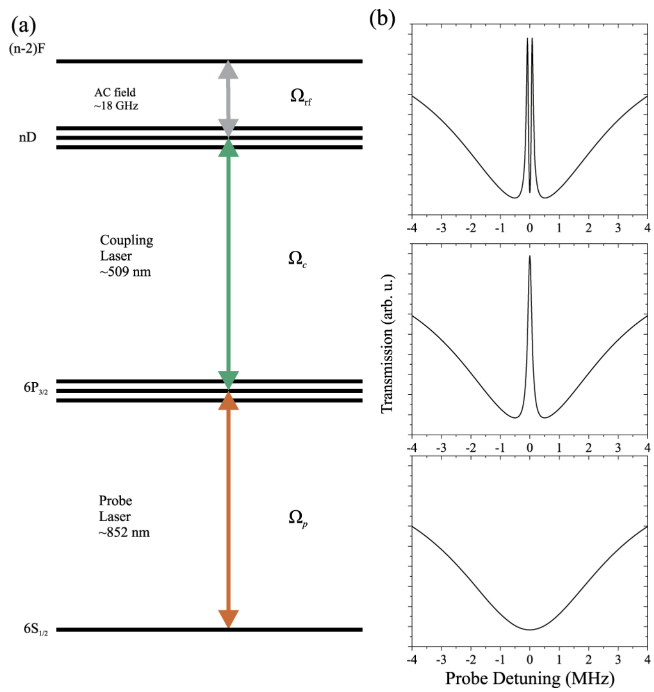

Figure 4: (a) The diagram shows a typical excitation scheme for Rydberg atom-based electrometry for Cs. (b)Probe detuning vs transmission graph.

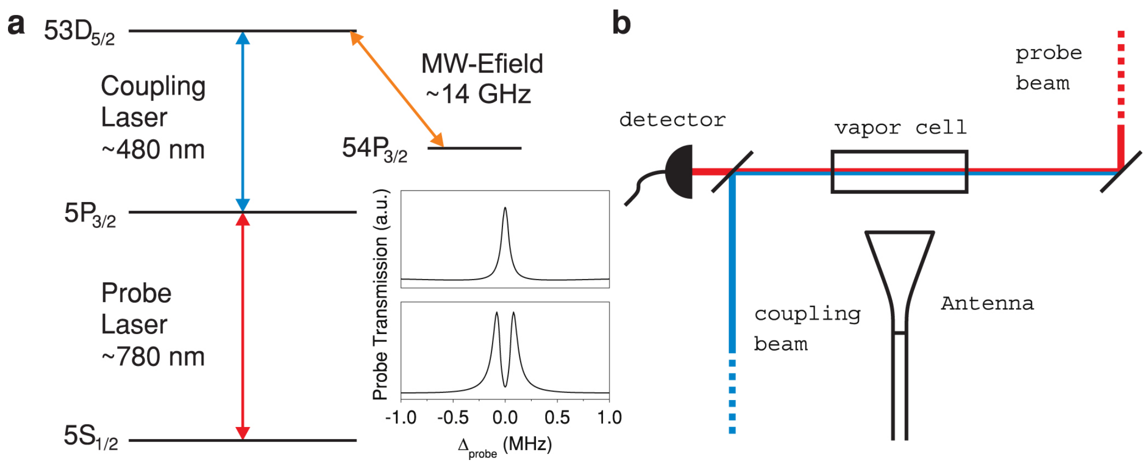

Figure 5: (a) An example atomic energy level structure for the measurement for the case of ^{87}Rb. The lasers are all generated using diode laser technology. A measurement takes place by recording the probe laser transmission in the presence of the coupling laser. If the RF–FI electric field was not applied then a narrow transmission peak for the probe laser is observed on resonance where the probe beam would normally be absorbed, upper graph in (a). When a resonant RF–FI electric field is applied to a third transition, a narrow absorption feature is induced within the transmission window, lower graph (a). (b) The experimental setup for testing. The probe and coupling fields counter-propagate through the cell.

the absorption spectrum. The upper panel shows the spectrum with all the fields present. A narrow absorption feature appears within the EIT transmission window.

The signal, 5, is extremely sensitive to the amplitude of the applied RF–FI electric field because the Rydberg atom transitions have extremely large transition dipole moments, the amplitude is converted into a frequency difference and the feature is the result of quantum interference between the different excitation pathways. Since EIT is a coherent multi-photon process, it is sub-Doppler so it can have relatively high spectral resolution in a vapor cell. Another advantage is that we have up-converted the RF–FI electric field signal to the probe laser frequency. The absorption is called a bright resonance since it is a quantum interference phenomena which is induced by RF-FI electric field. EIT signal is a dark resonance since it does not absorb the probe light.

5 Challenges in Sensing

There are various hindrances in measuring the electric field accurately. They are limited by laser linewidth, transit time broadening, Doppler mismatch between the probe and coupling lasers, shot noise and the decay and the dephasing rates of Rydberg states. They are due to collisions, blackbody radiation and spontaneous emission. Furthermore the background magnetic field of earth also affects the measurement. Noise arising from the frequency and intensity instability of the lasers, acoustic noise from components and other imperfections gives rise to statistical error. However there is significant room for improvement since the shot noise limit is yet to be achieved.

The Rydberg spectrum is very dense as the spacing between the Rydberg states scales as n^{-3}. Around n = 40, this translates

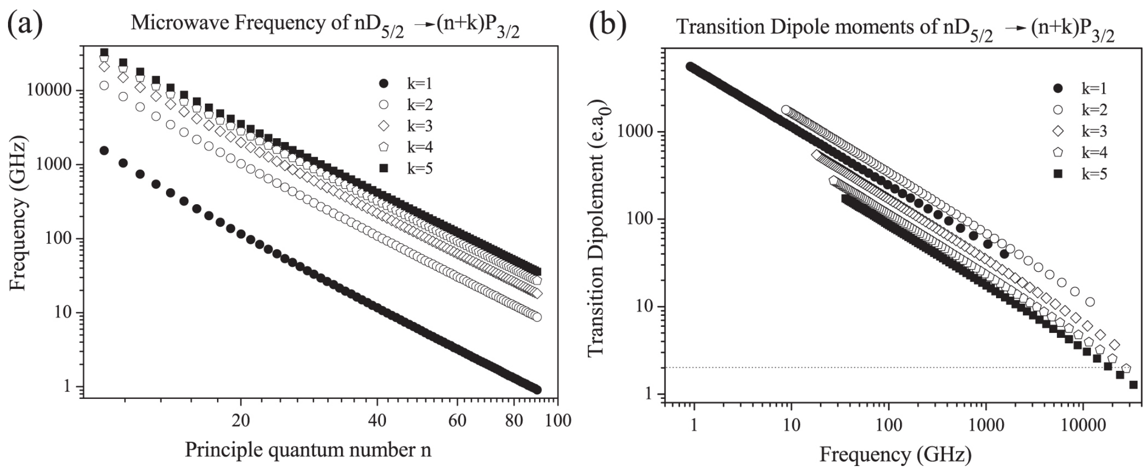

Figure 6: (a) This plot shows the transition frequency for several transitions as a function of n for Cs. (b) This figure shows the value of the transition dipole moment as a function of frequency for the same transitions in (a) for Cs. The figures give an idea of how broad the coverage is if one uses transitions that correspond toΔn ¿ 1 . The line in (b) corresponds to the transition dipole moment for the Cs D2 transition.

into resonances spaced by $\sim$ 500 MHz at frequencies $\sim$ 10 GHz, 6. In principle, the Rydberg levels can be shifted to provide continuous coverage of the RF–FI spectrum using dc electric fields to Stark shift the states. It is hypothesized that this can yield as accurate results as those measurements carried out in near zero background dc electric fields. A complication with using dc electric fields to tune the Rydberg states is that the transition dipole moments become hybridized. This complicates the calculation of transition dipole moments.

6 Applications

1. Use of the Rydberg atom provides a self-calibrating way to detect the electric field. It uses atoms, which are identical for the same element, so as to provide repeatability of results. It also includes fundamental constant i.e., Plank's constant ($\hbar$) and transition dipole moment which can be measured precisely using modern spectroscopic techniques. Therefore it is also SI traceable.

2. SLOW LIGHT
   Susceptibility is responsible for indicating the degree of polarisation of a material. Linear susceptibility has two parts;

   (a) Real (Re[χ])
   (b) Imaginary (Im[χ])

   Real part corresponds to the optical propagation speed while the imaginary part corresponds to the absorption. Susceptibility is also related to the refractive index of a material. The group velocity is related to the susceptibility of the medium by the relation;

   $$V_g = \frac{dw}{dk} = \frac{c}{n(w) + w\frac{dn}{dw}}$$

   Where n(w) is index of refraction and equals $1 + \frac{Re[\chi]}{2}$. If $\frac{dn}{dw}$ is greater than zero then V_g is less than c i.e. the case of normal dispersion, [13]. Thus giving rise to slow light which itself has various other applications such as optical buffer [14], relative motion sensing and Brillouin sensors.[15]

3. The Rydberg atom based sensors are applicable for electric field metrology, sensing, and communications [16] which

uses factors such as RF field strength, Voltage and power to determine electric field which has application in weather radar and satellite communications.

7 Conclusion

Recent work on Rydberg atom based electrometry has been discussed. The process of signal processing has developed in many ways. The classical antennas have been made to detect the electric fields accurately. However, there is a limit to the measurement using them. Thus, using the phenomena of quantum interference, atom based sensors have been developed and are further developing. The limit to their sensitivity is in $\sim pVcm^{-1}Hz^{-1/2}$ which gives them large room for improvement. Sensors which can function in the whole electromagnetic spectrum are being developed. They use the phenomena of Electromagnetically Induced Transparency (EIT) to enhance the sensitivity and accuracy of measurement and detection. The sensitivity of the Rydberg atom based sensors are already far superior than the classical antenna based sensors. Coupling occurs between the three hyperfine states of an alkali atom (Rb or Cs) and gives rise to new states called dark and light states. Quantum interference destructively takes place between probe and control laser beam and a transparency window is induced. This can be used for information processing at a very high accuracy.

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