Summary

Magnetic fields are ubiquitous in our universe, influencing various phenomena. Despite their prevalence, precise measurement of these fields remains challenging. Magnetometers, devices designed for magnetic field measurement, have evolved significantly since their inception. Different principles, such as the Hall effect, magnetoresistance, and induction, have contributed to advancements in magnetometer sensitivity, enabling detection limits ranging from microtesla to femtotesla.

Magnetometers are indispensable in numerous industries, including automation, aviation, geophysical surveys, and biomedical applications. They facilitate non-invasive monitoring of physiological functions. The Hall probe, while widely used, has limited sensitivity. Micro-Electro-Mechanical System (MEMS) magnetometers, commonly found in smartphones, offer nanotesla sensitivity. Fluxgate magnetometers provide picotesla sensitivity. Superconducting Quantum Interference Devices (SQUIDs) exhibit the highest sensitivity but necessitate cryogenic cooling, limiting their portability and affordability.

The demand for portable, room-temperature magnetometers has led to the development of atomic magnetometers. These devices employ optical pumping techniques, pioneered by Alfred Kastler. Resonant light interacts with alkali vapor, creating an imbalance in the Zeeman sub-levels. The atoms' polarization evolves in the presence of a magnetic field, which can be measured using a probe beam. Some magnetometers enhance sensitivity through spin precession or modulation of light intensity, frequency, or polarization. The Spin-Exchange Relaxation-Free (SERF) magnetometer currently stands as the most sensitive atomic magnetometer, surpassing $fT/\sqrt{Hz}$ sensitivity. This thesis aims to develop a magnetometer capable of detecting magnetic fields from DC to medium frequency RF.

For DC magnetometer, this research investigates the measurement of non-linear Faraday effect (NLFE) in cold atomic systems, a technique that holds significant promise for enhancing the sensitivity of optical magnetometry due to the narrow resonance linewidth. The study introduces a novel tunable differential imaging technique which improve the contrast ratio and the sensitivity compare to the usual crossed polarization or balanced polarization method. Depending upon the system and amount of rotation this technique gives freedom to maximize the contrast ratio depending upon the dynamic range of the imaging system.

The experimental setup utilizes three pairs of Helmholtz coils to maintain a constant external DC magnetic field throughout the measurement process in a Magneto optical trap (MOT). The probe beam has been made bigger in size to ensure that the atomic cloud interacts uniformly with it, which is critical for accurate Faraday rotation assessments. The research also addresses the challenges posed by transverse magnetic fields, which changes the position of the atomic cloud in the MOT making complication to measure the actual rotation due to NLFE. Using a camera enables us to observe the spatial variation of the NLFE. A theoretical model is developed to relate the total polarization rotation in the presence of transverse fields to the longitudinal field, thereby elucidating the complexities involved in measuring nonlinear Faraday rotation under varying magnetic conditions.

Empirical results demonstrate that the data aligns closely with the proposed expression for polarization rotation, indicating a significant improvement in the goodness of fit when applying the new model. A improvement of factor 7 as been achieved in the contrast ratio and sensitivity using this Tunable differential imaging technique compare to the other methods. A sensitivity of 33 $nT/\sqrt{Hz}$ and a spatial resolution of 16 μm has been demonstrated with a dynamic range of ≈ 520 mG which can be further improved. The dependence of the

transverse magnetic field in NLFE has also been shown in this thesis which highlight the potential of the tunable differential imaging technique for high-precision 3d vector magnetometry applications, paving the way for further exploration in ultracold atomic physics and related disciplines.

For a RF magnetometer which can work in medium frequency (100 kHz to 5 MHz) RF magnetic field, we investigates the nonlinear magnetoelectric effect (NME) in alkali atomic vapors for highly sensitive RF magnetic field sensing. A novel wave mixing technique utilizing a longitudinal static magnetic field to detect circular polarization of RF magnetic fields with an extinction ratio exceeding 250:1 is presented. This enables precise characterization of RF magnetic field ellipticity and facilitates the development of a reconfigurable circular polarizer. A sensitivity of 12 $pT/\sqrt{Hz}$ is demonstrated with a bandwidth of 256 kHz. The sensitivity can be improved to 30 ft/$\sqrt{Hz}$ by volumetric improvement which has been discussed. The current system has a sensitivity of 48 $pT/\sqrt{Hz}$ in completely unshielded environment which has been demonstrated. The dynamic range of this magnetometer is also very high (10^7) with a bandwidth of 256 kHz. The robustness against any transverse DC magnetic field make this RF magnetometer working in unshielded environment. A theoretical model is also presented in this thesis to describe the generation of light using NME process.

The conversion of binary phase shift key (BPSK) modulated RF magnetic fields into amplitude-modulated optical fields, generated through the NME, is critical for enhancing digital communication systems in the mid-frequency domain by improving signal integrity and reducing interference. Our research demonstrates the potential of the developed atomic receiver not only for advanced magnetometry but also for diverse applications in fields such as wireless communication and biomedical imaging.