Quantum Sensing with Neutral Atoms and High-Precision Diode Lasers

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Synopsis Our work is focused on developing compact laser systems and cold-atom platforms based on laser cooled ^{133}Cs atoms for precision quantum sensing. Our research integrates the development of accessible external cavity diode lasers and embedded frequency stabilization with investigations of cold-atom dynamics, collisional losses, detection noise and photon-mediated collective effects in magneto-optical traps. These advances provide the foundation for developing transportable cold-atom gravimeters and optical magnetometers with high sensitivity and stability for precision measurements of gravitational and magnetic fields in field applications.

Laser-cooled atomic ensembles serve as foun dational platforms for next-generation quantum technologies, enabling breakthroughs in precision spectroscopy, quantum computing, and quantum sensing. Translating their potential into practi cal applications requires compact, robust opti cal hardware and a quantitative understanding of atomic dynamics and detection noise. Our work is focused on laser-cooled ^{133}Cs ensembles in Magneto-Optical Trap (MOT), bridging founda tional atomic physics with field-deployable quan tum instrumentation. On the hardware and instrumentation front, we have developed accessible, high-performance optical subsystems tailored for cold-atom exper iments. We designed and developed a compact external-cavity diode laser (ECDL) in the Lit trow configuration, operating at the caesium D2 line. Built using readily available components, it features a custom collimation mount with a 3× wider adjustment range than commercial hold ers. The laser enables direct cooling and trap ping of ^{133}Cs atoms in a MOT without requir ing tapered amplifiers or injection locking [1]. To achieve long-term frequency stability, we de veloped an embedded digital PID locking sys tem based on an STM32 microcontroller, using dichroic atomic vapour laser locking (DAVLL) and a custom 150 V piezo driver. The system provides a 6 GHz mode-hop-free tuning range and reduces the laser linewidth to 93±2 kHz [2], enabling reliable trapping of ~ 1.5 × 106 ^{133}Cs atoms [3]. Alongside hardware development, we inves tigate collisional losses and collective effects in cold-atom clouds. We characterized light assisted collisions during fluorescence imaging to extract loss coefficients, reconstruct atom num bers and quantify detection noise and readout fidelity [4]. We also studied photon-mediated interactions and nonequilibrium dynamics in a Cs MOT through spatial density profiles, cloud width fluctuations and density correlations at dif ferent laser detunings. Using a generalized Lane Emden model and spectral correlation analy sis, we identified detuning-dependent interac tion regimes and scale-dependent density corre lations [5]. Building directly upon these validated hard ware platforms and noise-characterization frame works, our ongoing research is focused on trans lating cold-atom ensembles into practical, high precision quantum sensors. Specifically, we are developing cold-atom gravimeters and op tical magnetometers that leverage our compact laser architectures, embedded stabilization sys tems, and loss-compensated detection protocols to achieve high sensitivity and operational stabil ity for geophysical and navigation applications.

References

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