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Development of Control System and RF Synthesis Chain for Absolute Quantum Gravimeter at TCG-CREST

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Abstract

Accurate and stable acceleration due to gravity measurements are critical for mapping spatial and temporal density variation of Earth's subsurface, precision inertial navigation, advanced metrology, detecting underground structures, and many other applications. For precise measurement of gravity, absolute quantum gravimeter (AQG) exploits atomic matter wave interference to achieve exceptional sensitivity (≤ 1 μGal) as well as offering long-term stability and mitigates of mechanical drifts. Gravity measurement with an AQG involves several processes such as cooling and trapping Rubidium-87 (^{87}Rb) atoms in a magneto-optical trap (MOT), followed by optical molasses and polarization gradient cooling (PGC), state preparation, atom-interferometry, and population detection. The operational sequences in these processes demand extremely precise event triggering and synchronized instrument operation with sub-microsecond accuracy. Since the sensitivity and accuracy of gravity measurements with an AQG are highly dependent on timing precision, any deviation in the sequence can introduce phase noise and systematic errors, ultimately affecting measurement fidelity. In this article, we describe a control architecture of an absolute cold atom gravimeter and the implementation of timing sequences. The design of a radiofrequency synthesizer is also described, crucial for ultra-fast switching and frequency/power control of laser beams in an AQG.

1. Introduction

Precision measurement of gravitational acceleration (g) has significant applications in several applications such as inertial navigation, fundamental physics experiments, and geophysical surveys for resource exploration [1], [2], [3]. Cold atom interferometry-based Absolute Quantum Gravimeters (AQGs) are highly robust quantum sensors for gravity measurement, achieving measurements with sensitivity ≤1 μGal [4], [5]. These quantum gravimeters measure 'g' through matter-wave interferometry that exploits the wave nature of ultracold atoms offering other advantages such as long-term automated continuous operation, minimal noise, etc.

The ^{87}Rb isotope of rubidium is advantageous in AQGs due to the scope of efficient laser cooling, long coherence time, low expansion velocity, and well-established trapping techniques, ensuring high-precision gravity measurements. These atoms are trapped in a magneto-optical trap and cooled to microkelvin temperatures through laser cooling techniques and confined within an ultra-high vacuum (UHV) environment. A sequential interaction of these atoms with three Raman laser pulses (π/2, π, π/2) at equal intervals (T), causes the atomic momentum states to split, swap, and recombine [6], [7]. The resulting phase difference (ΔΦ) between momentum states acquired during the free-evolution stage i.e., between the two π/2 Raman pulses is directly proportional to gravitational acceleration and this information is extracted through the population detection of atomic states.

At TCG-CREST, India, we are developing a compact, low power consuming, and highly sensitive absolute quantum gravimeter (AQG) for different mentioned applications. In this article, we discuss the control system for precise execution of timing sequences and radiofrequency (RF) synthesis required in laser modulations and ultra-fast switching.

2. Optical Setup for MOT Generation

The absolute quantum gravimeter relies on a sequential operation as discussed above. The major processes are laser cooling and magneto-optical trapping (MOT), optical molasses, polarization gradient cooling (PGC), state preparation, atom-interferometry, and population detection. A schematic for optical setup for the tabletop version of absolute quantum gravimeter is shown in fig-1. In the optical setup, two 780 nm external cavity diode lasers (ECDLs) are used for generating cooling and repump beams. The cooling laser (ECDL-1) and the repump laser (ECDL-2) are frequency stabilized by locking them to ^{87}Rb atomic transitions $|^2S_{1/2}, F=2\rangle \leftrightarrow |^2P_{3/2}, F'=3\rangle$ (cooling transition) and $|^2S_{1/2}, F=1\rangle \leftrightarrow |^2P_{3/2}, F'=2\rangle$ (repump transition) respectively using saturation absorption spectroscopy (SAS) technique. One part of cooling laser beam is boosted using a tapered amplifier (TA) to generate required high laser intensity for efficient MOT loading. The repump laser is coupled with the cooling laser and ensures that the cooling process sustains a closed-loop transition cycle by preventing the atoms from populating undesired hyperfine levels during cooling cycle. The coupled beam is evenly split into three parts and delivered to the sensor head, where it is retroreflected for uniform Doppler cooling from all directions. The detuning in Doppler cooling and frequency/power ramping during polarization gradient cooling (PGC) is controlled with an acousto-optic modulator, labelled as AOM-2 in fig-1. The exposure of the repump beams, optical pumping beams, and detection beams is controlled through mechanical shutters.

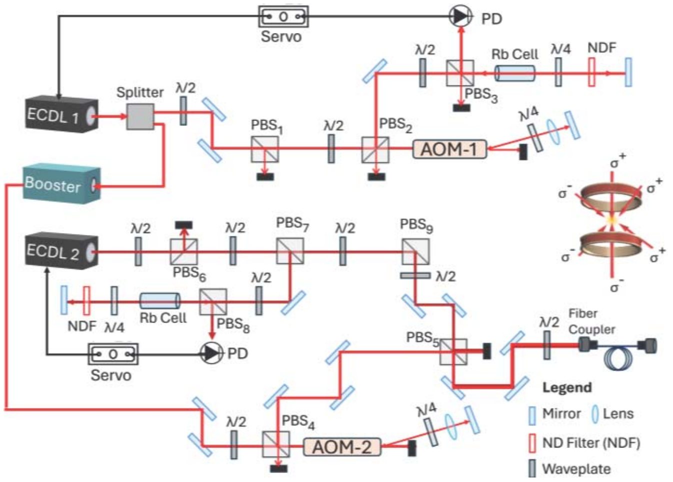

Figure 1. Optical setup for laser cooling and trapping and cooling of Rubidium-87 atoms.

The number of Rb atoms trapped with the described optical setup is of the order of 10^8. Further, an additional acousto-optic modulator (AOM-3) will be used for ultra-fast switching operations to control Raman pulses.

3. Control of Timing Sequence

The operation of an AQG relies on executing multiple precisely timed events with microsecond accuracy, such as controlling Raman pulses that typically last only a few microseconds. Figure 2 provides a simplified timing representation of the various operational phases and the switching of different modules and devices. Maintaining precise timing control is crucial for ensuring a uniform measurement cycle period that enables stable repeatable measurements. Any timing errors during atom interferometry can degrade phase coherence, reducing interference contrast and measurement fidelity. Since the sensitivity of gravity measurements scales with the square of the interrogation time, timing fluctuations can introduce significant phase noise and systematic errors, ultimately reducing measurement accuracy. As a result, uncontrolled timing errors can drastically diminish the AQG sensitivity.

As per the requirement of sub-microsecond precision in synchronized operation and the complexity of coordinating multiple devices, precise timing triggers and execution control are best achieved using FPGA-based solutions. A synchronized control system is implemented with an FPGA serving as the master controller to ensure precise and reliable operation. The FPGA is referenced with a stable 10 MHz signal from Rb atomic clock, reducing jitter and drift associated with internal oscillators that ensure precise synchronization of timing pulses.

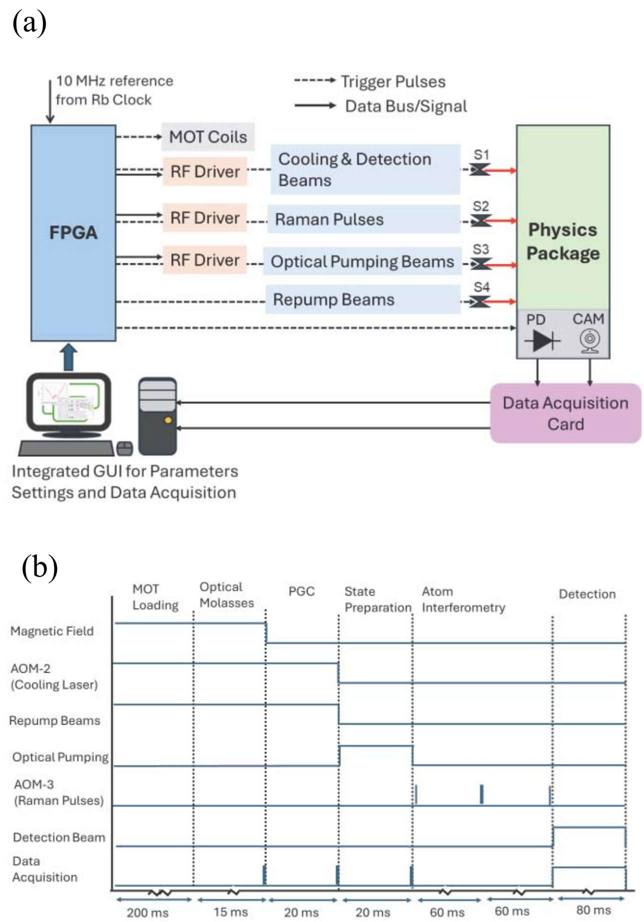

Figure 2. (a) Complete architecture for control system for absolute quantum gravimeter (AQG) at TCG-CREST. (b) Timing sequence of one clock cycle. Time-axis is not to scale.

The required trigger signals are generated by the FPGA that controls various mechanical shutters and also sends instruction at a high-speed rate to microcontroller units (MCUs) that are part of custom-designed and developed DDS-based frequency synthesizers. The MCUs takes trigger pulses and/or instruction data from the FPGA in real time and controls the frequency synthesizer to carry out processes like frequency and amplitude ramping for polarization gradient cooling (PGC) and frequency chirping with pre-programmed data in the MCUs. The parameters for these processes are predefined and can be changed through a developed software before starting the continuous operation of the AQG. The software also acquires data from photo detectors used to estimate state populations using a data acquisition system. Two CMOS cameras for imaging the MOT cloud are also included in the setup to image the cloud and characterize its temperature and free-fall path, needed to optimize the system. Data from these cameras is acquired by the developed GUI based software.

The RF drivers used in the system are one of the most important devices for the operation of AQG as they are used for fast frequency and simultaneous amplitude ramping for PGC, switching Raman pulses, as well as controlling power and laser modulation in the entire measurement cycle. The AOM drivers will be custom designed to use direct digital synthesis (DDS) technology to serve the purpose. The DDS chip AD9910 from analog devices that has 32-bit frequency resolution (0.23 Hz), will be used for generating RF signals [8]. This DDS chip has inbuilt functions for simultaneous frequency and amplitude ramping using an internal ramp generator that can change the amplitude (as percentage) and increment/decrement the frequency by a fixed number with ramp step time of 10 ns. Enabling these functions and preloaded settings and data in a profile will ensure precise frequency and amplitude ramping completing within defined duration. DDS based AOM drivers have an onboard microcontroller unit (MCU) such as Advanced RISC Machine (ARM) MCUs that receive trigger pulses from FPGA and required instructions to execute different processes described in this article. The MCU in turn communicates with the AD9910 IC as shown in fig-3 using parallel communication for fast data transfer that passes instructions within a few tens of nanoseconds.

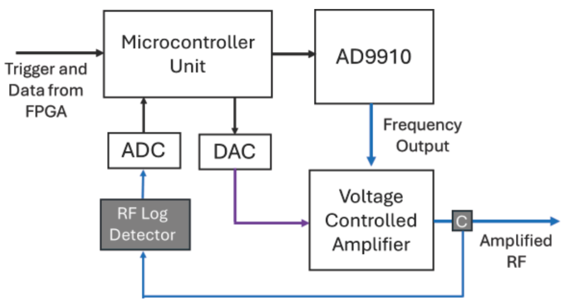

Figure 3. Block diagram of radiofrequency synthesizers for driving acousto-optic modulators (AOM) and controlling PGC, frequency chirping, and tuning laser power. C: Coupler, ADC: Analog-to-digital converter, and DAC: digital-to-analog converter.

A voltage-controlled amplifier is included at the final stage of frequency synthesizer for maintaining required stable RF power using a feedback loop. The control voltage comes through a digital-to-analog (DAC) converter, operated by the MCU. The feedback loop utilizes a signal split from a directional coupler as a monitoring parameter. The RF power from this split signal is measured by a calibrated RF logarithmic detector, which generates a proportional voltage. This voltage is digitized using analog-to-digital converter (ADC) and sensed by the MCU that stabilizes this signal using the feedback loop operated with developed control algorithm.

4. Conclusion

The hierarchical control structure that uses FPGA as master controller of sequence and MCU as controllers of RF synthesizers allows for precise execution of the experimental sequence while maintaining flexibility for real-time adjustments and feedback integration, and also reduces complexities and.

The architecture for controlling an AQG sequence using the AD9910 and a microcontroller offers a precise and efficient solution for high-speed quantum control. By utilizing parallel mode operation, profile switching, and the digital ramp generator (DRG), the system enables ultra-fast updates, allowing real-time modulation of frequency and amplitude. This approach provides several advantages, including high resolution with 32-bit frequency and 14-bit amplitude control, fast switching through parallel data loading, and simultaneous frequency and amplitude ramping for smooth quantum state transitions. Additionally, the ability to predefine profiles ensures rapid selection of gate parameters, enhancing flexibility in experimental setups. A key benefit of this design is miniaturization, as it eliminates the need for bulky commercial frequency drivers or commercial AOM drivers, reducing system size and power consumption.

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