PRECISION OSCILLATOR TECHNOLOGY WITH APPLICATION TO TESTING FUNDAMENTAL PHYSICS, DETECTING HIGH FREQUENCY GRAVITATIONAL WAVES, AND QUANTUM MEASUREMENT

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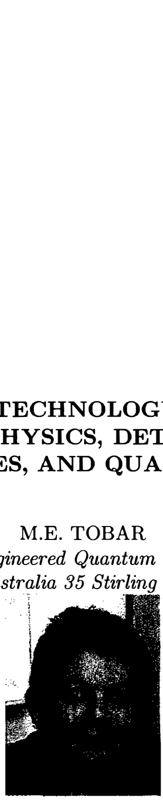

This paper summarises research programs at The University of Western Australia to develop precision oscillator technology based on cryogenic sapphire whispering gallery mode resonators and cryogenic quartz bulk acoustic wave oscillators. Research programs include precision tests of fundamental physics, experiments to detect high frequency gravitational waves and cosmic dark sector particles, as well as quantum measurement, and in particular to measure large mass harmonic oscillators at the ground state.

1 Oscillator Technology

1.1 Cryogenic Sapphire Oscillators based on Whispering Gallery Modes

At the University of Western Australia we have built the most stable and precise electromagnetic oscillator, the Cryogenic Sapphire Oscillator (CSO) at microwave frequencies with parts in 10^{16} frequency instabilities[1]. At the heart of any CSO is a cylindrical sapphire dielectric resonator with its rotational axis aligned with the crystal axis in which high-Q Whispering Gallery (WG) modes are excited.

Recently, characterization of the power to frequency conversion in the CSO has shown that fluctuations of power incident on the resonator is the primary limiting factor contributing to the frequency instabilities in the oscillator. At such high levels of precision the task of further optimisation to improve the CSO sets a challenge. The way forward is to lower the noise floor of the power control scheme. As outlined in[2] there are a few strategies to be followed. 1) To undertake a thorough search of noise in detectors (the limiting component) our calculations show that the radiation pressure noise floor can be reduced to a part in 10^{17} at 1 second of fluctuations. 2) A power versus frequency turning point may be engineered as spin resonance effects of impurities have opposite effect to radiation pressure, this would reduce the requirement of the power control. 3) Adaption of novel low-noise power detection using interferometer technology[3]. Any improvement in this technology will not only improve the oscillator performance, but the tests of fundamental physics through the application of this technology

1.2 *Cryogenic Quartz Technology based on Bulk Acoustic Wave Resonators*

Phonon-trapping Bulk Acoustic Wave (BAW) cavity resonator technology shows great potential for use in applications that require precision control, measurement, and sensing at the quantum limit. This is mainly due to the relatively high mechanical frequencies and extremely high Q-factors achievable at cryogenic temperatures ($Q \approx 10^{10}$) for frequencies ranging from a MHz to a GHz, beyond the capability of any other competing technology compared in[4]. This uniqueness has been perfected for decades for precision room temperature oscillators and related devices, culminating in $Q \times f$ products as high 2×10^{13} Hz, and in a collaboration with FEMTO-ST in Besancon, only recently has been extended to cryogenic temperatures attaining $Q \times f$ products as high 2×10^{18} Hz[5]. Thus, further improvement of BAW oscillators can only be achieved by cooling the resonators and reducing the resonator flicker phase self-noise, since this is the dominant noise source both at cryogenic and room temperature. The influence on the frequency stability of high-performance quartz oscillators on time scales of order 150 s is well-documented and it has been observed that the flicker self-noise decreases with decreasing power of the incident signal, and our recent results confirm that the resonators are thermal noise limited, and flicker free without the carrier[6]. Thus, the noise in the quartz oscillator is dependent on power, with the white noise floor decreasing with power, while the flicker noise increases. The best quartz typically has frequency instabilities of better than 10^{-13} limited by flicker fluctuations. However at cryogenic temperatures the white noise floor is reduced by 40 dB, allowing a much lower oscillator power and a large reduction of the flicker noise so the increased Q-factor may be exploited. Assuming the typical phase noise of -130 dBc/Hz at 1 Hz limited by the resonator self noise, the increase in Q-factor at 4K should see frequency instabilities as low as 2×10^{-16} through the development of Cryogenic Quartz Oscillators (CQO), and if this can be pushed down further due to power optimisations it is strongly feasible to push the stability into the 10^{-17} regime[7].

2 Precision Tests of Local Lorentz Invariance Violations

The broad experimental research for Lorentz Invariance Violations LIV is successfully bundled by test theories, such as the Standard Model Extension (SME)[8] and Robertson-Mansouri-Sexl theory[9,10], which enable the comparison and exchange of experimental results by collective efforts to put bounds to a number of test parameters. Experimental tests for LIV are performed across almost all sectors of physics (proton, neutron, electron and photons), LIV in the photon sector refers to scenarios where the velocity of light depends slightly on direction in space, boost velocity, and/or frequency, we undertake these experiments with rotating cryogenic sapphire oscillators[11]. Our most recent experiment in collaboration with Humboldt University of Berlin[11] (known as a modern Michelson-Morley experiment) put bounds on LIV of order 10^{-18}. This result is just into the range, which is able to falsify LIV in the photon sector beyond the electroweak transition, to push beyond this regime, better sensittivity is necessary and with improvements in CSO technology should see an order of magnitude improvement in the future.

In collaboration with UC Berkeley we have implemented room temperature quartz oscillators to set limit in the neutron sector [7]. This experiment was based on rotating commercial room temperature oscillators with 10^{-12} fractional frequency instabilities. The physical setup is that of a Modern Michelson Morley experiment, but tests phonon oscillations rather than photon oscillations and tests the spatial invariance of phonons to a part in 10^{15} with 120 hours worth of data[7]. CQOs have the possibility to improve this to parts in 10^{-19} if they perform as calculated with a fractional frequency instability of 10^{-16}.

3 Precision Tests to Detect High Frequency Gravitational Waves

There are a number of theoretical predictions for astrophysical and cosmological objects, which emit high frequency ($10^6 - 10^9$ Hz) Gravitation Waves (GW) or contribute somehow to the stochastic high frequency GW background[16]. We propose a new sensitive detector in this frequency band[16], which is based on existing cryogenic ultra-high quality factor quartz Bulk Acoustic Wave cavity technology[17,18,19], coupled to near-quantum-limited SQUID amplifiers at 20 mK[6]. We show that spectral strain sensitivities reaching 10^{-22} per $\sqrt{Hz}$ per mode is possible, which in principle can cover the frequency range with multiple (> 100) modes with quality factors varying between $10^6 - 10^{10}$ allowing wide bandwidth detection. Due to its compactness and well established manufacturing process, the system is easily scalable into arrays and distributed networks that can also impact the overall sensitivity and introduce coincidence analysis to ensure no false detections.

4 Precision Tests to Detect Dark Sector Particles

The axion is a hypothetical bosonic particle that was first proposed[20,21] as a consequence of Peccei and Quinns solution to the strong CP problem[22]. It is a particle with non-zero mass that interacts gravitationally and via a weak coupling to Standard Model particles; as such it belongs to a family called the Weakly Interacting Sub-eV Particles (WISPs). These properties make it both a very compelling dark matter candidate and extremely difficult to detect. In particular, axions with masses in the range of micro-eV to milli-eV could account for cold dark matter in galactic halos. Axions provide explanations for many cosmological observations, including the formation of caustic rings; they are an elegant and natural solution to many problems in physics.

Recently, Beck reported on a possible axion dark matter signal[23]. Beck postulates that a flux of dark matter axions would induce certain signals in Josephson junctions without the application of an external microwave field. This theory explains a previously reported anomalous signal in Josephson junctions[24] as being caused by the presence of axions with a mass of $110 \pm 2 micro-eV$ (26.6 GHz) and a local axion dark matter density of $0.05 GeV/cm^3$. Such a claim further compels full investigation over the possible range of masses. At UWA we are constructing an experiment to target this precise mass range, which will allow for verification or rejection of this claim. This first experiment will also serve as the pathfinder project for an expanded search over the 15 30 GHz mass range.

Similar cavity experiments to detect dark photons have been conducted in our laboratories. These experiments are generate and detect experiments and take the form of a light shining through the wall experiment[25,26,27]. More recently we developed a new experiment that uses the coupling of photons and axions to create a frequency shidt between two microwave oscillator cavities[28], which has the potential to improve these experiments by more than one order of magnitude.

5 Applications to Quantum Measurement

We are undertaking two experiments at the University of Western Australia with the goal to read out electromechanical systems in the ground state. The first is using quartz BAW resonators of order gram scale, which have the highest $Q \times f$ produce of any acoustic system by a few orders of magnitude, with the acoustic motion detected through the piezo-electric effect[29,30]. Motion has already been detected, which should be high enough in frequency that the quantum fluctuations of motion can be directly detected[31,18]. The second is through a high-Q acoustic sapphire dumbbell of order kg scale coupled parametrically through high-Q whispering gallery modes due to the strain dependent permittivity[32]. This experiment will need to make use of parametric cooling to reach this goal.

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