URSI AP-RASC, Sydney, Australia, 17 – 22 August 2025

Precision Measurement and Signal Generation to Test Fundamental Physics

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Abstract

This work will highlight our recent work to build new high precision measurement and signal generation techniques at the Quantum Technologies and Dark Matter Laboratory at the University of Western Australia, with the aim to test fundamental physics.

1 Introduction

The Quantum Technologies and Dark Matter Research Laboratory has a rich history of developing precision tools for both fundamental physics and translational applications. This includes the development and application of novel low-loss and highly sensitive resonant microwave photonic and phononic cavities, such as whispering gallery [1, 2] and re-entrant cavities [3, 4, 5, 6], as well as bulk acoustic wave structures [7, 8, 9, 10]. These cavities have been implemented as highly stable low-noise classical and atomic oscillators [11, 12, 13, 14, 15], low-noise measurement systems [16, 17, 18, 19], highly sensitivity displacement sensors [20, 21, 5], high precision electron spin resonance [22, 23, 24] and spin-wave spectroscopy, high precision measurement of material properties [25, 26, 27] and applications of low-loss quantum hybrid systems, which are strongly coupled to form quasi-particles [28, 29, 30].

2 Applications

Translational applications of our technology have included the realization of the lowest noise oscillators and systems for advanced radar and the enabling of high accuracy atomic clocks and ultra-sensitive transducers for precision gravity and quantum measurements, including electric scalar Aharonov-Bohm effects [31, 32]. Meanwhile there is currently a worldwide push to apply precision and quantum measurement techniques to major unsolved problems in physics, including the search for “Beyond Standard Model” physics. This effort focuses on understanding the nature of dark matter [33], and if monopoles exist [34, 35, 36], as well as unifying quantum mechanics with general relativity to develop a theory of quantum gravity. In this context, we present our latest results on the development of new electromagnetic cavity and oscillator designs that enable the coupling of photons, phonons, and spins in solid-state systems. These systems are designed to enhance interactions between electromagnetic fields, mechanical vibrations, and spin states, offering new opportunities to explore fundamental physics, adapted to carry out precision measurements aimed at testing key aspects of fundamental physics.

The type of experiments we are developing include searches for Lorentz invariance violations in the photon, phonon, and gravity sectors [37, 38, 39, 40, 41], possible variations in fundamental constants [42, 43], detection of wave-like dark matter[44, 45, 46, 47, 48], and tests of quantum gravity, gravitational Aharonov-Bohm effects [49, 50, 51, 52, 53, 54] and high-frequency gravitational waves [55, 56, 57]. We will describe the key design features of these cavities and oscillators, highlighting how their geometry, materials, and operating modes influence performance. Our experimental results demonstrate that these systems achieve high sensitivity and precision, making them promising tools for fundamental research and future quantum technologies.

References

[1] M. T. Hatzon, E. N. Ivanov, J. F. Bourhill, M. Goryachev, M. E. Tobar. Microwave-cavity-mode optimization by background antiresonance tuning. *Phys. Rev. Appl.*, 22:014081, Jul 2024.

[2] J. Krupka, K. Derzakowski, A. Abramowicz, M. E. Tobar, R. G. Geyer. Use of whispering-gallery modes for complex permittivity determinations of ultra-low-loss dielectric materials. *IEEE Trans. on MTT*, vol. 47, no. 6, pp. 752–759, 1999.

[3] J.-M. Le Floch, Y. Fan, M. Aubourg, D. Cros, N. C. Carvalho, Q. Shan, J. Bourhill, E. N. Ivanov, G. Humbert, V. Madrangeas, M. E. Tobar. Rigorous analysis of highly tunable cylindrical transverse magnetic mode re-entrant cavities. *Rev. of Sci. Instrum.*, vol. 84, no. 12, p. 125114, 2013.

[4] J. M. Pate, M. Goryachev, R. Y. Chiao, J. E. Sharping, M. E. Tobar. Casimir spring and dilution in macroscopic cavity optomechanics. *Nature Physics*, vol. 16, no. 11, pp. 1117–1122, 2020.

[5] S. Parashar, W. M. Campbell, J. Bourhill, E. Ivanov, M. Goryachev, M. E. Tobar. Upconversion of phonon modes into microwave photons in a lithium niobate bulk acoustic wave resonator coupled to a microwave cavity. *APL Photonics*, 9(11):111304, 11 2024.

[6] J. Bourhill, G. Cochet, J. Haumant, V. Vlaminck, A. Manchec, M. E. Tobar, V. Castel. Metalized 3-D printed plastic resonator demonstrating superconductivity below 4 k. *IEEE Trans. on Components, Packaging and Manufacturing Technology*, 14(11):2140–2143, 2024.

[7] M. Goryachev, D. Creedon, E. Ivanov, S. Galliou, R. Bourquin, M. E. Tobar. Extremely low-loss acoustic phonons in a quartz bulk acoustic wave resonator at millikelvin temperature. *Appl. Phys. Lett.*, vol. 100, no. 24, p. 243504, 2012.

[8] S. Galliou, M. Goryachev, R. Bourquin, P. Abbe, J. Aubry, and M. E. Tobar. Extremely low loss phonon-trapping cryogenic acoustic cavities for future physical experiments. *Nature: Scientific Reports*, vol. 3, no. 2132, 2013.

[9] M. Goryachev, D. Creedon, S. Galliou, M. E. Tobar. Observation of rayleigh phonon scattering through excitation of extremely high overtones in low-loss cryogenic acoustic cavities for hybrid quantum systems. *Phys. Rev. Lett*, vol. 111, no. 8, p. 085502, 2013.

[10] W. Campbell, S. Galliou, M. E. Tobar, M. Goryachev. Electro-mechanical tuning of high-Q bulk acoustic phonon modes at cryogenic temperatures. *Applied Physics Letters*, 122(3):032202, 01 2023.

[11] K. Benmessai, D. L. Creedon, M. E. Tobar, P.-Y. Bourgeois, Y. Kersalé, V. Giordano. Measurement of the fundamental thermal noise limit in a cryogenic sapphire frequency standard using bimodal maser oscillations. *Phys. Rev. Lett.*, vol. 100, p. 233901, Jun 2008.

[12] E. N. Ivanov, M. E. Tobar. Frequency stable microwave sapphire oscillators. *IEEE Microwave and Wireless Technology Letters*, 33(12):1642–1645, 2023.

[13] C. R. Locke, E. N. Ivanov, J. G. Hartnett, P. L. Stanwix, M. E. Tobar. Invited article: Design techniques and noise properties of ultrastable cryogenically cooled sapphire-dielectric resonator oscillators. *Review of Scientific Instruments*, 79(5):051301, 2008.

[14] C. A. Thomson, M. Goryachev, B. T. McAllister, E. N. Ivanov, P. Altin, and M. E. Tobar. Searching for low-mass axions using resonant upconversion. *Phys. Rev. D*, 107:112003, 2023.

[15] C. A. Thomson, M. E. Tobar, M. Goryachev. Generation of bimodal solitons in a sapphire whispering-gallery-mode maser at millikelvin temperatures. *Phys. Rev. A*, 105:033511, Mar 2022.

[16] E. N. Ivanov, M. E. Tobar. Low phase-noise microwave oscillators with interferometric signal processing. *IEEE Trans. on MTT*, 54(8):3284–3294, 2006.

[17] E. N. Ivanov, M. E. Tobar. Low phase-noise sapphire crystal microwave oscillators: current status. *IEEE Trans. on UFFC*, 56(2):263–269, 2009.

[18] E. N. Ivanov, M. E. Tobar, R. A. Woode. Microwave interferometry: application to precision measurements and noise reduction techniques. *IEEE Trans. on UFFC*, 45(6):1526–1536, 1998.

[19] M. E. Tobar. 9th symposium on frequency standards and metrology. *Journal of Physics: Conference Series*, 2889(1):011001, Nov 2024.

[20] G. L. Pimentel, O. D. Aguiar, J. J. Barroso, M. E. Tobar. Investigation of ultra-high sensitivity klystron cavity transducers for broadband resonant-mass gravitational wave detectors. *Journal of Physics: Conference Series*, vol. 122, no. 1, p. 012028, 2008.

[21] O. D. Aguiar, J. J. Barroso, R. M. Marinho, G. L. Pimentel, M. E. Tobar. Broadband resonant mass gravitational wave detection. *International Journal of Modern Physics D*, vol. 18, no. 14, pp. 2317–2322, 2009.

[22] W. G. Farr, D. L. Creedon, M. Goryachev, K. Benmessai, M. E. Tobar. Ultrasensitive microwave spectroscopy of paramagnetic impurities in sapphire crystals at millikelvin temperatures. *Phys. Rev. B*, vol. 88, p. 224426, Dec 2013.

[23] E. Hartman, M. E. Tobar, B. T. McAllister, J. Bourhill, M. Goryachev. Precision multi-mode microwave spectroscopy of paramagnetic and rare-earth ion spin defects in single crystal calcium tungstate. *Applied Physics Letters*, 125(16):164001, 10 2024.

[24] B. T. McAllister, Z. C. Zhao, J. F. Bourhill, M. Goryachev, D. Creedon, B. C. Johnson, M. E. Tobar. Conductivity freeze-out in isotopically pure Si-28 at millikelvin temperatures. *Phys. Rev. Appl.*, 21:064002, Jun 2024.

[25] J.-M. Le Floch, Y. Fan, G. Humbert, Q. Shan, D. Férachou, R. Bara-Maillet, M. Aubourg, J. G. Hartnett, V. Madrangeas, D. Cros, J.-M. Blondy, J. Krupka, M. E. Tobar. Invited article: Dielectric material characterization techniques and designs of high-Q resonators for applications from micro to millimeter-waves frequencies applicable at room and cryogenic temperatures. *Review of Scientific Instruments*, vol. 85, no. 3, p. 031301, 03 2014.

[26] Z. C. Zhao, M. Goryachev, J. Krupka, M. E. Tobar. Precision multi-mode dielectric characterization of a crystalline perovskite enables determination of the temperature-dependent phase transitions. *IEEE Trans. on UFFC*, 69(1):423–429, 2022.

[27] S. Galliou, J. Bon, P. Abbé, R. Vicarini, M. E. Tobar, M. Goryachev. Probing the acoustic losses of graphene with a low-loss quartz bulk-acoustic-wave resonator at cryogenic temperatures. *Materials Science and Engineering: B*, 287:116102, 2023.

[28] M. Goryachev, W. G. Farr, D. L. Creedon, Y. Fan, M. Kostylev, M. E. Tobar. High-cooperativity cavity QED with magnons at microwave frequencies. *Phys. Rev. Applied*, vol. 2, p. 054002, Nov 2014.

[29] S. Probst, A. Tkalčec, H. Rotzinger, D. Rieger, J.-M. Le Floch, M. Goryachev, M. E. Tobar, A. V. Ustinov, P. A. Bushev. Three-dimensional cavity quantum electrodynamics with a rare-earth spin ensemble. *Phys. Rev. B*, vol. 90, p. 100404, Sep 2014.

[30] G. Flower, J. Bourhill, M. Goryachev, M. E. Tobar. Broadening frequency range of a ferromagnetic axion haloscope with strongly coupled cavity–magnon polaritons. *Physics of the Dark Universe*, 25:100306, 2019.

[31] R. Y. Chiao, H. Hart, M. Scheibner, J. Sharping, N. A. Inan, D. A. Singleton, M. E. Tobar. Energy-level shift of quantum systems via the scalar electric Aharonov-Bohm effect. *Phys. Rev. A*, 107:042209, Apr 2023.

[32] M. T. Hatzon, G. R. Flower, M. Goryachev, J. F. Bourhill, M. E. Tobar. Sharp electromagnetically induced absorption via balanced interferometric excitation in a microwave resonator. *Phys. Rev. Appl.*, 23:024058, Feb 2025.

[33] C. Boutan, G. Carosi, L. J. Rosenberg, G. Rybka, K. M. Backes, C. Bartram, M. Baryakhtar, M. D. Bird, C. Braggio, D. Budker, R. T. Co, E. Daw, A. Dixit, A. A. Geraci, C. Lee, S. Lee, D. Marsh, C. O'Hare, K. Saikawa, C. P. Salemi, Y. K. Semertzidis, A. Sonnenschein, A. Spector, M. E. Tobar, J. Vogel, A. Zhitnitsky. Axions Beyond Gen 2. *International Journal of Modern Physics A*, 38(33n34):2330012, 2023.

[34] M. E. Tobar, C. A. Thomson, B. T. McAllister, M. Goryachev, A. V. Sokolov, A. Ringwald. Sensitivity of resonant axion haloscopes to quantum electromagnetodynamics. *Annalen der Physik*, n/a(n/a):2200594, 2023.

[35] M. E. Tobar, A. V. Sokolov, A. Ringwald, M. Goryachev. Searching for GUT-scale QCD axions and monopoles with a high-voltage capacitor. *Phys. Rev. D*, 108:035024, Aug 2023.

[36] B. T. McAllister, A. Quiskamp, C. A. J. O'Hare, P. Altin, E. N. Ivanov, M. Goryachev, M. E. Tobar. Limits on dark photons, scalars, and axion-electromagnetodynamics with the organ experiment. *Annalen der Physik*, n/a(n/a):2200622.

[37] M. E. Tobar, P. Wolf, A. Fowler, J. G. Hartnett. New methods of testing Lorentz violation in electrodynamics. *Phys. Rev. D*, 71:025004, Jan 2005.

[38] M. Nagel, S. R. Parker, E. V. Kovalchuk, P. L. Stanwix, J. G. Hartnett, E. N. Ivanov, A. Peters, M. E. Tobar. Direct terrestrial test of Lorentz symmetry in electrodynamics to 10^{-18}. *Nature Communications*, 6:8174 EP, 09 2015.

[39] A. Lo, P. Haslinger, E. Mizrachi, L. Anderegg, H. Müller, M. Hohensee, M. Goryachev, M. E. Tobar. Acoustic tests of Lorentz symmetry using quartz oscillators. *Phys. Rev. X*, vol. 6, no. 1, pp. 011 018–, 02 2016.

[40] M. Goryachev, Z. Kuang, E. N. Ivanov, P. Haslinger, H. Müller, M. E. Tobar. Next generation of phonon tests of Lorentz invariance using quartz baw resonators. *IEEE Trans. on UFFC*, vol. 65, no. 6, pp. 991–1000, June 2018.

[41] C.-G. Shao, Y.-F. Chen, Y.-J. Tan, S.-Q. Yang, J. Luo, M. E. Tobar, J. C. Long, E. Weisman, V. A. Kostelecký. Combined search for a Lorentz-violating force in short-range gravity varying as the inverse sixth power of distance. *Phys. Rev. Lett.*, vol. 122, p. 011102, Jan 2019.

[42] M. E. Tobar, P. Wolf, S. Bize, G. Santarelli, V. Flambaum. Testing local Lorentz and position invariance and variation of fundamental constants by searching the derivative of the comparison frequency between a cryogenic sapphire oscillator and hydrogen maser. *Phys. Rev. D*, vol. 81, p. 022003, Jan 2010.

[43] M. E. Tobar, P. L. Stanwix, J. J. McFerran, J. Guéna, M. Abgrall, S. Bize, A. Clairon, P. Laurent, P. Rosenbusch, D. Rovera, G. Santarelli, "Testing local position and fundamental constant invariance due to periodic gravitational and boost using long-term comparison of the SYRTE atomic fountains and H-masers. *Phys. Rev. D*, vol. 87, p. 122004, Jun 2013.

[44] V. V. Flambaum, B. T. McAllister, I. B. Samsonov, M. E. Tobar. Searching for scalar field dark matter using cavity resonators and capacitors. *Phys. Rev. D*, 106:055037, Sep 2022.

[45] J. F. Bourhill, E. C. I. Paterson, M. Goryachev, M. E. Tobar. Searching for ultralight axions with twisted cavity resonators of anyon rotational symmetry with bulk modes of nonzero helicity. *Phys. Rev. D*, 108:052014, Sep 2023.

[46] A. Quiskamp, B. T. McAllister, P. Altin, E. N Ivanov, M.Goryachev, M. E Tobar. Direct search for dark matter axions excluding alp cogenesis in the 63-to 67-μev range with the organ experiment. *Science Advances*, 8(27):eabq3765, 2022.

[47] B. T. Mcallister, S. R. Parker, E. N. Ivanov, M. E. Tobar. Cross-correlation signal processing for axion and wisp dark matter searches. *IEEE Trans. on UFFC*, 66(1):236–243, 2019.

[48] A. Quiskamp, B. T. McAllister, P. Altin, E. N. Ivanov, M. Goryachev, M. E. Tobar. Exclusion of axionlike-particle cogenesis dark matter in a mass window above 100 μeV. *Phys. Rev. Lett.*, 132:031601, 2024.

[49] W. M. Campbell, M. E. Tobar, M. Goryachev, S. Galliou. Improved constraints on minimum length models with a macroscopic low loss phonon cavity. *Phys. Rev. D*, 108:102006, 2023.

[50] G. Tobar, I. Pikovski, M. E. Tobar. Detecting kHz gravitons from a neutron star merger with a multimode resonant mass detector. *Classical and Quantum Gravity*, 42(5):055017, 2025.

[51] R. Y. Chiao, N. A. Inan, M. Scheibner, J. Sharping, D. A. Singleton, M. E. Tobar. Gravitational Aharonov-Bohm effect. *Phys. Rev. D*, 109:064073, Mar 2024.

[52] M. E. Tobar, M. T. Hatzon, G. R. Flower, M. Goryachev. Scalar gravitational Aharonov–Bohm effect: Generalization of the gravitational redshift. *Applied Physics Letters*, 125(9):094002, 08 2024.

[53] R. Y Chiao, N. A Inan, M. Scheibner, J. Sharping, D. A. Singleton, M. E Tobar. Time-dependent Aharonov-Bohm effect for electromagnetic and gravitational scalar potentials. *Journal of Physics: Conference Series*, 2889(1):012062, nov 2024.

[54] R. Y. Chiao, N. A. Inan, D. A. Singleton, M. E. Tobar. Temporal Pound–Rebka experiment as gravitational Aharonov–Bohm effect. *International Journal of Modern Physics D*, 33(15):2441021, 2025/02/21 2024.

[55] M. Goryachev, W. M. Campbell, I. S. Heng, S. Galliou, E. N. Ivanov, M. E. Tobar. Rare events detected with a bulk acoustic wave high frequency gravitational wave antenna. *Phys, Rev. Lett.*, 127(7):071102, aug 2021.

[56] W. M. Campbell, M. Goryachev, M. E. Tobar. The multi-mode acoustic gravitational wave experiment: Mage. *Scientific Reports*, 13(1):10638, 2023.

[57] M. E. Tobar, C. A. Thomson, W. M. Campbell, A. Quiskamp, J. F. Bourhill, B. T. McAllister, E. N. Ivanov, M. Goryachev. Comparing instrument spectral sensitivity of dissimilar electromagnetic haloscopes to axion dark matter and high frequency gravitational waves. *Symmetry*, 14(10), 2022.