Precision Metrology and Frequency Generation using Cryogenically Cooled Low-Loss Crystalline Whispering Gallery Mode Resonators

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This talk will summarise recent work on cryogenically cooled low-loss crystalline Whispering Gallery (WG) mode resonators on behalf of the Frequency and Quantum Metrology Research group at the University of Western Australia (UWA).

At UWA we have developed the use of cryogenically cooled sapphire crystals operating as WG mode dielectric resonators to make extremely stable and low-noise frequency sources [1]. This is possible due to the extremely high Q-factor of more than one billion and the existence of residual paramagnetic impurities within the crystal lattice, which supply a susceptibility that acts opposite to the lattice permittivity to annul the frequency temperature characteristic some where between 5 to 10 K [2]. We will present our latest results related to high stability cryogenic oscillators as well as results of precision spectroscopy of impurity ions in low-loss crystalline WG mode resonators.

First, we will discuss Cryogenic Sapphire Oscillators, where we show that the current limit to the frequency instability of $10^{-16}$ is due to radiation pressure induced power to frequency conversion of the WG mode resonator itself of -0.15 Hz/mW [3]. Second, we will discuss the effect of paramagnetic impurities in sapphire to; 1) create population inversion using the three-level Fe$^{3+}$ ion (concentration of 10 ppb) to generate a stable frequency of 12 GHz [4]; 2) non-linear effects of higher concentrations of Fe$^{3+}$ (of >100 ppb), which includes observation of four-wave mixing [5] and the generation of a high-stability frequency comb as well as third harmonic generation [6]; 3) The recent discovery of population inversion and masing between two high-Q WG mode resonances coupled to the same spin-bath due to spin-spin interactions [7]. Finally, using hybrid WG modes and Electron Spin Resonance techniques, interactions between photons and paramagnetic ions in crystalline microwave cavities are studied [8]. Rigorous spectroscopy of single-crystal sapphire and rare earth doped YAG and YSO was performed over the frequency range of 8-19 GHz, and external DC magnetic fields of up to 1 Tesla. Measurements of a high purity sapphire reveal the presence of Fe$^{3+}$, Cr$^{3+}$, and V$^{2+}$ impurities, with quadrupole and hyperfine structure, as well as coupling between spins and photons of up to 6MHz. Also, new transitions in Erbium doped YSO crystals are observed in the strong coupling regime and will be presented at the conference.

References