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Active Optical Clock: Seventeen Years of Progress and Next Steps

The concept of the active optical clock (AOC) [1] was proposed seventeen years ago by prof. Jingbiao Chen. After early calculations and experiments that demonstrated the advantages of "cavity-pulling suppression" and "narrower linewidth", the development of AOCs soon became an active competition involving many research groups that proposed schemes based on different atomic gain mediums, and different energy-level structures. The AOC has great promise for applications in quantum metrology, as it can overcome the thermal noise of the reference cavity that limits conventional lasers, making AOC a promising candidate for future atomic clocks.

Due to the significant advantages, the AOC has received extensive attention from international colleagues, and dozens of institutes such as NIST, JILA, Niels Bohr Institute, and University of Hamburg, etc., have conducted research on AOCs. Current experimental schemes include AOCs based on thermal atomic vapor cell, thermal atomic beam, laser slowed atomic beam, optical lattice, and magneto-optical trap (MOT) trapped atoms. The Niels Bohr Institute used ^{88}Sr atoms imprisoned in a MOT operating in bad-cavity region as a quantum reference to achieve a quasi-continuous superradiant lasing through cavity-enhanced atomic interactions with a linewidth of 820 Hz. JILA [2] has reduced the frequency stability of AOC to 6×10^{-16} @ 1 s with a linewidth of narrower than 2 Hz.

Peking University has recently conducted research around Cs four-level AOC [3], mainly including: 1) A continuous wave (cw) 1470 nm AOC with a linewidth of 53 Hz was realized based on the dual-wavelength good-bad-cavity technique. 2) We proposed a laser referenced on a version of velocity-grating Ramsey-Bordé atom interferometry with greatly improved atom utilization, which can generate optical Ramsey fringes with an amplitude enhanced by 1000-fold or more. 3) An inhibited laser was innovatively proposed, expanding the working regime of the classical AOC from the resonant cavity condition to the far off-resonance condition. It is proved that the suppressed cavity-pulling effect of the inhibited laser is further enhanced by a factor of $(\frac{2\mathcal{F}}{\pi})^2$ compared with the resonant state-of-the-art superradiant laser. 4) An exact expression for the FWHM of the Fabry-Pérot (FP) cavity Airy distribution was derived, which solves the problem of inapplicability under ultra-low reflectivity conditions in the conventional formula. 5) We achieved the first continuously operating extremely bad-cavity laser with a cavity finesse close to the limit of 2 (corresponding to a reflectivity of 0.5%). Experimentally, we obtained a cavity-pulling coefficient that is nearly 70 times less sensitive to cavity thermal and technical noise than conventional good-cavity lasers.

The AOC uses the stimulated radiation signal of atoms directly as an optical frequency standard and operates in the deep bad-cavity region. The gain linewidth is much narrower than the cavity mode linewidth, so the laser frequency depends mainly on the quantum transition rather than the cavity-mode center frequency. Currently, one of the major directions in the development of AOCs is cw operation. Peking University has carried out cold-atom four-level AOC with simultaneous cooling, repumping, and pumping, which are expected to realize cold-atom-based AOC operating continuously with linewidths of the order of Hz. JILA, RIKEN, and the European Union are also conducting AOC superradiant experiments based on moving optical lattices, and have now achieved the use of optical lattices to transport atoms into resonant cavities. In the near future, we believe that continuously operating AOC superradiant lasers based on moving optical lattices will be realized.

References

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