Investigation of Continuously Repumped Superradiance in ^{88}Sr

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***Summary*— We present the recent developments of our work towards demonstrating key features of continuous superradiant lasing, such as below-natural linewidth frequency stability. We discuss the development of a quasi-continuous lasing scheme coupling cold ^{88}Sr atoms to an optical cavity. This system can produce pulses that are longer than the natural lifetime of the lasing transition $^1S_0 \leftrightarrow {}^3P_1$, which allows us to gauge the frequency characteristics of true steady-state superradiant lasing.**

Keywords—optical atomic clocks, superradiance, frequency standards

State-of-the-art optical atomic clocks rely on ultra-stable lasers to achieve fractional stabilities of below 10^{-18} [1-3]. Such clocks use a passive stabilization scheme, where the laser is stabilized to a high-finesse reference cavity and a sample of atoms for short and long-term stability, respectively. A proposed improvement over such reference lasers is to use bad-cavity superradiant lasing obtained directly from an ensemble of atoms, removing the need for a separate reference cavity for laser stabilization. In the bad-cavity regime, the spectral width of the atomic ensemble is much smaller than the cavity linewidth, and thus the phase information that defines the lasing output will be stored in the atomic ensemble rather than the cavity field. This suppresses frequency fluctuations in the lasing due to mechanical and thermal noise, which is a current limitation in passive atomic clocks [4,5].

Here, we seek to test some key-predictions of the frequency characteristics of continuous superradiant lasing. In our system we have demonstrated strong collective effects in an ensemble of ^{88}Sr atoms coupled to an optical cavity. On the $^1S_0 \leftrightarrow {}^3P_1$ clock transition with linewidth $\gamma = 2\pi \times 7.5$ kHz we have achieved superradiant pulses with peak powers of 10 μW after doing single population inversion pumping pulses. However, the collectively enhanced rate of emission results in pulses much shorter (≈ 100 ns) than the natural lifetime of the excited state (22 μs) [6], which results in the frequency properties of the emitted light being severely Fourier limited. Increasing the duration of these pulses, or obtaining a continuous superradiant signal, would allow for probing whether the frequency characteristics of the superradiant light reach the proposed below-natural linewidth frequency stability of a superradiant laser [7]. However, no continuous superradiant scheme for metrology purposes has been realized yet.

In our system, we cool 40 million Sr88 atoms to 2 μK and trap them in the center of an optical cavity using a two-stage magneto-optical trap (MOT). The cavity has a length of 21 cm and a linewidth $\kappa = 2\pi \times 780$ kHz. The atoms in the cavity are distributed randomly along the nodes and antinodes and have inhomogeneous coupling to the cavity. After the preparation of the atomic ensemble, we turn off the MOT coils and switch on a bias magnetic field of 2 Gauss. This splits the $^3P_1$ magnetic sublevels by $2\pi \times 4$ MHz allowing us to use the stretched states as intermediate states in a three-level laser. By using a combination of 679 nm, 707 nm, and 688 nm repumping lasers, we can recycle the atomic population and repopulate the excited state after the atoms have started lasing. Our high intra cavity atom number allows us to lower the repumping rate to limit the heating, compared to earlier experiments using a similar repumping scheme [7]. This system of repumping allows us to extend the lasing by several orders of magnitude, and to obtain ms long beat signals between emitted superradiant pulse and our reference laser.

The beat signal reveals below natural linewidth behavior of the superradiant lasing, with a measured cavity pulling factor of ≈ 0.1. This result gives an indication of the advantages of superradiant lasing and justifies further experiments towards the generation of truly continuous superradiant signal.

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