Optical Lattice Laser

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***Abstract*—Atoms with narrow-linewidth transition trapped within the Lamb-Dick regime of optical lattice are proposed be used as laser gain medium to build a laser. The gain medium atoms can be the alkaline-earth species, Magnesium, Calcium, and Strontium, including Ytterbium. These atoms possess promising super-narrow optical clock transitions, but here, this clock transition is proposed to be used as the lasing transition of the output laser. This optical lattice laser with expected super-narrow linewidth will be an active optical clock with high accuracy and stability.**

I. INTRODUCTION

With the great development of optical comb, the femtosecond laser frequency divider[1,2], the accuracy and stability of optical frequency standard can be transferred to users need frequency standards almost at any frequency regime, from optical frequency to microwave wave(MW)[1-3]. The performance of realized optical clock is currently comparable with the best fountain MW atomic clock, around 1×10^{-15}. The potential accuracy of optical clock is expected will be two orders of magnitude better than the fountain MW atomic clock, like 1×10^{-17} even better[4-7].

There are many quantum absorbers with transition line quality factor $Q\geq10^{19}$ [5,6], and various optical clock experimental schemes based on ion trap, fountain[5,6], optical lattice trapped atoms[4,7], three-level[8] or four-level [9]coherence.

But we can't exhaust the expected resolution of the 1mHz linewidth clock transition with current laser technology[5]. The recorded narrowest linewidth of laser source is 0.16Hz[10,11], which is achieved with a super-cavity mounted in an isolated vacuum chamber and the whole laser system is covered with a $9m^3$ wooden enclosure lined with lead foam. The most recent study showed the thermal noise limit is reached under this good environment[12]. Unfortunately, the cryogenic cavity system is not good at "long-term" situation since one have to refill liquid nitrogen every few hours[13-14].

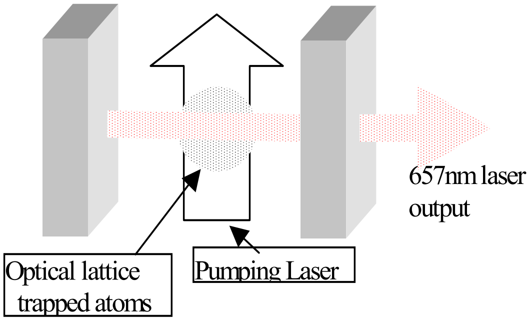

Fig.1 Optical lattice laser system

Thus the most important thing to develop the next generation optical atomic clock is the available laser source with narrow linewidth , or say, the laser with adequate long coherence time, which currently is limited by the cavity length noise.

In this report, we developed a new concept: optical lattice laser. Atoms with narrow-linewidth transition trapped within the Lamb-Dick regime of optical lattice[4,7] are proposed be used as laser gain medium to build this laser as showed in Fig.1. The gain medium atoms can be the alkaline-earth species, Magnesium, Calcium, and Strontium, including Ytterbium. These atoms possess promising super-narrow optical clock transitions[5], but here, this clock transition is used as the lasing transition of the output laser. This optical lattice laser will not only be a laser source with expected super-narrow linewidth, but also be one sort of active optical clock[15] with high accuracy and stability.

II. MAIN FEATURES OF OPTICAL LATTICE LASER

First of all, the gain medium atoms are trapped in Lamb-Dick regime of far-off-resonance dipole trap operated with "magic wavelength", which cancels the alternative current (ac) Stark shift of the clock transition as the optical clock scheme proposed by Katori[4,7]. Second, the high finesse laser cavity is an ultra-stable cavity with thermal and vibration isolation mounted in an evacuated vacuum chamber[10,16]. The mirrors and spacer (the spacer between cavity mirrors is not showed in Fig.1) are made of Zerodur or ULE(Ultra-low thermal expansion) and optically contacted together, which has been used as reference cavity

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to narrow laser linewidth below 1Hz[10,16]. As a laser cavity, we have to adjust its one mode to be resonant with lasing transition.

As an example, we discuss a scheme based on the 657nm Calcium $^3P_1$-$^1S_0$ 400Hz-linewidth lasing transition as shown in Fig.2.

After laser cooling in 423nm blue MOT and 657nm red MOT, Ca atoms must be loaded into 800.8nm "magic wavelength" lattice traps[17]. With this special wavelength, the 657nm Calcium $^3P_1$-$^1S_0$ clock transition only affected by the ac Stark shift due to the lattice laser at the level of mHz after adjusting the lattice laser wavelength.

Since the atoms are trapped in optical lattice, some intrinsic broadenings(like the phase and intensity noise of lattice laser) are reduced to so small that the gain linewidth of laser medium is around the $^3P_1$-$^1S_0$ natural 400Hz-linewidth. Given the loss rate of laser cavity (mode linewidth) is 400kHz, which can be reached with 5cm cavity length and 7,500 finesse. Then the ratio of cavity loss rate and gain linewidth is 1000.

To construct a three-level laser system, one can use 423nm, 1201nm to excite atoms into $^3P_2$ via $^1P_1$. When the 616.2nm pumping laser and 610.3nm re-pumping laser are also used as shown in Fig.2, all atoms are pumped into ^3P via $^3S_1$. More pumping lasers needed when the Zeeman sublevels are considered, but the whole pumping procedure can be simplified to an effective three-level laser system as shown in Fig.3. In this way, one can simply use the classical three-level laser theory[18] to describe this optical lattice laser.

From the steady state solutions of three-level laser rate equations, we get an expression of population inversion easily.

The population inversion threshold[18] is,

$$\Delta N_{threshold} \equiv N_{upper} - N_{lower} = \frac{8\pi n^3 \nu^2}{c^3 t_{cavity}} \qquad (1)$$

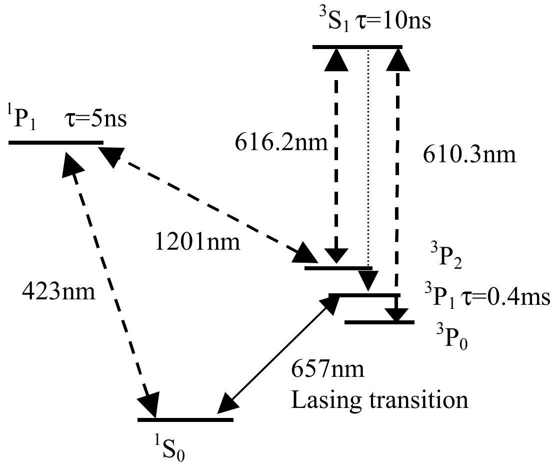

Fig.2 Energy level diagram of Calcium involved in the optical lattice laser

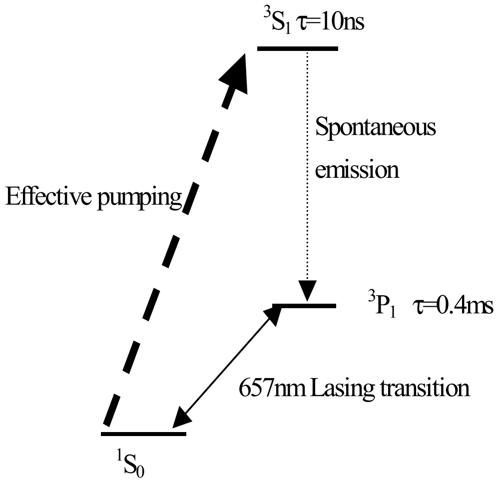

Fig.3 Reduced three-level laser system

with the cavity loss rate[18],

$$t_{cavity}^{-1} = (c/n)\left[\alpha - (1/l)\ln r_1 r_2\right] \qquad (2)$$

where r_1, r_2 are the cavity mirrors' reflectivities and α is the average distributed loss constant. And it should be noted that the gain linewidth is the natural linewidth of the upper lasing state in the optical lattice laser.

From (1), atomic density of $10^6\ atoms/cm^3$ is required for the population inversion threshold. By the Schawlow-Townes formula[18], the linewidth of the optical lattice laser is,

$$\Delta\nu_{laser} = \frac{\Gamma_{gain}}{4\pi \bar{n}_{cavity}} \frac{N_{upper}}{N_{upper} - N_{lower}} \qquad (3)$$

where $\bar{n}_{cavity}$ is the average photon number in the laser cavity mode. With ^{40}Ca $^3P_1$-$^1S_0$ lasing transition, 1Hz linewidth laser can be achieved with accuracy and short term stability at subHertz level[15], and it is possible to narrow the laser linewidth to the order of mHz by our estimation when the coupling constant between cavity and atom is more weak and the broadening of gain is reduced. Detailed analysis will be published elsewhere. As mentioned above, when the ratio of cavity loss rate and gain linewidth is 1000, the effect of the cavity length noise on the laser linewidth is dramatically reduced to the form of cavity pulling shift as that in active Hydrogen clock[15,19]. For the 1Hz cavity length noise with vertical mount configuration[16], it only contributes 1mHz cavity noise to the linewidth of optical lattice laser. This is a main advantage of optical lattice laser comparing with any ultra-stable cavity stabilized laser, in which the laser linewidth is limited by the cavity length noise as discussed before.

III. SUMMARY AND PERSPECTIVES

In summary, an active optical clock scheme based on the optical lattice atoms is developed. SubHertz Linewidth of the laser can be achieved at this laser system and the cavity length noise is almost eliminated when the cavity loss rate is much wider than the laser gain linewidth when narrow-line transition is used as lasing transition. As an example, we have discussed the case of ^{40}Ca $^3P_1$-$^1S_0$ lasing transition, including the way of loading the medium atoms into the lattice trap, pumping method, oscillation conditions, and the possibility to reach the quantum limit of linewidth, the Schawlow-Townes linewidth, in this laser system. More general, similar scheme is conceivable for any free atoms with narrow-line transition. Particularly, a four-level atomic system will be preferred comparing with the three-level laser system discussed here because higher pumping efficiency will be available and the light frequency shift caused by the pumping laser can be reduced dramatically. Besides as narrow linewidth laser sources, we expect its promising applications in laser spectroscopy and optical atomic clock, where it will be a new class active optical atomic clock. Meanwhile, comparing with the one-atom laser[20] and ion-trap laser[21] used to investigate the cavity quantum electrodynamics (QCED), the optical lattice laser discussed above also provides an "optical-lattice cavity" system, which can be used to study the QCED with N atoms[22] once the strong atom-cavity coupling regime can be reached.

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