Different ways to active optical frequency standards

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Abstract. Active optical frequency standard, or active optical clock, is a new concept of optical frequency standard, where a weak feedback with phase coherence information in optical bad-cavity limitation is formed, and the continuous self-sustained coherent stimulated emission between two atomic transition levels with population inversion is realized. Through ten years of both theoretical and experimental exploration, the narrow linewidth and suppression of cavity pulling effect of active optical frequency standard have been initially proved. In this paper, after a simple review, we will mainly present the most recent experimental progresses of active optical frequency standards in Peking University, including 4-level cesium active optical frequency standards and active Faraday optical frequency standards. The future development of active optical frequency standards is also discussed.

1. Introduction

Recently great progress has been made in optical clocks, and the 10^{-18} level accuracy and stability has been experimentally realized [1-3]. However, for optical frequency standards working at passive regime, a local oscillator with excellent short-term stability is necessary, where a probing laser is usually prestabilized to a super-cavity with the Pound–Drever–Hall (PDH) technique. The linewidth of the local oscillator is currently the main limitation of optical clocks' stability. However, due to the inevitable Brownian cavity-length noise, to further improve the stability of optical clocks is still a great challenge.

The concept of active optical frequency standard was conceived ten years ago [4,5], where a weak feedback with phase coherence information in optical bad-cavity limitation is formed, and the continuous self-sustained coherent stimulated emission between two atomic transition levels with population inversion is realized. The mechanism of active optical frequency standard makes the output frequency insensitive to the cavity length noise, thus has a potential much narrower linewidth than that of local oscillators in passive optical clocks. Meanwhile, since the output frequency is determined by the atomic transition, it can be applied as quantum frequency standards directly. The mechanism of active optical frequency standards is similar to that of Hydrogen masers, which has a superior short-term stability among microwave atomic clocks. Theoretically, the active optical frequency standard has the potential frequency stability as Hydrogen masers in microwave regime, thus has the advantage of much improved fractional stability with an operating frequency exceed the oscillators in the microwave domain by about five orders of magnitude. We would like to point out that, there is no analog of active Faraday optical clock in microwave regime.

Since the concept of active optical frequency standard was proposed, some preliminary considerations [4-6] summarized and presented in the 7th Symposium on Frequency Standards and Metrology [6] have triggered wider interests on different ways [8-19] to the creation of active optical frequency standards with unique techniques and elegant ideas[8-12]. Different ways with neutral atoms at 2-level, 3-level, 4-level energy structures with thermal and laser cooled and trapped configurations [7-9], Raman laser [10], sequential coupling [11] and moving optical lattice configuration [12] have been investigated recently. To make continuous-wave active optical frequency standards with cold atoms, one also can apply sequential coupling technique [11,12], synchronization between two ensembles of 3-level atoms [12,13], or cold atomic beam. The bad-cavity Rb Raman laser has been investigated with very beautiful results [10]. The effect of interaction between atoms on frequency stability and accuracy of active optical clock has been calculated theoretically[14], which also shows that active optical frequency standards have the characteristic of suppressing the cavity pulling effect, and the output linewidth can break quantum noise limitation. Active ^{88}Sr optical clock at 7.6 kHz natural linewidth 689 nm transition with cold atomic beam is under developing in Niels Bohr Institute [20], and trapped 1D lattice atoms in JILA near the crossover from good-cavity to bad-cavity regime in quasi steady-state lasing shows a prospective linewidth of 6.0 kHz [21].

In this paper, we will mainly present the most recent experimental progresses of active optical frequency standards in Peking University, including 4-level Cesium active optical frequency standards with measured 380 Hz linewidth [15-18] and active Faraday optical frequency standards with measured 281 Hz linewidth [19]. The future development of active frequency standards is also discussed.

2. Four-level active optical frequency standards

2.1. Lasing of cesium four-level active optical frequency standards

The way of 4-level active optical frequency standard has been proposed to avoid the sensitivity of light shift due to pumping laser. Recently, in this way, the Cs four-level active optical frequency standards have made a progress experimentally [15,16]. With the 459 nm or 455 nm pumping laser applied to the atoms, the population inversion between $7^2S_{1/2}$ and $6^2P_{3/2}$ levels is performed. The continuous self-sustained stimulated emission at 1469.9 nm is realized with the whole system operating in deep optical bad-cavity regime, of which the ratio between cavity bandwidth and gain bandwidth is 55.08.

As the main characteristic of the cesium four-level active optical frequency standard, the suppression of cavity pulling effect is examined using a Fabry-Perot interferometer (FPI). It turns out that when the cavity mode frequency is detuned 281.6 MHz away, the 1469.9 nm output light frequency shifts only 6.8 MHz. Therefore the cavity pulling effect was reduced to 2.4% compared with ordinary laser. This effect can reduce the influence of environmental vibrations on active optical frequency standards, and in consequence the inevitable thermal Brownian-motion noise of cavities can be effectively suppressed in active optical clock. This experimental result of strongly suppressed cavity pulling effect clearly demonstrates that active optical clock owns potential narrower linewidth than that of super-cavity stabilized laser [22,23].

The linewidth of the 1469.9 nm output light is measured by the heterodyne signal between two independent setups. The results show that the output linewidth of each experimental setup is 380 Hz, which is much narrower than that of ordinary laser based on alkali atoms considering there is no any vibration isolation measure. Similarly, we have also observed the continuous self-sustained 1359 nm ($7^2S_{1/2}$ - $6^2P_{1/2}$) stimulation emission of the Cs four-level active optical frequency standard [17].

2.2. Good-bad cavity dual-wavelength active optical frequency standard

Even though the cavity pulling effect has been suppressed, the residual perturbation of the cavity still affects the frequency stability greatly. To stabilize the main cavity length, we propose a scheme of He-Ne 633 nm and Cs 1359 nm good-bad cavity dual-wavelength active optical frequency standard [18]. In the scheme, the 633 nm and 1359 nm stimulated emissions share a common cavity, and the 633 nm laser is designed to work in good-cavity laser regime, i.e., the cavity mode linewidth for 633 nm is designed to be much narrower than the He-Ne 1.5 GHz laser gain bandwidth. At the same time, the

1359 nm stimulated emission still works in bad-cavity regime. The 633 nm laser is subsequently frequency stabilized to a super-cavity with PDH technique [22,23], hence the main cavity of the good-bad cavity active optical frequency standard is stabilized. The stability of 1359 nm bad-cavity output frequency is then expected to be improved by at least 1 order of magnitude than that of the 633 nm PDH stabilized laser because of the suppression of cavity pulling effect. The quantum limited linewidth of 1359 nm laser of the good-bad cavity active optical clock is estimated to be 72.5 mHz, and it can be reduced to mHz when a large waist mode cavity is applied to increase the effective atoms. The frequency stability and accuracy of 1359 nm output signal we finally obtain with thermal Cs atoms will be worse than its theoretical value, because of the existence of classic noises. So that the utilization of laser cooled and trapped atoms is necessary to avoid the disadvantageous influence from thermal motion of atoms. For alkali atoms like Cs, Rb and K, the available diode lasers and techniques of laser cooling and trapping will be helpful in the way of active optical frequency standards based on cold alkali atoms.

3. Active Faraday optical frequency standards

In all above mentioned ways [4-18] to the active optical frequency standards, the quantum reference of optical frequency standard and the stimulated optical emission of gain medium are both from the same atomic transition of the same atoms. This requirement strongly limits available quantum system. The active Faraday optical frequency standard, as demonstrated by a recent experiment [19], spatially separates the quantum reference of frequency standard and the stimulated emission of gain medium. In the active Faraday optical frequency standard [19,24], a narrow linewidth Faraday atomic filter, which can be a very general 2-level atomic transition, is used as quantum reference of optical frequency standard, while the stimulated emission of gain medium can be provided by Ti: sapphire and dye, besides semiconductor diode materials [19,24]. This unique way of active optical frequency standard opens the door for various atomic transitions and alternative gain media to optical clocks. In this way, the Faraday effect found 170 years ago, starts to play a quantum reference role in modern optical clocks.

In the experimental scheme demonstrated in [19,24], an ultranarrow bandwidth Faraday atomic filter based on cesium atoms acts as a quantum frequency selector, of which the bandwidth is 25 MHz and the transmission is 18%. The filter is then placed inside the extended cavity of a laser diode with anti-reflection coating, the 852 nm ($6P_{1/2}$-$6S_{1/2}$) stimulated emission of active Faraday optical frequency standard is realized by adjusting the extended cavity mirror. A maximum output power of 75 μW is obtained. Suppression of cavity pulling effect in active Faraday optical frequency standard is measured by beating the output light with pumping laser. When changing the extended cavity frequency within 350 MHz, the centre frequency of the beat signal varied within a range of 40 MHz. Therefore the cavity pulling coefficient is reduced to 11% compared with common lasers.

The output light frequency linewidth is measured by the heterodyne signal between two independent setups to be 281 Hz [19,24,25]. The result is 19000 times smaller than the natural linewidth of the Cs 852 nm transition line and two orders of magnitude better than frequency-stabilized lasers in good-cavity regime with atomic filter or interference filter working as frequency selectors. In the next step, we will apply the mechanism of active Faraday optical clock to measure the Cs 852 nm transition frequency to an expected accuracy of Hz level, even though its natural linewidth is as wide as 5.2 MHz. In the view of laser spectroscopy, this unique mechanism of active Faraday optical clock provides us an active laser spectroscopy based on the stimulated emission within bad-cavity regime for many general optical transitions with natural linewidth as wide as several megahertz.

To further improve the frequency stability of active Faraday optical frequency standards, utilization of laser cooled and trapped atom in magic wavelength optical lattice is a promising solution [25]. One can use the 689 nm transition of strontium atoms trapped by magic wavelength optical lattice, which has a natural linewidth of 7.6 kHz. With the existence of homogeneous magnetic field with appropriate intensity, we can realize an ultra-narrow linewidth Faraday optical filter at 689 nm transition. If one uses semiconductor diode or Ti: Sapphire as gain medium, by weak feedback of laser resonator at bad-cavity regime, one can realize Faraday active optical clock based on cold atoms [25]. The relevant research is on-going. According to reference [26], the 689 nm transition of strontium atoms trapped in magic lattice in hollow-core photonic crystal fibres can realize an optical thickness of 2.5, so it is possible to achieve a rotation angle near to π /2 in an experiment scheme shown in figure 1. Considering the high symmetry of m=1 and m=-1 Zeeman sublevels, the influence of magnetic field to the Faraday active optical frequency standard can be controlled within required region.

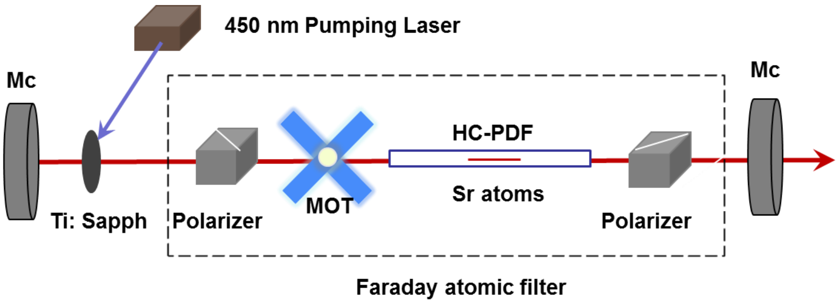

Figure 1. (Colour online) The proposed experimental scheme of active Faraday optical clock based on Sr atoms trapped in magic optical lattice in hollow-core photonic crystal fibres with Ti:Sapphire laser gain operating at bad-cavity regime.

4. Conclusion

In this paper we mainly present the most recent experimental progresses of active optical frequency standards in Peking University, including 4-level cesium active optical frequency standards and active Faraday optical frequency standards in bad-cavity regime [25]. Under the present experimental conditions, noise of cavity length is still the main limitation of frequency standard measured linewidth. For the future progress to improve the frequency stability, we need to stabilize the cavity length through the PDH technique combined with the dual-wavelength good-bad cavity method [17,18]. Since the thermal motion of atoms brings many influences caused by classic effects, it needs further investigation to realize active optical frequency standards based on laser cooled atoms and ions. We believe the ^{88}Sr active optical clocks at 689 nm 7.6 kHz transition at cold atomic beam configuration [20], trapped 1D lattice configuration [21], or Faraday configuration [19,25] are very promising for continuous self-sustained operation of Sr active optical clock in the near future. A blue Cs magneto-optical trap operating at 455 nm transition is under development in Peking University to investigate the 4-level Cesium active optical frequency standards and active Faraday optical frequency standards with cold Cs atoms.

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