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Progress Towards the Development of a Portable All-optical Atomic Clock Based on a Two-photon Transition in Warm Atomic Vapor

S. Jana*(1), B. K. Sahoo(2), and A. Sharma(1,3)
(1) Department of Physics, Indian Institute of Technology Tirupati, Yerpedu-517619, Andhra Pradesh, India
(2) Atomic, Molecular and Optical Physics Division, Physical Research Laboratory, Ahmedabad-380009, India
(3) Center for Atomic, Molecular, and Optical Sciences and Technologies, Indian Institute of Technology Tirupati, Yerpedu-517619, Andhra Pradesh, India

Abstract

Optical clocks represent the hallmark of precise timekeeping. The most precise atomic clocks are laboratory-based ones that utilize transitions in the microwave/optical domain of neutral atoms or trapped ions. These clocks define an international time scales, confirm the consistency of physical constants and stimulate the search for new physics outside the Standard Model. The other area is the regime of portable atomic clocks based on warm atomic vapor, which is small, power-efficient and deployable in the field with a variety of civilian applications, including sensing, communication and navigation. Two-photon resonance and optical transition based field deployable clocks present a viable alternative that may outperform current commercial chip scale clocks by at least a factor of 10 in terms of both long-term and short-term stability. For portable clocks, two-photon transitions in alkaline earth metals are of special interest. One of the systematic inaccuracies in the optical reference is eliminated by using counter-propagating laser beams to create Doppler-free spectroscopy. At IIT Tirupati, we are engaged in developing the next generation of atomic vapor based portable frequency standard using two-photon transition in Rubidium (Rb) for atomic sensing and quantum positioning applications. This article discusses the physics behind the two-photon transition in Rubidium atoms suitable for a clock reference. Briefly, it discusses the experimental methodology for realizing an optical clock using warm rubidium vapor.

1. Introduction

The development of the atomic clock radically changed how time is measured and kept. We are capable of measuring one second down to one part in 10^7 billion [1] because of ongoing research and sophisticated technologies. The development of optical clocks [2], which is a culmination of Nobel Prize-winning research, including laser-cooling [3], ion trapping [2] and optical frequency comb [4], has allowed for this remarkable accurate timekeeping. Every time the clock gets more accurate, new applications are made, or the performance of those that already exist is enhanced. From John Harrison's discovery of the chronometer, which revolutionized deep-sea navigation, to the atomic clock, which serves as the foundation of contemporary GPS navigation and is precise to a few meters, clocks have been utilized for navigation throughout history [5]. To verify the consistency of fundamental constants [6, 7] and find gravitational wave signatures in the radio-frequency pulse timing drift of a pulsar [8], ultra-high stable optical clocks are employed. These clocks are also used for measuring geode lines to predict a volcanic eruption or an earthquake [9]. Microwave clocks [10] are mostly used for civilian applications like communication, navigation [11], digital broadcasting, accurate time stamping on banking and share market transactions. These clocks are crucial for military purposes as well [12].

Tremendous progress made in the fields of laser stabilization, optical frequency comb, laser cooling and trapping of atoms and ions have resulted in the development of ultra-precise atomic clocks based on optical transitions. These developments have allowed the realization of optical atomic clocks with unrivalled performances and fractional instabilities well below 10^{-18}, finding applications in fundamental physics tests, relativistic geodesy, quantum communication networks, QKD (Quantum Key Distribution) schemes and time and frequency metrology.

Atomic frequency standards fall into one of two categories. The first one has remarkable accuracy in the order of 10^{-18} and is an ultra-high stable frequency clock based on laser cooling and trapping of atoms and ions. These high-performing, state-of-the-art optical atomic clocks are fragile, laboratory-scale devices due to their intricate laser systems. The second type is a compact frequency standard based on microwave transition in Cs (cesium) and Rb (rubidium) [10], used for civilian purposes. As microwave transitions are used as a frequency reference in these clocks, they have stability in the order of 10^{-10}. We need to create a portable but precise clock to fill the gap between these two regions. This paper will discuss how two-photon transition-based Rb clocks are a viable option to bridge this gap. The Rb two-photon transition [13] has previously been a viable candidate for high stability clock. As the two-photon transition falls into the optical range, this immediately increases the quality factor of the oscillator. Due to the possibility of a Doppler-free spectroscopy arrangement [13-15], the spectral linewidth (334kHz) of this two-photon transition is only constrained by the lifespan of the excited state.

2. Principles of Atomic Clock

An oscillator that produces regular oscillations and a counter that counts these oscillations make up the core of a clock (Fig. 1). Different periodic occurrences, such as the motion of astronomical objects, the oscillation of a pendulum and the vibration of quartz crystal have been exploited by humans as the oscillator of clocks [16]. Maxwell suggested using the oscillation of atomic vibration as a clock's oscillator.

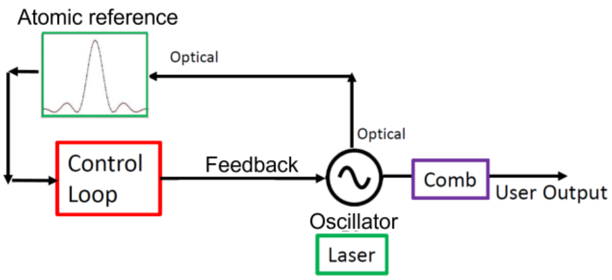

Figure 1. Block diagram of an atomic clock. It consists of an external frequency source that is stabilized to the atomic transition

Quantum mechanically, each atom has a well-defined discrete energy level. Atoms can move from one energy level to another when exposed to an external radiation field at a specific frequency (resonance frequency) by absorbing a specific quantum of energy from the field, or an atom at a high energy level can come down to low energy level by emitting a specific quantum of energy. The frequency of this energy quantum that was absorbed or released is given by

$$f_0 = \frac{E_2 - E_1}{h} \qquad (1)$$

Where E_2 is the energy of the higher level and E_1 is the energy of the lower level and h is Planck's constant. Since the atoms of an element are identical, their absorption or emission of energy should create the same frequency. So, an atom could be served as a perfect oscillator for a clock. The quality factor Q, characterizes the quality of an atomic oscillator. If the frequency of the transition is f_0 and the linewidth of this transition is Δf_0, then this parameter is defined as

$$Q = \frac{f_0}{\Delta f_0} \qquad (2)$$

Thus, the quality factor of an optical frequency clock will be higher than that of a microwave transition clock.

3. Two-photon transition

A two-photon absorption (TPA) allows an atom or molecule to go to a higher energy level that was previously barred by an electric-dipole transition, Two-photon transitions in atomic vapor are inherently Doppler (as net momentum transferred to the atom is zero) and recoil free, if the examination of the atomic vapor is conducted using two laser beams that are anti-parallel [14], which eliminates the need for tight confinement of atoms during interrogation. Moreover, fluorescence at a distinct wavelength, which can be easily separated from

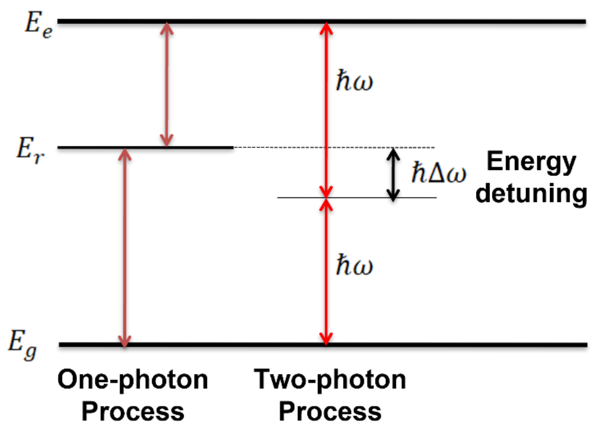

Figure 2. Schematic of the energy level diagram for a two-photon transition vs. a one-photon process. E_g, E_r and E_e are the ground, intermediate and excited states, respectively. $\Delta\omega$ is the detuning from the energy level E_r

the probing laser wavelength, occurs along with the two-photon transition. This makes it possible to measure the two-photon clock transition with a very high signal-to-noise ratio. Furthermore, the clock stability may be improved by optimizing the two-photon excitation rate, which depends on the product of the intensity of the two beams that are providing two photons responsible for the two-photon spectroscopy. All the aforementioned benefits of a two-photon transition support our decision to use a two-photon clock transition instead of a delicate and complex method like laser cooling and atom trapping. The clock becomes portable because of this.

A two-photon transition does not imply successive or a combination of stepwise one-photon excitation (two successive one-photon excitations). In a true sense, the atom at the ground state is directly excited to the excited state by two-photon absorption. The energy detuning is the most important parameter in calculating the two-photon transition rate. There is no physical transition connecting the ground to a virtual intermediate state. The transition probability comes from the Lorentzian tail of the real transitions nearby ($E_g \rightarrow E_r$ and $E_r \rightarrow E_e$) as shown in Fig. 2. Consequently, the smaller the energy detuning, the stronger the two-photon transition is.

Degenerate two-photon spectroscopy is a viable alternative to mitigate unwanted Doppler effects due to the thermal motion of the target species. This technique requires that the two photons be used for excitation of a target atomic state and these two photons should have the same frequency and if possible, originate from the same source. Two-photon based frequency standards are motivated by the desire to utilize a Doppler-free transition based on existing technology with a simple design employing existing glass vapor cell technologies and commonly available lasers to arrive at a portable design and form factor that has the potential to reduce the size, weight, power and technical challenges while still maintaining high precision required of a next-generation portable atomic frequency standard.

4. Energy level diagram of Rubidium (Rb)

Among all the alkali metals, Rubidium's $5S_{\frac{1}{2}} \rightarrow 5D_{\frac{5}{2}}$ (Fig. 3) stands out among them since it offers several benefits. Because the detuning of the energy of the virtual state in relation to the stationary state determines the two-photon transition rates, the fortunate existence of a virtual level close to $5P_{\frac{3}{2}}$ makes it possible for this two-photon transition to occur with low laser power. A spectrally resolvable fluorescence signal from $6P_{\frac{3}{2}} \rightarrow 5S_{\frac{1}{2}}$ at 420 nm is frequently used to detect this two-photon transition in Rubidium. We must precisely measure this two-photon transition frequency in order to create a clock out of the Rb two-photon transition. We will use this Doppler-free two-photon transition as the clock reference for our portable atomic clock in our lab at IIT Tirupati.

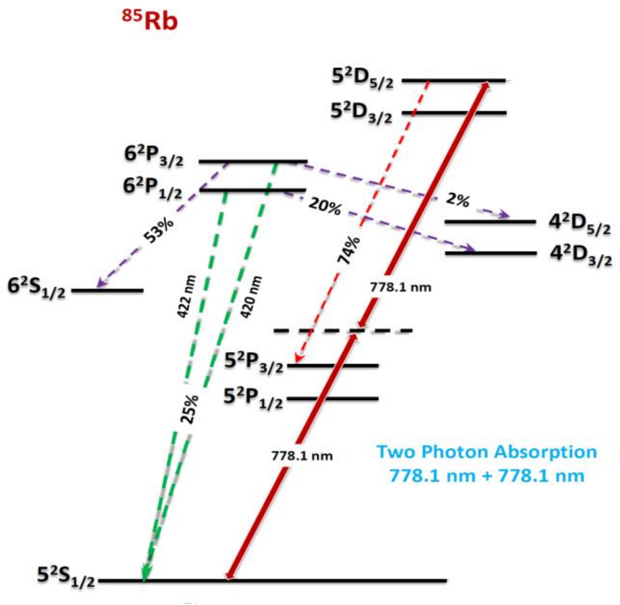

Figure 3. Relevant rubidium (^{85}Rb isotope) energy level diagram highlighting the two-photon transition of interest in our current proposal

In the case of the Rubidium (Rb) two-photon transition at 778.1 nm, fluorescence is readily observable at 420 nm using a photo-multiplier tube (PMT), and stray light in the near infrared is rejected with standard optical filters. The Rb atom is excited from the $5S_{1/2}$ ground state to the $5D_{5/2}$ state using two photons at 778.1 nm. From the $5D_{5/2}$ state, the atom decays to the $6P_{3/2}$ state by emitting a photon at 5.23 µm. The $6P_{3/2}$ state has a lifetime of about 120 ns leading to a narrow natural linewidth of about 1 MHz and decays to the $5S_{1/2}$ ground state by emitting a photon at 420 nm. The two-photon transition in Rubidium (Rb) at 778.1 nm has shown promise as an optical atomic frequency standard with good short-term ($< 3\times10^{-12}$ over a 1 s integration time) stability and a respectable medium to long-term stability well below $< 5\times10^{-13}$ over a 1000 s integration time [10].

5. Proposed work

The two extended cavity diode lasers will be employed to induce this two-photon transition in the rubidium vapor cell. Their wavelength is 778.1 nm. Electronic controls will be used to regulate the cell's temperature, thereby providing an indirect control over the vapor density. The coupling with the atomic reference will be accomplished using a typical PID (Proportional Integral Differential) controller, and these lasers will also function as local oscillators. Once the laser is locked with the two-photon transition frequency, fluorescence is detected using a photodiode. At this moment, the sum of the two laser frequencies is the same as the two-photon transition frequency and this frequency will be measured by an optical comb.

6. Conclusion

The two-photon transition allows us to get better clock stability without using more involved and extensive technology like laser cooling and trapping of ions and atoms that involves designing vacuum systems, traps for neutral atoms and/or ions, etc. The need for indigenous development of highly accurate portable atomic clocks is increasing with time. Since these portable clocks can be utilized as an onboard frequency standard in the next satellites. For ISRO, this will be extremely advantageous. Currently, ISRO purchases portable clocks from European manufacturers. Our defense industry can also employ these clocks to synchronize radar systems, enhance wireless communication, and prevent signal jamming. In the introduction section, we highlighted several civil and strategic applications of portable atomic clocks.

7. Acknowledgements

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