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Development Operation and Characterization of Cesium Beam Atomic Clock

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ABSTRACT

We report the development, operation and characterization procedure of the first ever Cesium Atomic Beam Clock in Pakistan. The importance of the National Time and Frequency standards is duly highlighted in the context of a developing country. The active program spans a time of about three years and the Ramsey Interferometric signals, i.e., the fundamental physical phenomenon, recorded recently depict a 25 kHz broad Rabi profile incorporating a much narrower Ramsey fringe having width of about 800 Hz only clearly demonstrate a clean, smooth, stable and accurate operation of the clock.

Keywords: *Cesium, Atomic clock, Atomic coherence*

1. Introduction

1.1 Importance of a National Time and Frequency Standard

Time is one of the vital variable that makes the world go around i.e. through which we address all the dynamical issues [1] and the clocks based on atomic transitions i.e. atomic clocks are known to be the best, accurate and stable time keeping gadget. In this regard, atomic clocks based on cesium atomic beam technology are taken to be the primary time standard whereas the Rubidium vapour cell clocks, manitricurised to good portabilities and synchronized to the primary source are often utilized as the secondary time standards. It is worth mentioning here that the selected primary frequency and time standard exhibits an extremely high stability in the limits of few parts in 10^{13} whereas accuracy ranges to 10^{14} in general. Thus the atomic clocks have tremendous advantage over the conventional clocks including the most recent quartz crystal based one that may error a few seconds in a month or so. Since atomic clocks employ atomic or molecular internal states therefore such atomic quantum mechanical oscillators obeying quantum mechanical dynamics are usually prone to a number of environmental effects including temperature, humidity, pressure, vibration and other static noises. Another very vital and technically high favorable parameter is the fact that all the atoms of any specific element or isotope are exactly identical and exhibit precisely the same properties. Thus one can design a universal clock based on, say ^{133}Cs that can be utilized everywhere. Atomic clocks, though not explicitly evident, are actually the backbone of modern civilization on many grounds including commercial, defense, finance, science and technology. E-commerce is now serving as the most modern mode of finical dealing and heavily relied tool being utilized for transactions and business collaborations enacted by both the multinationals as well as world's biggest economies. Now internet causo-temporal connectivity and data transfer sequencing is carried through precise time signatures generated by atomic clocks which are most stable instruments operating at unpresidential accuracy. The reason for this is that rate of the pulse launching at one location of the communication network must be precisely synchronized with the expected arrival time at the destination. This is needed to ensure authenticity and security of the communication. Similarly for all other areas of life where the time sequencing is crucial are heavily dependent on the availability of atomic clocks. This includes missile and aircraft navigation, GPS related control systems, seismic, radar ranging and position finding with an accuracy of few centimeters over intercontinental distances as well as testing and quality insurance of many electronics devices. Similarly, in technical and scientific research areas, the need for precise, accurate and stable time providing equipment is even more vital. Many of the recent experimental discoveries and verifications of the theoretical predictions have been carried out using atomic clocks. For example, the verification of relativistic time dilation, redefinition of the units for physical quantities and precise determination of the universal constants are some of the scientific applications of the atomic clocks. Einstein's Equivalence Principle suggests that fundamental constants stay constant with time [2]. However some latest theories conjecture slight variations. Such dilemmas are now being addressed experimentally through atomic clocks (Cs and Rb) for constants, for example, Rydberg constant R as well as fine structure constant α along with their respective temporal slow variations, if any. In this respect, the latest conjecture about neutrino's velocity exceeding than the velocity of light is worth mentioning. The dilemma was somehow connected with the improper coupling of the atomic clock based GPS system with the measuring detectors [3].

1.2 Atomic Time: A Pico History

It is a well-known fact that each individual atom of a specific element, due to its unique internal structure, yields

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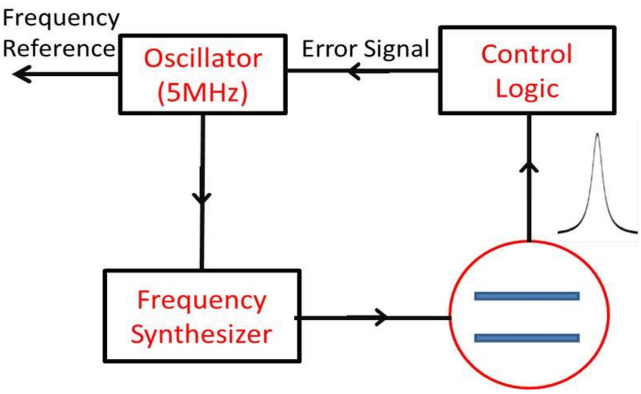

Fig. 1: Schematic diagram of feedback loop for atomic clock.

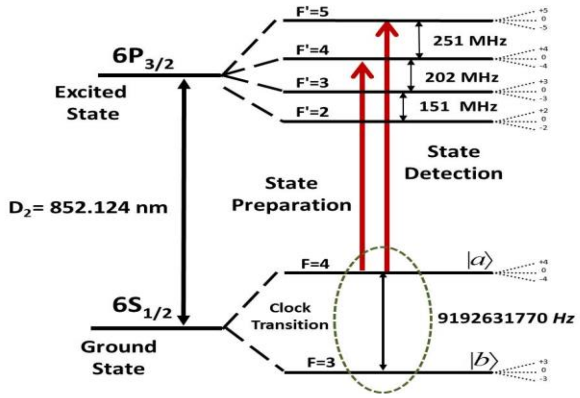

Fig. 2: Sketch of a Cesium two-level atomic system with lower (upper) level designated by | b > (| a >).

emission and absorption electromagnetic spectra at similar frequencies and this unique property of the atoms furnish us with the fundamental principal for construction of an atomic clock. A microwave generator provides the desired atomic transition frequency. This frequency is optimized through coupling with the atoms and consequently the mismatch between the atomic frequency and microwave oscillator is minimized. The microwave oscillator serving as the pumping source is then coupled and precisely locked to the desired transition at its resonance with the help of a feedback circuit as shown in Fig. 1.

Here, it is quite evident that for high enough precision, one should select an atomic transition ν_0 with minimum possible line width $\Delta\nu_0$ whereas the interaction time of the atom-field coupled system should be taken as large as possible. Based on this suggested mechanism, one always get an extremely high quality factor $Q = \nu_0/\Delta\nu_0$ for the hyperfine transition under consideration. Moreover, we need to strive hard experimentally to furnish a thin atomic beam with minimum possible velocity as it helps to cut short the Doppler shifts.

However the idea of an atomic clock encompasses a relatively long history. Sir William Thomson (Lord Kelvin), firstly in 1879 pointed out that atoms could provide a stable, reliable and accurate frequency standard or time standard because frequency is inversely proportional to time i.e. frequency is the number of waves received or recorded per second. Lord Kelvin further stated that yellow light emitted by sodium atoms corresponds to something in the atom that vibrated about 50 trillion times a second. This idea of an atom as a stable oscillator was further elaborated by Isidor Rabi [4] while working on the effect of applied magnetic field on atomic beams. He was later awarded Noble Prize in 1945 on this work. He suggested utilizing Cesium atoms ^{133}Cs for the purpose of the construction of an atomic clock. However, people first thought of using the most simple atom i.e. hydrogen to demonstrate time and frequency standard. But the problem with hydrogen is that it emitted at frequencies more than 10^{15} Hertz (in visible spectrum) for which there was no ultrafast counter available at the time. The feasible alternative was to employ atoms having energy difference between levels that fall in the range of microwaves. Here cesium again become vital because the energy difference between its ground state hyperfine doublet, i.e., $6S_{1/2}$ ($F = 3$, $m_F = 0 \leftrightarrow F = 4$, $m_F = 0$) corresponds to a manageable frequency of 9192631770 Hertz and this is equivalent to vibrations of about 10 billion times a second and corresponds to a wavelength of 3.26 centimeter (Fig. 2).

In the meantime, Ammonia Clock was demonstrated in 1949 at National Bureau of Standards (NBS), America [1]. The clock was a massive gadget comprised of 30-foot long copper pipe and microwave was fed from end to end. Apart from the size, the ammonia clock was hampered by many defects like Doppler broadening due to high molecular velocities and relatively broadband microwave absorption. Later on, P. Kusch in 1951, again at NBS, built the first operating Cesium atomic beam clock based on Rabi's method of single microwave-beam interaction. P. Kusch also got Noble prize for the achievement. Another improvement was suggested by Norman Ramsey in 1949 while working at Harvard University [5]. Ramsey showed that instead of using a long tube immersed in microwaves, one can get much better resolution, through quantum interference, if the atoms are subjected to two instead of one, spatially separated short burst of microwaves. Ramsey was subsequently awarded Noble prize for the technique which is now well known as Ramsey Interferometry [6, 7]. Louis Essen at the UK National Physical Laboratory (NPL) implemented the Ramsey's idea and the first such Cesium atomic beam clock became operative at NPL in 1955. This atomic oscillator when coupled with frequency multipliers/ converters, detectors, quartz crystal oscillators along with the feedback control loop was found to be have an excellent accuracy with an error of only one second in 10^8 years with a good enough stability [8]. Although, with the advent of Quantum technologies in recent past, Atomic Fountain Clock based on cold atomic ensemble in a magneto-optical trap and Optical Lattice Clock with the accuracies in the range of 10^{-16} and 10^{-18}, respectively, have been successfully demonstrated but still Cesium Atomic Beam Clock (CABC) is serving as the primary time standard universally [9]. Thus, as stated earlier, our present primary time and frequency standard utilizes the transition between two ground state hyperfine levels of stable Cesium isotope ^{133}Cs and the transition lies in the microwave region of the electromagnetic spectrum [10].

"The second is the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom at a temperature of 0K, or 1 second = 9192631770 periods of the ^{133}Cs, | F = 3, m_F = 0 > ↔ | F = 4, m_F = 0 > hyperfine transitions".

At the moment, A fountain clock based on Cesium NIST-F1 is serving as the Primary Time and Frequency Standard in USA since 2000 as per Time and Frequency Division – NIST, Boulder, USA. The uncertainty of this clock was about 1×10^{-15}, but around January 2013, the uncertainty has been lowered to about 3×10^{-16}. Thus the NIST-F1 is playing its due role towards International Atomic Time (TAI), same is the case of many other fountains employed in national standard laboratories around the world.

2. Cesium Atomic Beam Clock

2.1 Theoretical Description

The working principal of Cesium Atomic Beam Clock (CABC) is based on the quantum interference that occurs through the atom's interaction with the two spatially separated electromagnetic fields [11]. The separation between the field is taken to be L, such that L > > *l*, where "*l*" is the length of each Ramsey zone. Each such interaction acts as the beam splitter for atomic internal degrees of freedom and is equivalent to a Hadamard transformation mathematically [12]. Such a setup is now known as Ramsey Interferometer, an interferometer that operates within an atom. Consider a two level atom with lower level designated by |b > and upper level is represented by |a > as shown in the Fig. 2. Assuming a multi-level atomic system to be two-level is justified in the context of precise, resonant and narrow pumping schematics whether carried out through lasers or microwaves. This is because by employing narrowband pumping methodology, one can safely isolated the desired levels from the rest of the structure. Thus, we assume that, before interaction with the classical field, the atom is initially in its ground state, i.e., | ψ (t = 0) > = |b >. The subsequent interactions with the first Ramsey field are governed by the semi-classical interaction picture Hamiltonian:

$$H_I = \frac{-\hbar\Omega_R}{2}(\sigma_+ + \sigma_-) \quad (1)$$

where σ_+ = | a > < b | (σ_- = | b > < a |) is raising (lowering) atomic operator and Ω_R is the resonant Rabi frequency defined as $\Omega_R = \xi\,\rho_{ba} / \hbar$ with ρ_{ba} = < b| e.r |a > being electric-dipole transition matrix element ξ is the amplitude of the electric field and $\hbar$ is the Plank's constant [13, 14]. In order to simplify the theme, we have assumed atomic dipole to be aligned with the field. Now when atom is initially in the ground state | b > then Ramsey interaction under the above mentioned Hamiltonian lasting for arbitrary time t_1 leads to the following state vector:

$$|\psi(t_1)\rangle = \mathrm{Cos}\left(\frac{\Omega_R t_1}{2}\right)\Big|b\rangle + i\,\mathrm{Sin}\left(\frac{\Omega_R t_1}{2}\right)\Big|\,a\rangle \quad (2)$$

However, for an atom initially in the excited state, the unitary Hamiltonian evolution again for the time t_1 furnishes us with the following Ramsey transformation:

$$|\psi(t_1)\rangle = i\mathrm{Sin}\left(\frac{\Omega_R t_1}{2}\right)\Big|b\rangle + \mathrm{Cos}\left(\frac{\Omega_R t_1}{2}\right)\Big|\,a\rangle \quad (3)$$

Thus initially ground state atom C_b (t = 0) = 1, after an interaction lasting for time t_1 in the first Ramsey Zone, is prepared into the coherent superposition of its energy levels (Eq. 3) [13, 14]. This superposition then evolves freely for a certain preselected time t_{fe} before the atom interacts with the second Ramsey zone. This free evolution effectively imparts a local phase φ_{fe} to the quantum state mentioned above. The state, after free evolution, thus takes the form:

$$|\psi(t_1, t_{fe})\rangle = \mathrm{Cos}\left(\frac{\Omega_R t_1}{2}\right)\Big|b\rangle + ie^{i\varphi_{fe}}\mathrm{Sin}\left(\frac{\Omega_R t_1}{2}\right)\Big|\,a\rangle \quad (4)$$

The free evolution phase φ_{fe} is very critical for the clock operation and depends on many parameters depending upon the nature of transition involved and time corresponding to free evolution. Next, the atoms enter the second Ramsey zone. This interaction, lasting for a time t_2, is the same as described previously and is governed by the same Hamiltonian (Eq. 1). However, the initial probabilities amplitudes are changed as $C_b(t_2 = 0) = \mathrm{Cos}(\Omega_R t_1 / 2)$ and $C_a(t_2 = 0) = i\,\mathrm{Exp}(i\varphi_{fe})\mathrm{Sin}\,(\Omega_R t_1 / 2)$. The quantum state of the two-level atom, after its emergence from the second Ramsey zone, comes out to be:

$$|\psi(t_1, t_{fe}, t_2)\rangle = [\mathrm{Cos}\left(\frac{\Omega_R t_1}{2}\right)\mathrm{Cos}\left(\frac{\Omega_R t_2}{2}\right) + ie^{i\varphi_{fe}}\,\mathrm{Sin}\left(\frac{\Omega_R t_1}{2}\right)\mathrm{Sin}\left(\frac{\Omega_R t_2}{2}\right)]|b\rangle + [\mathrm{Cos}\left(\frac{\Omega_R t_1}{2}\right)\mathrm{Sin}\left(\frac{\Omega_R t_2}{2}\right) - ie^{i\varphi_{fe}}\mathrm{Sin}\left(\frac{\Omega_R t_1}{2}\right)\mathrm{Cos}\left(\frac{\Omega_R t_2}{2}\right)]|a\rangle \quad (5)$$

Here we take interaction time for each Ramsey zone i.e. cavity to be equivalent to *π/2* Rabi cycle i.e. symmetric Hadamard transformations. Such interaction times can be selected and optimized around a specific value by keeping in view the field strength, atomic velocity and the width of the interaction region i.e., Ramsey cavity length. Symmetric Hadamard transforms imply $\mathrm{Cos}(\Omega_R t_1 /2) = \mathrm{Sin}(\Omega_R t_1 /2) = \mathrm{Cos}(\Omega_R t_2 /2) = \mathrm{Sin}(\Omega_R t_2 /2) = 1/\sqrt{2}$, and thus above expression becomes:

$$|\psi(t_1 = \frac{\pi}{2\Omega}, t_{fe}, t_2 = \frac{\pi}{2\Omega})\rangle = \frac{1}{2}[(1 + ie^{i\varphi_{fe}})\,|b\rangle + (1 - ie^{i\varphi_{fe}})|a\rangle] \quad (6)$$

The above expression explicitly depicts that ideally we may tune the final atomic state detection to a desired pattern through the phase $\mathrm{Exp}(i\varphi_{fe})$ acquired from the free evolution of the atom. It subsequently yields a near delta function detection pattern for the atomic ensemble. For example, for free evolution yielding a phase $\mathrm{Exp}(i\pi/2)$, one always get all the atoms duly detected into their respected excited state |a > due to the quantum interference occurring in the second Ramsey zone. However, in real experimental scenario, one has to work with electromagnetic sources having finite frequency widths, atoms with thermal velocities exhibiting noticeable velocity spreads and other cavity related anisotropies. Therefore, experimentally we always record a narrow fringe known as the Ramsey Fringe. For a more technical, thorough and rigorous theoretical discussion one is referred to [8, 9].

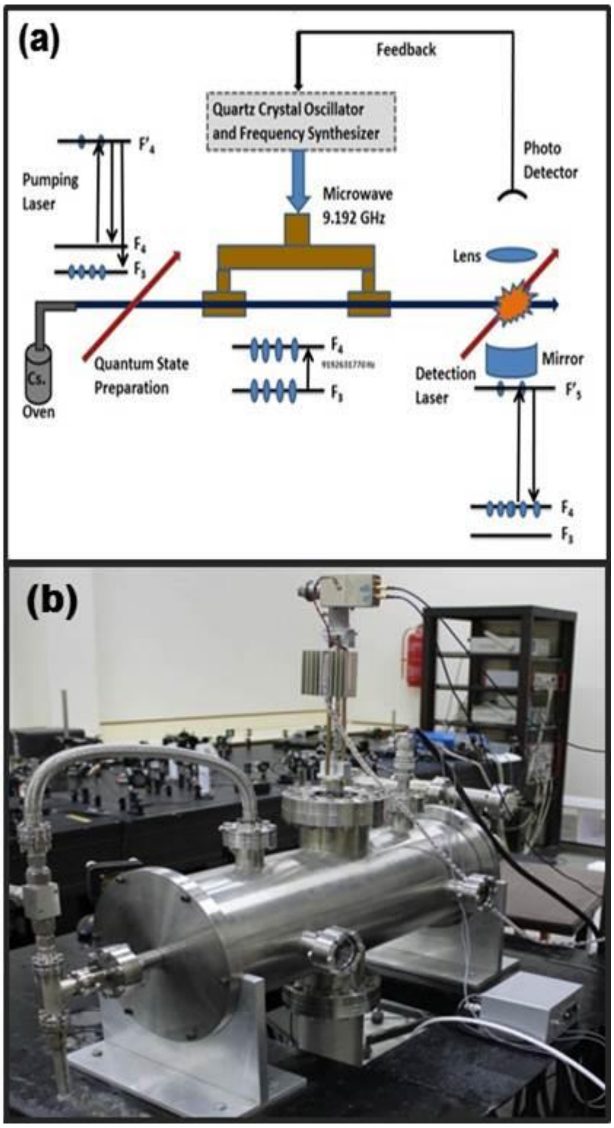

Fig. 3: (a) Schematic diagram and (b) The actual experimental setup of the Cesium Atomic Beam Clock (CABC) at NILOP.

2.2 *Experimental Setup at National Institute of Lasers and Optronics (NILOP)*

The experimental setup of Cesium Atomic Beam Clock fabricated and installed at NILOP is shown in Fig. 3 below along with a schematic sketch. It is comprised of a cylindrical stainless steel vacuum vessel with diameter 20 cm and length 90 cm, Cesium source i.e. an encased ampule heated in the range (80-100) ^{0}C, graphite plates for the collimation of the atomic beam, a central magnetic field termed as C-field, vacuum system consisting of rotary pump, turbo pump and ion pump as well as the fluorescence detection system. In total there are 10 coupling ports fitted with the cylinder. Four see-through windows for the laser beams, a port for the vacuum system coupling, a specifically designed microwave inlet port, two ports encompassing electrical feed-through needed for recording of fluorescence signal and magnetic fields and two ports for the in and out of the Cesium atomic beam. The internal fittings of the clock assembly are shown in Fig. 4a as photographic image Fig. 4b explicitly shows the bi-zonal microwave cavities.

The setup operates at sufficiently high vacuum level (10^{-8} mbar) in order to avoid decoherence effects produced by the collision of Cs atoms with the residual gas atoms/molecules. This high level vacuum is achieved and maintained through continuous operation of (Rotary and Turbo) pump system. Additionally an Ion pump is also coupled with the system that operates via a UPS to cope with the electrical failure emergencies. Cesium metal ampoule is incorporated into the atomic source assembly and is heated up to a temperature in the range (80-100) $^{\circ}$C. The thermally generated Cs vapors then pass through a stainless steel capillary (60 mm long with an inner bore dia of 1.2 mm). Therefore, we get a dilute, well collimated and uniform atomic beam emerging out of capillary.

The atomic beam divergence is further controlled within 200 micro-steradians by inserting three graphite collimating discs each having a fine hole of 1cm diameter at the centre. These graphite discs, apart from the collimation also work as an efficient surface absorbers for the stray Cesium atoms diverging out of the main atomic beam. This fine atomic beam then interacts with the first low intensity (10mW) laser (Toptica DL 100 Diode Laser System) operating around 852nm and tuned to $| 6S_{1/2}, F = 4 > \rightarrow | 6S_{3/2}, F' = 4 >$ dipole transition of the Cs atoms.

This state preparation procedure effectively prepares all the atoms into the quantum state $| 6S_{1/2}, F = 3 >$. These atoms in the quantum state $| 6S_{1/2}, F = 3 >$ then enter the Ramsey interferometric set up comprised of two microwave cavities (Fig. 4). These cavities are fed with almost equal microwave fields of frequency ≈ 9.2GHz through a properly designed waveguide. Furthermore, the applied microwave field is made tunnable in the range ±100 kHz by employing a pulse generator (Stanford Research Systems: Model DS345). The interaction of atoms with the field inside thee cavities are adjusted by controlling the magnitude of microwave field, prepared initially into $|6S_{1/2}, F = 3 >$ state, with the first Ramsey cavity leads to the generation of the coherent superposition of $|F = 3, m_F = 0 >$ and $|F = 4, m_F = 0 >$ of the ground state $6S_{1/2}$ hyperfine structure.

Here it is worth noting that the degeneracy of hyperfine states is removed by applying a small magnetic field, called C-field inside the cavity setup and subsequently $|m_F = 0>$ states are selected for the clock transition because such states are found prone to external magnetic fields. This C-field is generated with the help of two coils. The specific configuration yields us with a magnetic field that is perpendicular to the velocity of moving Cs atoms and hence it lifts the degeneracy prevailing in the hyperfine sublevels m_F related to the Cesium ground state configuration. As depicted in Fig. 4, the specifically designed U- shaped microwave cavity or resonator, made from pure, oxygen free copper, is divided into two exactly identical interaction zones with each having a dimension of 10 mm × 5 mm. This set of resonators

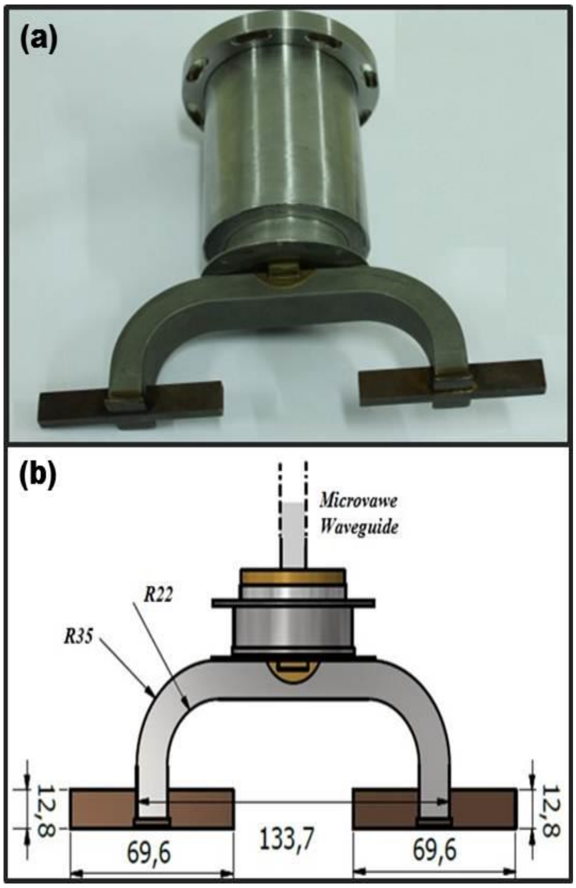

Fig. 4: (a) Photographic image of microwave cavities forming Ramsey interferometer and (b) Scaling diagram of the two-zone Ramsey microwave cavity.

or cavities carry standing microwave field that interacts with the atoms for a specified time defined by the cavity width and velocity of the atoms. So the spread in velocity causes interaction time errors with microwave field which consequently leads to widening of Ramsey Fringe. The distance between the between the two Ramsey zones is selected to be 90 mm. This separation between the cavities is specifically selected keeping in view the average atomic velocity to yield a specific phase during the free-evolution of atoms between the cavities. The quality factor $Q = v_0/\Delta v_0$ of the cavity comes to be 500 resonant to the desired transition, i.e., 9.2 GHz. A μ-metal shielding is used around the cavity region to avoid perturbations caused by the external magnetic field. Therefore, this shielding is vitally important for the stability and accuracy of the atomic clock. The atoms while passing from the first cavity prepared in coherent superposition evolve freely in between the cavities for a distance of 90mm. After the free evolution that imparts the desired local phase to the coherent superposition, the atoms enter into the second Ramsey cavity carrying same field as the first cavity. The interaction of the atom with the second cavity leads to the quantum interference resulting into the appearance of a much narrower fringe (800 kHz), called Ramsey fringe. As the atoms leave the second cavity, they interact with a detection laser beam tuned to |F = 4> → |F' = 5> transition. Thus we note that, as a consequence of Ramsey interference, all the atoms in the beam end up into the upper hyperfine ground state | 6 $S_{1/2}$, F = 4, m_F = 0 >. As stated above, this is checked and optimized by driving the atoms optically through the transition | 6$S_{1/2}$, F = 4 > → |6$S_{3/2}$, F' = 5 > through a laser while subsequent fluorescence signal is recorded through a high efficiency photodiode. Frequency of the applied microwave is tuned and locked to the exact resonance, i.e., v_0 = 9.192631770 GHz.

It is worth noting here that initially, during the developing phase of the Cs atomic clocks, the quantum state preparation and the detection was conventionally carried through Stern-Gerlach technique, because atoms with F = 3 and F = 4 hyperfine levels act as tiny magnets with opposite polarities [8, 15]. The advent of appropriate lasers, however, hinted out towards optical pumping schemes that are much more efficient for the state preparation and detection. Optical schemes are practically more feasible and effective compared to their earlier counterpart, i.e., inhomogeneous multi-pole magnets because they do not yield residual magnetic fields as well as the lossless conservation of the atomic beam. Thus the Ramsey fringe is finally recorded at a locally fabricated detection system comprising of a concave mirror (f = 10 mm) and a lens (f = 10 mm) that focus the emitted signal over a sensitive large area photodiode. The microwave frequency once locked to the atomic hyperfine transition (|F = 3, m_F = 0 > ↔ | F = 4, m_F = 0 >) yields a frequency standard and this frequency when down converted electronically to 1Hz furnishes us with the Atomic Time Standard. Present article, however, describes only the frequency tuning and the recording of the Ramsey fringes that defines the main physics package of the atomic clock. Rest of the procedure i.e. frequency locking and down conversion is fundamentally an electronic based manipulation, a work that is underway right now.

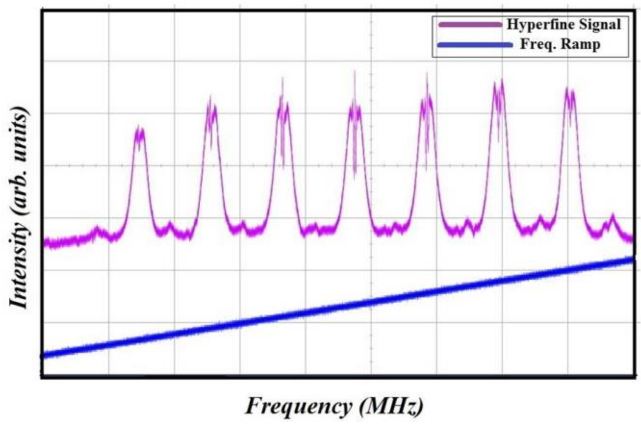

Fig. 5: The recorded seven possible Zeeman peaks 6 $S_{1/2}$ (F = 3) → 6 $S_{1/2}$ (F = 4) corresponding to the allowed transitions $m_F = 0$. The frequency sweep used is 900 kHz.

Fig. 5 illustrates all the seven possible Zeeman spectral peaks 6 $S_{1/2}$ (F = 3) → 6 $S_{1/2}$ (F = 4) corresponding to the allowed transitions $\Delta m_F = 0$ and Fig. 6 depicts the recorded signal of the Ramsey central fringe enveloped in the broader Rabi profile and corresponds to the ground state hyperfine transition (F = 3, m_F = 0) ↔ (F = 4, m_F = 0). The signal is

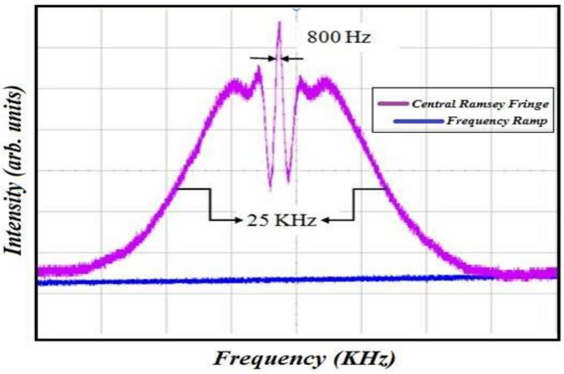

Fig. 6: Central Ramsey fringe enveloped in the broader Rabi profile registered experimentally at NILOP. The fringe corresponds to the ground state hyperfine transition (| F = 3, $m_F = 0$ > ↔ | F = 4, $m_F = 0$ >); $\Delta m_F = 0$ and marks the major physics theme of any atomic time and frequency standard.

comprised of a narrow spectral peak called Ramsey central fringe ~ 800 Hz which is found encompassed under a highly broadened spectral spread called Rabi pedestal. This broader Rabi profile is experimentally connected to the broadening caused by transit time for the atoms traversing through the two spatially separated microwave zones or cavities. Similarly the natural velocity spread of the thermal atomic beam also plays a major role in shaping the Rabi pedestal. Now this pedestal (25 kHz) is stringently important while working with the atomic beam clocks whose working depends on thermally generated beam as compared with the fountain atomic clocks that utilize optically cooled atomic samples via magneto-optical trapping and laser cooling setups (70 Hz). The Rabi profile for the beam clock is broader as compared to fountain clock because the thermal atomic beams exhibit higher velocity spreads that leads to interaction time imprecision. However, in the fountain clocks, cold atoms have negligibly small velocities and hence highly precise atom-field interaction times can be selected that leads to narrow Rabi pedestals in general. This specific broadened Rabi profile is a consequence of diverse effects taken together. Although, both Rabi and Ramsey structures depend upon the atomic parameters but the extreme narrowing of the Ramsey fringe in comparison with Rabi profile is a direct consequence of the quantum interference, as stated earlier. One of the major contributions comes from the atoms that miss transition in any one of the interaction zone. Moreover, the characterisation parameters like Rabi frequency, second order Doppler shift and second order Zeeman effect also contribute in the overall broadening and should be incorporated into the analysis carefully. Therefore, the readership and impact of the article will increase.

3. Results and Discussions

As mentioned above, we, at NILOP, have demonstrated the operation of Ramsey interferometer, a basic phenomenon upon which CABC are commonly built, using a thermal, diluted and highly collimated beam of Cs atoms. This yielded us with a highly stable atomic oscillator coupled with a microwave field through an optimized interaction. Therefore, the locked field frequency gives us a precise, stable frequency standard that can be electronically converted into the corresponding time signal. The work for frequency-time conversion is underway right now. As stated earlier, Fig. 6 illustrates the central Ramsey fringe incorporated into much broader Rabi envelope with the central peak belonging to the clock transition $\Delta m_F = 0$ (| F = 3, $m_F = 0$ > → | F = 4, $m_F = 0$ >). This graphical data clearly exhibits a 25 KHz broad Rabi profile carrying inside an extremely narrow Ramsey fringe of width about 800 Hz only. The symmetry of the data recorded suggests that there are no appreciable cavity anisotropy effects and the minimal noise level is a witness against decoherence that potentially destroy a superposition state.

Accuracy of the clock is generally defined as the degree of exactness of the registered data in comparison with the true value. Hence accuracy criterion designates the offset errors from the ideal value. Thus, while dealing with the frequency and time standard, the accuracy of any atomic clock under investigation furnish us with the time error or related frequency error or offset from the internationally approved numerical value of the primary time/frequency standard. As already stated above, the performance of an atomic clock depends upon many diverse experimental as well as natural parameters. The most prominent in this regard are stability, random frequency dithering and the accuracy. Stability of the clock is gauged under two distinct temporal regimes i.e. short term stability and long term stability. Stability in both the regime is gauged through the Allan variance [9]. Further studies related to the parameters causing instability explicitly reveal that offset in the frequency of a hyperfine transition may be induced by many physical and natural phenomena as well as the external perturbations. Thus such frequency may be attributed to the factors like black body transitions, Doppler Effect, Zeeman Effect and variations in the gravitational field. Thus keeping these uncontrollable and mostly random fluctuations in mind, one is left only with the option to apply statistical means for the evaluation of the stability of all the precise oscillators including the atomic clock. Thus, as mentioned above, this statistical evaluation is carried out with the help of Allan variance [16, 17]. It can be roughly defined as the one half of the square of the difference between two consecutively recorded values, i.e., $(y_{n+1}-y_n)^2$ averaged over the sampling time t. Mathematically one can express Allan variance as follows:

$$\sigma_y^2(t) = \frac{1}{2}\langle(y_{n+1} - y_n)^2\rangle \tag{7}$$

where y_n stands for the fractional error in the frequency with the average taken over the τ i.e. the sampling period. Using this fractional frequency offset, one can easily defined the normalized frequency through following expression:

$$y_n = \langle\frac{\delta v}{v}\rangle_n \tag{8}$$

here v stands for the reference clock frequency and δv is the corresponding frequency error. Now in order to get statistically accurate estimate, the average is carried over n sampling periods. Now if y's are collected through the manipulation of a random and entirely uncorrelated function or white noise then it is well known that the division by two in above expression transforms Allan variance to be equivalent to the classical variance. Allan variance is conventionally employed to assess to overall stability of many sensitive and precise oscillators and this also includes oscillators like frequency-stabilized lasers as well as the atomic clocks. The stability of the atomic clock is thus yielded by the $\sqrt{\sigma(\tau)}$, i.e., square root of the Allan variance:

$$\sigma(t) = \left[\pi Q_{at}\frac{S}{N}\right]^{-1}\left[\frac{t}{\tau}\right]^{\frac{1}{2}} \quad (9)$$

here τ denotes the aggregate sampling time, Q_{at} refers to the quality factor the involved atomic resonant transition, S/N marks the signal-to-noise ratio corresponding to the sampling time τ, *t* represents the time for one cycle. Now the slope of $\sqrt{\sigma(\tau)}$ plotted against sampling time τ in log-scale is commonly employed to characterize the specific noise type in an atomic clock. Averaging over time is taken to yield aggregate estimate of the clock's instability. The trend is a complicated function of various parameters mentioned above.

For the CABC at NILOP, the short-term stability was gauged by comparing the recorded data with the study carried by one of the author at the Institute de Física de São Carlos, Universidade de São Paulo, Brazil [9].

For the Brazilian time and frequency standard, they used a commercial atomic clock i.e. Agilent-5071A along with a computerized GPIB interfaced data acquisition and processing system to determine the short term stability of their indigenously developed atomic clock. Fig. 7 exhibits the measured values σ for their Cesium Beam Atomic Clock corresponding to a sampling time of about 10000s. Comparison through the recorded Ramsey fringes in both the cases clearly demonstrates that the short term stability of the present Clock setup at NILOP is almost of the same orders as that of the Brazilian setup, i.e., $\sigma(\tau) = (6.6 \pm 0.2) \times 10^{-10} \times \tau^{-0.5\pm0.1}$.

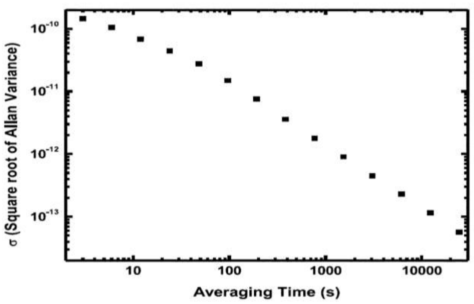

Fig. 7: The graph representing the measured values for short term stability σ of the Brazilian cesium beam atomic clock.

5. Conclusions

Physical principle of the atomic clock is based on the quantum superposition and the quantum interference i.e., Ramsey interference that results from such a superposition state. This paper reports the experimental engineering and manipulation methodology of the state, a highly tedious and technical task in itself. Further, the article amply demonstrate how, by working in quantum domain, one can gain excessively accurate results i.e., in present case the difference between the widths of Rabi's profile (25 kHz) and that of the Ramsey's fringe (800 Hz). Experimental recording of the Ramsey fringes thus stands witness to the demonstration of the physical package of an atomic clock. The rest of the work belongs to electronics control and frequency down conversion which is quite trivial. This is underway right now. However, the present demonstration has opened up a new vista for the experimental exploration of atomic media through quantum means which is quite novel in this part of the world.

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