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Review

Indigenisation of the Quantum Clock: An Indispensable Tool for Modern Technologies

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Abstract: Time and frequency (T&F) measurement with unprecedented accuracy is the backbone for several sophisticated technologies, commensurate with the evolution of human civilisation in the 20th century in terms of communication, positioning, navigation, and precision timing. This necessity drove researchers in the early 1950s to build atomic clocks that have now evolved to a state-of-the-art level, operating at optical wavelengths as optical atomic clocks, which use cold and trapped samples of atomic/ionic species and various other sophisticated diagnostic test techniques. Such *ultrahigh*-precision accurate clocks have made it possible to probe fundamental aspects of science through incredibly sensitive measurements. On the other hand, they meet the T&F synchronisation standards for classical and emerging quantum technologies at the desired level of accuracy. Considering the impact of optical atomic clocks in the second quantum revolution (quantum 2.0), they have been identified as an indispensable critical technology in worldwide quantum missions, including in India. This article reviews the present international scenario regarding optical atomic clocks and their related technologies and draws a roadmap for their indigenisation over the next decade.

Keywords: atomic clock; optical clock; ion trap; optical lattice; precision measurement; fundamental science; quantum technology; quantum metrology; quantum communication

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1. Introduction

Atomic clocks [1–5] are among the most incredible machines developed in the last century, following the prescriptions suggested by Isidor Isaac Rabi and his student Norman Foster Ramsey [6,7], which gradually brought timekeeping to an unprecedented level of accuracy by incorporating several other state-of-the-art technologies within them. With the advent of lasers, precision spectroscopy of atoms became commonplace. It was only a matter of time until research groups worldwide developed laser-based optical manipulation, cooling, trapping, and other novel techniques to improve the measurement accuracy of isolated quantum systems. Of particular interest, atomic clocks were aided by laser–atom interaction techniques, which improved their accuracy by several orders of magnitude. The microwave (MW) caesium atomic clock, which uses the doubly split hyperfine ground state as the oscillator frequency, was the first to utilise laser cooling and trapping techniques to improve measurement sensitivity. The Allan deviation characterises the fundamental fractional frequency instability of an atomic clock as

$$\sigma = \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T}{N \times \tau}} \tag{1}$$

where Q ($=\nu_0/\Delta\nu$) depicts the quality factor for the clock transition at a frequency ν_o and with a natural linewidth $\Delta\nu$ [8]. Here, N is the number of experimenting atoms/ions, τ is the integration/averaging time, and T is the cycle time for a single measurement. It is evident that if one were to choose a clock transition at the optical wavelengths (ν_o~10^{15} Hz), the sheer gain in the quality factor would reduce σ, given all the other parameters are unchanged. Highly forbidden optical transitions having ultranarrow natural linewidths (sub-Hz $\Delta\nu$) are obvious choices for optical clocks that are nontrivial to excite. Therefore, extremely narrow linewidth lasers are required to build accurate clocks using them. In 2001, the first optical atomic clock based on singly charged ions was demonstrated at NIST, USA [9]; it was followed by one based on neutral atoms, demonstrated at the University of Tokyo, Japan, in 2005 [10]. With current fractional accuracies reaching a few parts in ~10^{-19}, the superiority of state-of-the-art optical atomic clocks over the best MW clocks is clearly demonstrated, as the latter has about three orders of magnitude lower fractional uncertainty. Thus, undoubtedly, optical clocks serve as a better frequency standard than the current MW-based international standard (SI) definition of the second, which is likely to be redefined by its optical counterpart in the near future [11–14]. Table 1 compares the performance of the world's best MW and optical clocks based on the caesium fountain, and a single trapped ^{27}Al^{+} and neutral ^{171}Yb atoms in an optical lattice, respectively, developed by NIST in the USA and mention their potential applications. The results clearly show that the future relies on optical clocks in all aspects—performance, applications, and portability—compared with MW clocks. As a matter of fact, optical clocks would require about three orders of magnitude less averaging time than MW clocks to achieve a certain fractional frequency uncertainty, which translates to an efficient timekeeping mechanism due to a faster rate of time and frequency (T&F) data transmission. For example, caesium fountains require approximately 20 days for establishing their intercomparison at 10^{-16} levels of accuracy via MW communication techniques such as the common view global navigation satellite system (CVGNSS) or two-way satellite time and frequency transfer (TWSTFT). In the case of optical clocks, this same level of accuracy can be reached in ~1000 s, and specialised optical communication techniques such as two-way fiber optic time transfer (TWFOTT) enable the intercomparison of remote systems. Thus, not only are the clock transitions probed at the optical wavelengths, but the optical clock technology was boosted by the invention of the optical frequency comb [14–21] and the development of extremely narrow linewidth lasers (<1 Hz) [22–27] stabilised to very high-finesse (> 200,000) optical resonators (Fabry–Pérot cavities), which were built upon improvements in several key areas such as optical coatings, silicon-based photonics, micro/nanofabrication, and cryogenic systems.

Table 1. Typical parameters and performance metrics of microwave-based caesium (Cs) fountain and optical atomic clocks using a single trapped aluminium ion (^{27}Al+) and neutral ytterbium atoms (^{171}Yb) in an optical lattice.

Performance Metric [Unit]	**Microwave**	**Optical**	
	^{133}Cs Fountain [28]	**Trapped ^{27}Al+ [29]**	**^{171}Yb Optical Lattice [30]**
νo [GHz]	9.192631770	1,121,138.58639	518,672.072664
Δν [Hz]	0.1	8×10^{-3}	7×10^{-3}
Q [$\times 10^{15}$]	91.92×10^{-6}	140.142	74.096
Systematic uncertainty [$\times 10^{-19}$]	1100	9.4	14
σ at 1s [$\times 10^{-16}$]	1700	12	1.5
Applications and functionality	Present SI standard, T&F metrology	Ultrahigh-accuracy T&F metrology, quantum metrology, fundamental science, miniaturisation for compact/transportable clock	

As shown in Figure 1 there are two most common types of optical atomic clocks: the type using a single atomic ion and the type using an ensemble of neutral atoms. With improvements in trapping, cooling, and readout techniques, it has become possible to manipulate atoms and/or ions at a single quantum level in a well-controlled environment.

In the case of ions, one uses a radiofrequency (RF) trap, namely the Paul trap [31], to confine a single ion of interest, laser cool it to the lowest motional state of the trap, and then probe its clock transition. Due to the long confinement time τ (which could be as long as months) of the trapped ion, repeated spectroscopic measurements on the single ion for a given clock transition are performed to reach the desired level of accuracy [32,33]. In contrast, neutral atoms are initially laser-cooled, collected in a magneto-optical trap, and localised in a magic wavelength optical lattice, and subsequently, their clock transitions are probed in a repeated manner to yield their frequency [34–37]. There are other ongoing efforts to realise optical clocks, such as using an array of optical tweezers to trap neutral atoms individually and performing spectroscopy on these isolated quantum systems to derive the clock's frequency [38–41]. For charged particles, multi-ion clocks using a specially engineered complex chip ion trap [42,43] and using highly charged ions [44–46] are under development. These new approaches are far from realising the fractional uncertainties that are routinely observed in current-day state-of-the-art optical clocks using single trapped ions and atoms in an optical lattice. So far, there have been regular competition between the optical lattice and single-ion optical clocks; among them, $^{27}\mathrm{Al}^{+}$ reached the best fractional accuracy of 9×10^{-19}.

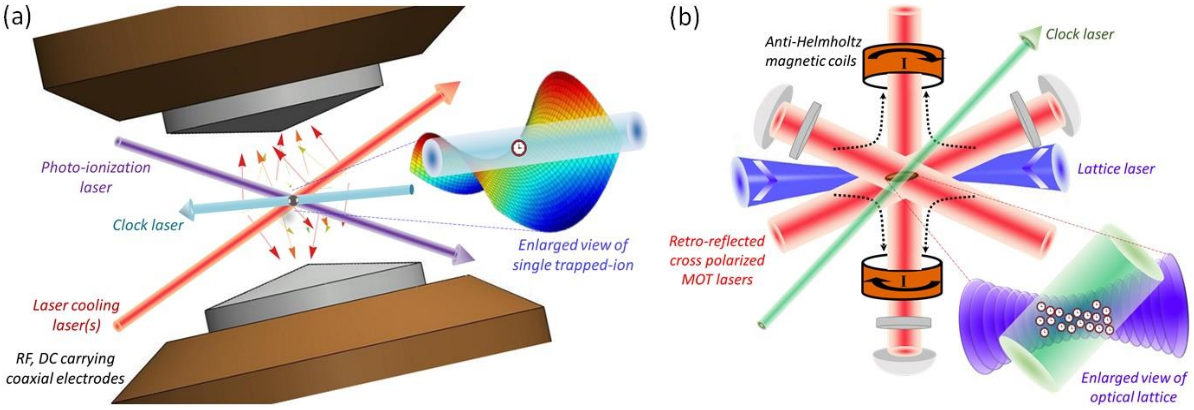

Figure 1. Optical atomic clocks: (**a**) single ion trapped in an end-cap-type Paul trap and (**b**) neutral atoms confined in optical lattices. Enlarged view shows a single ion trapped by an oscillating quadrupole potential and an ensemble of atoms localised in a pancake-shaped 1D optical lattice.

The most prominent application of optical atomic clocks is time and frequency metrology with unprecedented accuracy. Around the world, there are designated federally funded laboratories, such as National Measurement Institutes (NMIs), and a few pioneering labs that use optical clocks for the accurate realisation of the second, even though these clocks are secondary standards at present and expected to be the primary standards. Ultrahigh-accuracy T&F measurements have several applications that profoundly impact current-day society, from day-to-day life to the strategic sectors. The most important of these applications pertain to satellite-based navigation, communication, surveillance, space missions, e-commerce, digital archiving, meteorology, automatization in transport, stock markets, smart power grids, industry 4.0, the Internet of Things (IoT), and more. With the advent of sophistication in these technologies, particularly the technologies based on quantum (q) phenomena, e.g., q-communication, q-computer, q-internet, and so on, the requisite levels of time, frequency, and phase synchronisations and time stamping among the distributed devices are becoming more and more stringent. These can be met only by optical atomic clocks and all-optical T&F transfer mechanisms that inevitably enhance the MW signals' accuracy as well, by high-fidelity optical-to-MW conversion [14] through optical frequency comb technology. Within the country of India, the most immediate applications for such optically generated highly accurate ultrastable MW references will be helpful in the T&F synchronisation of setups, e.g., the national primary timescale at the National Physical Laboratory (NPL) in New Delhi-, IRNSS Network Timing (IRNWT) centres in Bangalore and Lucknow; synchronising land and space-based distributed defence systems, e.g., for secure and glitch-free operations of Doppler radar systems; wireless communication; navigation in hostile terrain or underwater where GPS signals may not be available; phase synchronisation of very-long-baseline interferometry (VLBI); an array of radio antennas, e.g., GMRT and Ooty radio telescopes; time synchronising among worldwide gravitational wave (GW) detectors; and many more applications. These shall substantially benefit from the ultralow-noise, ultrastable, and narrow-linewidth MW sources derived from optical frequency standards [26] and disseminated through phase-stabilised optical fibers [47,48]. In addition to their functions of timekeeping and synchronisation, optical clocks serve as a powerful tool for probing fundamental physics and studying q-metrology and q-information processing. These nationally and internationally distributed optical clocks need to be operated in a real-time network mode [49]. A small number of developed countries have come together with their optical clocks and already demonstrated some landmark ultrasensitive measurements such as searching for the constancy of fundamental constants [50–53] and fundamental symmetries [54,55]. Among the various other experimental approaches, the networked optical clock is the most accurate one and plays crucial roles in extending our present knowledge in science, e.g., the extension of the standard model, testing the general theory of relativity, and so on. The present sensitivity of the optical clocks can distinguish between the influence of Earth's gravity at <1 cm height difference to the clock transition frequency, which is thus used for accurate long-distance levelling [30], q-geodesy [56], and oil and mineral explorations [57]. Other than these applications, the broader scope of using space-based optical clocks includes the detection of GW [58], cosmic microwave background radiation (CMBR), dark energy (DE), and/or dark matter (DM) [59,60], and the testing of *CPT* symmetry [54] which are still in the proposal stage but shall evolve in the coming years. Due to the broad applicability and scope of optical clocks in science and technology, together with their strategic applications, the underlying research in this field has gained immense momentum in the last two decades. Developed nations such as the USA, the UK, France, and Germany, and a few developing countries such as China, South Korea, Thailand, and India are putting their best efforts in this direction.

This article describes the present international status of optical atomic clocks, their enormous scope for studying fundamental aspects of sciences, their ability to meet the unavoidable requisites of sophisticated classical and quantum technologies, and their ability to ensure timekeeping at an unprecedented level of accuracy. We also describe the present national scenario towards the indigenous development of optical atomic clocks and highlight the goals and scope of establishing real-time networking among them. Furthermore, we propose a concrete short- and long-term roadmap that Indian researchers who are either pursuing or planning to start research in this technology-intensive field are encouraged to follow to cope with the global standards.

2. International Status

The single trapped ion has the benefit of longer interrogation times and negligible collisional broadening of the clock transition. The latter is suppressed due to the absence of intra-ionic collisions and results only from collisions with residual gas molecules drastically reduced in an ultrahigh-vacuum (UHV) environment. In addition, perturbations due to the stray fields can be minimised at the trap centre, and/or can be accurately estimated. In general, ion micromotion due to the trap driving RF is an unavoidable perturbation that results in ion heating, second-order Doppler shifts, and scalar Stark shifts. However, the proper choice of the ion trap operating parameters—based on novel designing, careful material selection, precision engineering, electric field compensation and efficient cooling of the ion ensure its localisation near the RF-null and the minimisation of micromotion-induced systematics. Other dominant systematic shifts in the clock transitions arise due to the black-body radiation (BBR) of the ambient environment, the quadrupole moment of the states, and Zeeman shifts, which may be minimised by their accurate determination and by accounting for them in the measurement. The atomic ions ^{27}Al^{+}, ^{40}Ca^{+}, ^{88}Sr^{+}, ^{115}In^{+}, ^{171}Yb^{+}, and ^{199}Hg^{+} are the most popular choices so far, whereas ^{137,138}Ba^{+}, ^{175}Lu^{+}, ^{205}Tl^{+}, and $^{223–229}$Ra^{+} are also being studied by some groups. The choice of the ionic species depends on the high Q-factor of their respective clock transitions and exploring scientific motives enhanced by their unique atomic properties [61]. The hyperfine-induced 3s^{2} ^{1}S$_{0}$ $|F = 5/2>$ -3s3p ^{3}P$_{0}$ $|F = 5/2>$ transition in ^{27}Al^{+} (the aluminium ion) at 267 nm with $\Delta\nu$ = 8 mH has reached the world-best accuracy of 9.4×10^{-19} as demonstrated by NIST, USA [29]. For this ion, simple laser cooling is not viable due to the unavailability of lasers at the required wavelength, and to overcome this, it is sympathetically cooled using either precooled ^{9}Be^{+} or ^{25}Mg^{+} ion reservoirs. In addition, for the same reason, rather than using direct fluorescence detection, the ^{27}Al^{+} ion uses quantum logic spectroscopy [29]. Among the others, the most popular species is ^{171}Yb^{+}, which accommodates two quadrupole (E2) clock transitions and one octupole (E3) clock transition at the wavelengths of 411 nm, 435 nm, and 467 nm, respectively. Its highly forbidden E3 transition with $\Delta\nu < 1$ nH is the narrowest known and most suitable optical transition for building a trapped-ion frequency standard. So far, accurate results on ytterbium-ion clocks have been demonstrated by PTB, Germany, and NPL, UK, and they have reached $\Delta\nu/\nu_{o} = 3 \times 10^{-18}$ [62]. The calcium-ion clock has the potential to serve as an accurate clock since its unique magic rf operated trap mutually cancels the micromotion-induced scalar Stark shift and the second-order Doppler shift, which was first demonstrated in Sr^{+} at NRC, Canada and recently applied in a liquid-nitrogen-cooled ion trap by WIPM, China for Ca^{+} [63]. Without detailing each species individually [61], the worldwide efforts on the trapped-ion optical clocks are captured in Table 2; they are pioneered by NIST, USA; PTB Germany; NPL, UK; and NRC, Canada, and several other developing countries are actively engaged in developing optical clocks.

Table 2. A list of species demonstrated as optical frequency standards worldwide is shown with their reported fractional accuracy and frequency standards.

Species	Clock Transition	Wavelength in Vacuum [nm]	Measured Clock Frequency [Hz]	Fractional Uncertainty [$\times 10^{-17}$]	Short-Term Stability $(\sqrt{\tau/s})^{-1/2}$	Same-Species Comparison Performed (Yes/No)	Accuracy of the Same-Species Comparison	Lab, Country [Ref.]
					Singly charged atomic ions in a Paul trap			
$^{27}Al^{+}$	$^1S_0$-$^3P_0$	267.4	1121015393207857.4(7)	0.094	1.2×10^{-15}	No *		NIST, USA [29]
$^{40}Ca^{+}$	$^2S_{1/2}$-$^2D_{5/2}$	729.3	411042129776393.2(1.0)	240	2.9×10^{-13}	No		SYRTE, France [64]
			411042129776393.0(1.6)	390	4.0×10^{-13}	No		NIM, China [65]
			411042129776398.4(1.2)	300	2.4×10^{-14}	No		NICT, Japan [66]
			411042129776401.7 (1.1)	7.7	2.3×10^{-14} (20 ms)	Yes	Not reported	WIPM, China [67]
$^{88}Sr^{+}$	$^2S_{1/2}$-$^2D_{5/2}$	674	444779044095486.71(24)	3	2.2×10^{-14}	Yes	4×10^{-17}	NPL, UK [68]
			444779044095485.5(9)	1.2	3.0×10^{-15} (1 s)	Yes	Not reported	NRC, Canada [69]
			444779044095485.271(59)	1	3.3×10^{-15}	No		PTB, Germany [70]
$^{115}In^{+}$	$^1S_0$-$^3P_0$	236.5	1267402452900967(63)	5000	–	No		MPIQ, Germany [71]
			1267402452901040.1(1.1)	85	1.7×10^{-13}	No		NICT, Japan [72]
$^{138}Ba^{+}$	$^2S_{1/2}$-$^2D_{5/2}$	1762.2	170126432449333.00	33	1.5×10^{-15} (1000 s)	No		NUS, Singapore [73]
$^{171}Yb^{+}$	$^2S_{1/2}$-$^2D_{3/2}$	435.5	688358979309307.82(36)	5231.6	4.1×10^{-14}	No		PTB, Germany [74]
			688358979309308.42(42)		1.0×10^{-14}	Yes	$1.3(1.2) \times 10^{-15}$	NPL, UK [75]
$^{171}Yb^{+}$	$^2S_{1/2}$-$^2F_{7/2}$	466.9	642121496772645.150(1)	0.2757.9	1.0×10^{-15}	No		PTB, Germany [74]
			642121496772644.91(37)		-	No		NPL, UK [52]
$^{176}Lu^{+}$	$^1S_0$-$^3D_1$	847.7	3536399159522(60)	-	1.2×10^{-15}	Yes	3.7×10^{-18}	NUS, Singapore [76]
$^{199}Hg^{+}$	$^2S_{1/2}$-$^2D_{5/2}$	281.6	1064721609899145.30(69)	69	7×10^{-15} (1 s)	No		NIST, USA [77]
					Neutral atoms in an optical lattice			
^{24}Mg	$^1S_0$-$^3P_1$	457.7	655659923839730(48)	7000	2.0×10^{-13}	No		PTB, Germany [78]
^{24}Mg	$^1S_0$-$^3P_0$	458.0	655 058 646 681 864.1(5.3)	700	1.5×10^{-15}	No		LUH, Germany [79]
^{40}Ca	$^1S_0$-$^3P_1$	657.5	455986240494144(5.3)	1200	3.0×10^{-15}	No		PTB, Germany [80]
			455986240494135.8(3.4)	750	2×10^{-16}	No		NIST, USA [81]

Table 2. *Cont.*

Species	Clock Transition	Wavelength in Vacuum [nm]	Measured Clock Frequency [Hz]	Fractional Uncertainty [$\times 10^{-17}$]	Short-Term Stability $(\sqrt{\tau/s})^{-1/2}$	Same-Species Comparison Performed (Yes/No)	Accuracy of the Same-Species Comparison	Lab, Country [Ref.]
					Neutral atoms in an optical lattice			
^{87}Sr	$^1S_0$-$^3P_0$	698.4	429228004229873.65(37)	0.20	4.8×10^{-17}	-		JILA, USA [82]
			429228004229873.10(0.17)	31	3.0×10^{-15}	Yes	2.8×10^{-16}	SYRTE, France [83]
			429228004229873.00(07)	1.5	5.0×10^{-17} (120 days)	No		PTB, Germany [84]
			429228004229873.082(76)	18	7.0×10^{-15}	No		NICT, Japan [85]
			429228004229872.0(1.6)	370	2.4×10^{-13} (8 s)	No		NMIJ, Japan [86]
			429228004229873.4(4)	0.72	1.8×10^{-16}	Yes	2.0×10^{-18}	RIKEN, Japan [87]
^{88}Sr	$^1S_0$-$^3P_0$	698.4	429228066418009(32)	7000	-			SYRTE, France [88]
^{171}Yb	$^1S_0$-$^3P_0$	578.4	518295836590865.2(0.7)	0.2	1.5×10^{-16}	Yes	5×10^{-19}	NIST, USA [30]
			518295836590863.54(26)	50	1.0×10^{-14} (1 s)	No		NMIJ, Japan [89]
			518295836590863.75(14)	1.7	3.2×10^{-15}	No		KRISS, S. Korea [90]
			518295836590863.61(13)	2.8	2.7×10^{-15} (1 s)	No		INRIM, Italy [91]
^{199}Hg	$^1S_0$-$^3P_0$	265.6	1128575290808155.1(6.7)	5707.2	1.2×10^{-15} (1s)	No		SYRTE, France [92]
			1128575290808155.4(1.1)		3.0×10^{-15}	No		RIKEN, Japan [93]
^{169}Tm	$^2F_{7/2}$-$^2F_{5/2}$	1140	262 954 938 269 213(30)	<0.5	$<10^{-14}$	No		LPI, Russia [94]

Additional initiatives from other countries for developing optical clocks are as follows: The Russian National Metrology Institute (VNIIFTRI) is developing a strontium lattice clock and the Korea Research Institute of Standards and Science (KRISS) is developing an ytterbium lattice clock; The National Institute of Metrology Thailand (NIMT) and Mahidol University are jointly developing an ytterbium-ion clock; The University of Western Australia is developing an ytterbium lattice clock; Turkey's National Metrology Institute (TÜBİTAK) is collaborating with VNIIFTRI to develop a strontium lattice clock; In India, the National Physical Laboratory, New Delhi and the Inter University Centre for Astronomy and Astrophysics, Pune are developing ytterbium-ion clocks, the Indian Institute of Science Education and Research, Pune is developing a strontium lattice clock, and the Indian Institute of Technology Tirupati is developing a calcium-ion clock.

The lattice clocks [95] typically use around 100 to 10,000 atoms, thus providing a higher signal-to-noise ratio (S/N) than a single ion. However, decoherence caused by off-resonant scattering of photons from the lattice laser leads to the degradation of the S/N and potentially shifts the clock frequency by line pulling. While the large number of atoms N reduces the quantum projection noise by a factor of $1/\sqrt{N}$, on the other hand, intra-atomic cold collisions (s-wave-dominated elastic collisions) due to their large densities result in a shift in the clock frequency. Further, collision with the thermal background gas limits the confinement time of the atoms within the lattice. This restricts τ to be ~1 s, which is disadvantageous compared with the single-ion clocks. Although the optical lattice is created using lasers at the magic wavelength, it still induces light shifts to the clock frequency through various processes. Hidetoshi Katori first proposed the magic wavelength optical lattice clock in 2003 [96]. Therefore, RIKEN, the University of Tokyo, NMIJ, and NICT in Japan have always been pioneers in this technology. Other than this additional systematics, a BBR shift is always present due to the ambient temperature of the trapping environment.

Neutral ^{87,88}Sr, ^{171}Yb, and ^{199}Hg atoms are the most popular species for building lattice clocks, whereas some groups have also worked with ^{24}Mg and ^{40}Ca atoms. Degenerate fermionic ^{87}Sr atoms, using a hyperfine-induced $5s^2\ ^1S_0\ |F = 1/2> -5s5p\ ^3P_0\ |F = 1/2>$ transition at 698 nm and having single-site occupancy in a 3D optical lattice, have recorded the best fractional accuracy, 2.5×10^{-19}, at NIST, USA [97]. This experiment probes the clock transition using the world's narrowest linewidth ($\Delta\nu$ = 26 mHz) laser at the central frequency of 429 THz. The ytterbium-atom optical lattice clocks were reported with a fractional frequency of 1.4×10^{-18} again by NIST, USA [30]. The Boulder Atomic Clock Network (BACON) collaboration between two neighbouring institutes, i.e., NIST and JILA, which are 3.6 km apart from each other in Boulder in the USA, is the custodian of the world's best trapped-ion and lattice-based optical clocks using ^{27}Al$^+$, ^{87}Sr, and ^{171}Yb, respectively [29,30,97]. Recently, the BACON collaboration established the most stable optical fiber network between them and reported the measured mutual frequency ratios of these three optical clocks with a fractional accuracy of $< 8 \times 10^{-18}$ [98]. This level of sophistication enabled them to pursue *high*-precision measurements for exploring fundamental science and the most accurate timekeeping. Several other laboratories around the world, as given in Table 2, have also developed state-of-the-art optical lattice clocks, and many other countries, including India, are working towards developing such optical atomic clocks (see Table 2 footnote).

The status of the optical clock's accuracy over the last two decades based on single trapped ions and neutral atoms in optical lattices is shown in Figure 2. The clock's accuracy has shown significant improvement by five orders of magnitude since the beginning, reaching a few parts in 10^{18} level of accuracy. The scope of such ultraprecise clocks is no longer limited to lab-level experiments; advanced countries are rapidly adopting long-distance and even intercontinental networking among optical clocks. A highly sophisticated two-way fiber optic time transfer (TWFOTT) technique that uses phase-stabilised optical fibers to transport photons, conserving their phases over very long distances, is used for direct intercomparison of the geographically distributed optical clocks with extremely high precision compared with the MW or normal optical communication techniques. Some such examples of TWFOTT networks belong to (i) the European Association of National Metrology Institutes (EURAMET) among participating EU agencies, (ii) NIST ↔ Univ. of Boulder in the USA, (iii) INRIM ↔ LENS in Italy, (iv) LPL ↔ Reims in France, (v) MPQ ↔ PTB in Germany, (vi) Vrije Univ. ↔ Univ. Groningen in Netherlands, (vii) NICT ↔ Univ. Tokyo in Japan, (viii) Univ. Malta ↔ Univ. Sicily in Italy (submarine link), and (ix) an urban fiber link in China (through the desert). Here, the symbol ↔ stands for bidirectional coupling to establish the TWFOTT. The Robust Optical Clocks for International Timescale (ROCIT) in Europe is an established network for time and frequency metrology with unprecedented accuracy, whereas TWFOTT links enable the countries mentioned above to intercompare their optical clocks in a selective manner at the highest level of accuracy, even up to 10^{-19}.

Such a facility leads to the pursuance of high-end fundamental science research, such as possible extensions of the standard model (SM) by probing the temporal constancy of the dimensionless fundamental constants and searching for violations of fundamental symmetries, testing the general theory of relativity, mapping time-dependent geodetic changes, the establishment of data for vertical height measurement systems and enabling accurate levelling, searching for underground resources, and many more applications. On the other hand, these highly stabilised optical links can also be used to apply quantum technologies such as quantum communication, quantum internet, testing quantum hypotheses, etc. Beyond interlaboratory intercomparison of ultrahigh-accuracy optical clocks, many applications require transporting the "reference" photons to a remote location; these applications include carrying out chronometric levelling-based geodesy, searching for oil/natural gas, VLBI, optical frequency calibration, space applications, and many more.

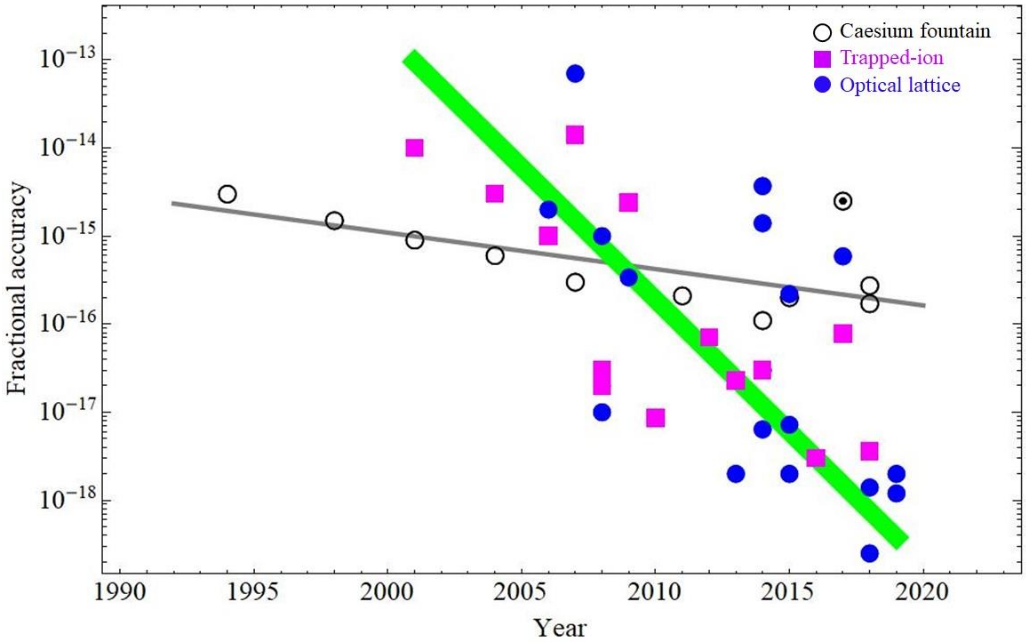

Figure 2. Worldwide status of optical clocks with their reported accuracies based on a single trapped ion (magenta) and neutral atoms in optical lattices (blue) over the last two decades. Accuracies of microwave caesium fountain clocks (black) are also depicted here for comparison. The reported accuracy of the only developed Indian caesium fountain at NPL, New Delhi (NPLI-CsF1) is indicated by the dot surrounded by a circle (black), and is about an order of magnitude lower in accuracy than the world's best fountain clock [99]. The solid lines indicate the MW (grey) and optical (green) clocks' data to indicate the improvement rates in their accuracy.

Figure 3 highlights the performance of some commonly used commercial atomic clocks. Starting with the development of Cs and Rb beam/vapour clocks during the 1960s and hydrogen maser during the 1980s, portable atomic clocks received a significant boost from the NIST-DARPA program in the USA in 2005 with the development of the chip-scale atomic clock (CSAC). Commercial CSACs were launched in 2011, soon followed by the Rb-based miniature atomic clock (MAC). Around 2015 the first commercial cold atom-based portable optical atomic clock was launched by a French spin-off from the Institut d'Optique d'Aquitaine. During the same period, a wide range of "out-of-the-lab" applications motivated miniaturisation of the associated technologies to develop a mobile/transportable compact optical clock to replace the current RF standards. A transportable Sr lattice clock is already operational at PTB in Germany [100], whereas several other laboratories are developing such portable clock systems using different species; some such examples include Al-ion clocks in Germany [101], Sr lattice clocks in Italy [102], Germany [103], Japan [104], and the UK [105,106], Yb-ion clocks in France [107], Ca-ion clocks in China [108], Hg-ion clocks in the USA [109], and Yb-atom clocks in the USA [110]. A detailed review of the present status of transportable optical clocks and projected goals can be found elsewhere [111]. Some of the manufacturers of these in-house developed transportable clocks are now partnering with industries and other agencies to make them commercially available, which is mostly part of their national quantum missions since an accurate clock is one of the indispensable prerequisites for the working of multiple quantum-enabled technologies. For example, Germany's opticlock is one such effort that will be packaged within two standard 19-inch racks and is expected to be available soon [112]. Some other similar efforts are the iqClock from the European quantum flagship program [113], SLATE from the UK Quantum Technology Hub [114], and similar efforts from the USA.

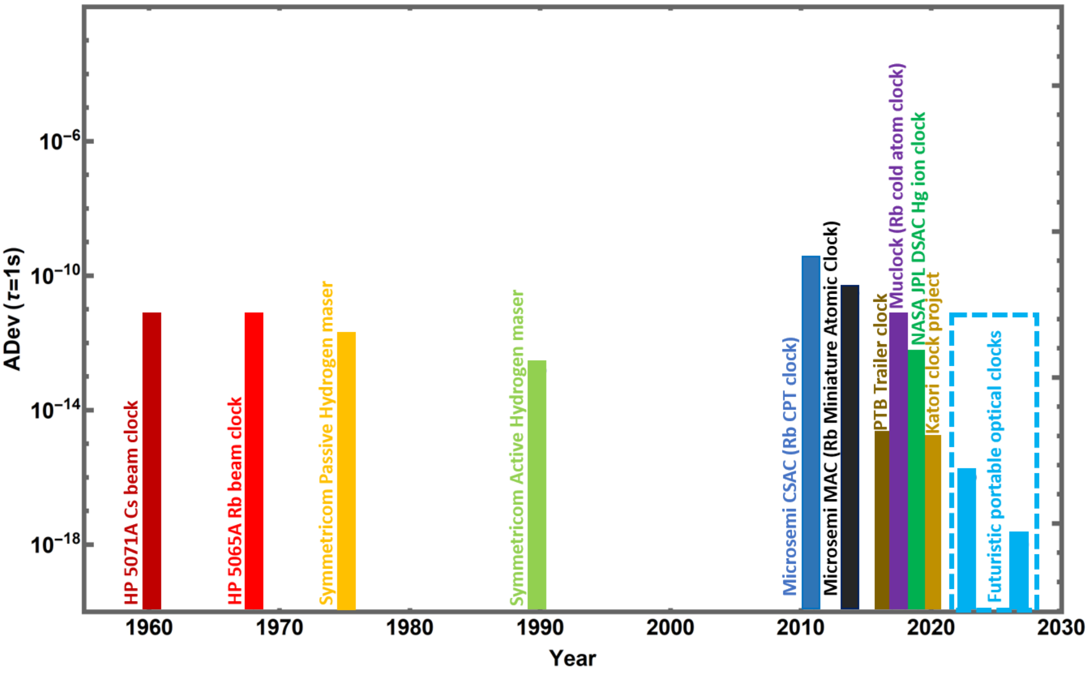

Figure 3. At a glance, Allan Deviations (ADevs) of the commercially available portable microwave and forthcoming optical atomic clocks indicate their performances. Colours were arbitrarily chosen only to distinguish the different types.

In summary, the international efforts on optical atomic clock technology focus on (i) the development of trapped-ion and optical lattice clocks with unprecedented accuracy, (ii) establishing national and global phase-stabilised optical fiber networks for connecting geographically distributed clocks, and (iii) the miniaturisation of the optical clocks in order to develop portable and compact systems for civilian and strategic applications.

3. National Scenario and Scope

In 2013, attempts at the indigenisation of optical atomic clocks were first initiated in India by NPL Delhi based on Yb-ion clocks, and in 2015, IISER-Pune started an ultracold Sr experiment with one of the aims being to develop a lattice clock using this experiment. IUCAA Pune and IIT Tirupati have recently started developing two new optical atomic clock experiments based on Yb and Ca ions, respectively. As described in the previous section, optical clocks have attracted immense interest over the last two decades for being identified as indispensable prerequisites for various quantum technologies, the forthcoming redefinition of the second, and timekeeping with unprecedented accuracy resources for ultrahigh-precision experiments for fundamental scientific tests. Thus, optical clocks (sometimes called quantum clocks) are part of the various quantum missions worldwide, including in India. Indian efforts to develop this critical technology shall certainly boost the various national quantum missions (especially the NM-QTA and the NM-ICPS) and related initiatives. This section gives a brief overview of all the ongoing efforts to develop optical clocks in India and draws a concrete roadmap to reaching global standards.

The ytterbium-ion clock is very promising for T&F metrology and exploring fundamental sciences due to the following reasons: (i) the International Committee for Weights and Measures (CIPM) has endorsed its highly forbidden 6s $^2S_{1/2}$ $|F = 0, m_F = 0>$–$4f^{13}6s^2\,^2F_{7/2}$ $|F = 3, m_F = 0>$ E3-transition at a 466.9 nm (≈642 THz) wavelength as one of the secondary frequency standards and it will be a potential candidate for future redefinition of the SI second, (ii) it has three first-order Zeeman insensitive clock transitions at the optical wavelengths, (iii) the required lasers for photoionisation, laser cooling, and exciting the clock transitions are available commercially off-the-shelf, (iv) the trapped Yb ion chemically reacts with residual H_2 and produces hydride which again photodissociates to Yb^+ which is retrapped in the presence of its near UV cooling laser at the wavelength 369.5 nm, (v) its $4f^{13}6s^2\,^2F_{7/2}$ state has the highest-known (theoretically calculated) sensitivity for measuring the possible breaking of fundamental symmetries and time-dependent changes in fundamental constants, and (vi) the Yb-ion clock is a unique platform as the intercomparison of its E3 and 6s $^2S_{1/2}$ $|F = 0>$–$4f^{14}5d\,^2D_{3/2}$ $|F = 2>$ E2-transitions offers a measurement of the temporal constancy of the fine-structure constant (α) in a single system. For these reasons, IUCAA Pune has started building an Yb-ion clock at its recently developed Precision & Quantum Measurement laboratory (PQM-lab is led by Subhadeep De: https://pqmlab.iucaa.in/, accessed on 5 April 2023), whose focus will be precision measurements to test hypotheses in science and contribute to the possible extensions of the standard model, and studying various aspects of quantum metrology in order to support quantum initiatives in the country. In contrast, NPL New Delhi is keen to develop an Yb-ion optical clock which, in the future, can be used as a reference standard for T&F (led by Subhasis Panja: https://www.nplindia.org/index.php/science-technology/indian-standard-time-metrology-division/time-and-frequency-metrology-section/, accessed on 5 April 2023). In order to pursue the Yb-ion experiment, NPL has already developed a handful of instruments, e.g., a first-generation end-cap-type Paul trap including its drivers [115–119], an oven to produce a nearly collimated Yb atomic beam [120], a novel technique for frequency-stabilising all the required lasers at different wavelengths using a single reference, a wide range of high-end electronics [121–125], a sophisticated imaging system to resolve particles at a submicron resolution [126], and others. IUCAA has started developing some state-of-the-art technologies, such as a precision ion trap (in collaboration with the team of Sadiq Rangwala at RRI, Bangalore), an ultrastable reference Fabry–Pérot cavity to produce a sub-Hz linewidth clock laser at the stability of a few parts in 10^{17} in 1 s (in collaboration with the team of Sandip Haldar at IIT Goa), and phase stabilisation of the optical fiber to implement TWFOTT. The latter examples are requisites for ion- and atom-based optical clocks, and their other interdisciplinary applications, upon the indigenisation of these key technologies, shall make India self-reliant in this field.

The calcium ion is advantageous as a species to build an accurate compact (portable) optical clock due to the availability of compact laser systems at the required wavelengths. Recently, it has captured significant attention due to its unique magic radiofrequency (RF) trap operation and subsequent demonstration as an accurate optical clock [63]. Keeping these developments in perspective, the Precision Measurement Laboratory established at IIT Tirupati (led by Arijit Sharma: https://sites.google.com/view/arijitsharma, accessed on 5 April 2023) has started developing a compact optical clock using $^{40}Ca^+$ and is currently engaged in developing various subsystems to fulfil its objectives. The ultimate goal of this initiative is to deliver a 19-inch rack-mounted robust turnkey optical clock system for mobile, remote, and industrial applications. Such a mobile clock shall allow Indian researchers to pursue quantum geodetic measurements and other high-accuracy timestamping applications such as those required by financial and stock markets and network service providers. In the long term, this compact system can further be modified to a portable space-qualified clock adequate for a payload, which shall uplift India's space mission in the future. Apart from the above program, Sharma's group is also leading the development of portable all-optical atomic clocks based on Rb (rubidium) vapour cells.

Strontium-atom optical lattice clock development is being pursued by the Atomic Physics and Quantum Optical Lab at IISER Pune (led by Umakant D. Rapol: http://www.iiserpune.ac.in/~umakant.rapol/, accessed on 5 April 2023*)*. This experiment developed several subsystems associated with the experimental setup and demonstrated the slowing of a Sr atomic beam coming out of a hot atomic oven [127] and the capture of the atoms into a magneto-optical trap [128]. The choice of developing a Sr atomic clock was motivated by fundamental science exploration by intercomparing it with the Yb-ion clock at the neighbouring institute, IUCAA Pune [129]. The Sr-atom and Yb-ion clocks are among the most lucrative combinations to probe α-variation, as the E3-clock transition of $^{171}\mathrm{Yb}^{+}$ has the highest sensitivity to α, whereas the hyperfine-induced clock transition of $^{88}\mathrm{Sr}$ is barely sensitive to it. For this reason, IUCAA and IISER Pune have put forward a proposal to establish a phase-stabilised optical fiber link between these two institutes, which are about 4 km apart from each other [129], to execute their scientific objectives. The joint effort between these two Pune-based institutes is a pilot project before the nationwide deployment of phase-stabilised fiber optic links, which is needed for ultrahigh-accuracy intercomparison via TWFOTT; T&F dissemination to specialised users such as ISRO, the armed forces, and so on; and various other sensitive and strategic applications in the optical domain.

The present national scenario towards the indigenisation of optical clocks and related technologies clearly shows significant voids in the areas of (i) lab-based optical clocks, (ii) optical clock networks, and (iii) portable optical clock developments, relative to their advancements in pioneering countries such as the USA, EU countries, Canada, Japan, and China (Table 1). Considering their enormous potential in quantum-enabled technologies and due to their broad strategic scope and applicability, with a possibility of sanctioning export control on some, if not all, of these critical technologies, India must champion the efforts for their indigenisation. Keeping this vision in perspective, in Figure 4, we provide a realistic 10-year roadmap, divided into three major work packages (WPs), so that India can become competitive at the international level. Over the next decade, we need to mainly focus on (i) developing ready-to-use "lab-based" optical clocks; (ii) establishing a pan-India optical clock network that connects NPL, IISER Pune, IUCAA, and IIT Tirupati, and possibly extend to ISRO and other timekeeping labs via TWFOTT; and (iii) developing ready-to-use compact out-of-the-lab optical clocks (mobile/transportable optical clocks). Detailed subsets under these three WPs and year-wise work plans associated with each of the WPs are given in Figure 3. The timescale associated with each stage was calculated based on development time starting from scratch, and the typical lead time needed to make the raw materials available despite various constraints in the country. Collaboration among the participating institutes and industry associations is necessary for the successful accomplishment of these works, and could even boost the projected timeline. The formation of a national consortium focussed on the development of optical clocks and related technology would be helpful for the execution and dissemination of the technology and the knowledge behind it in the future.

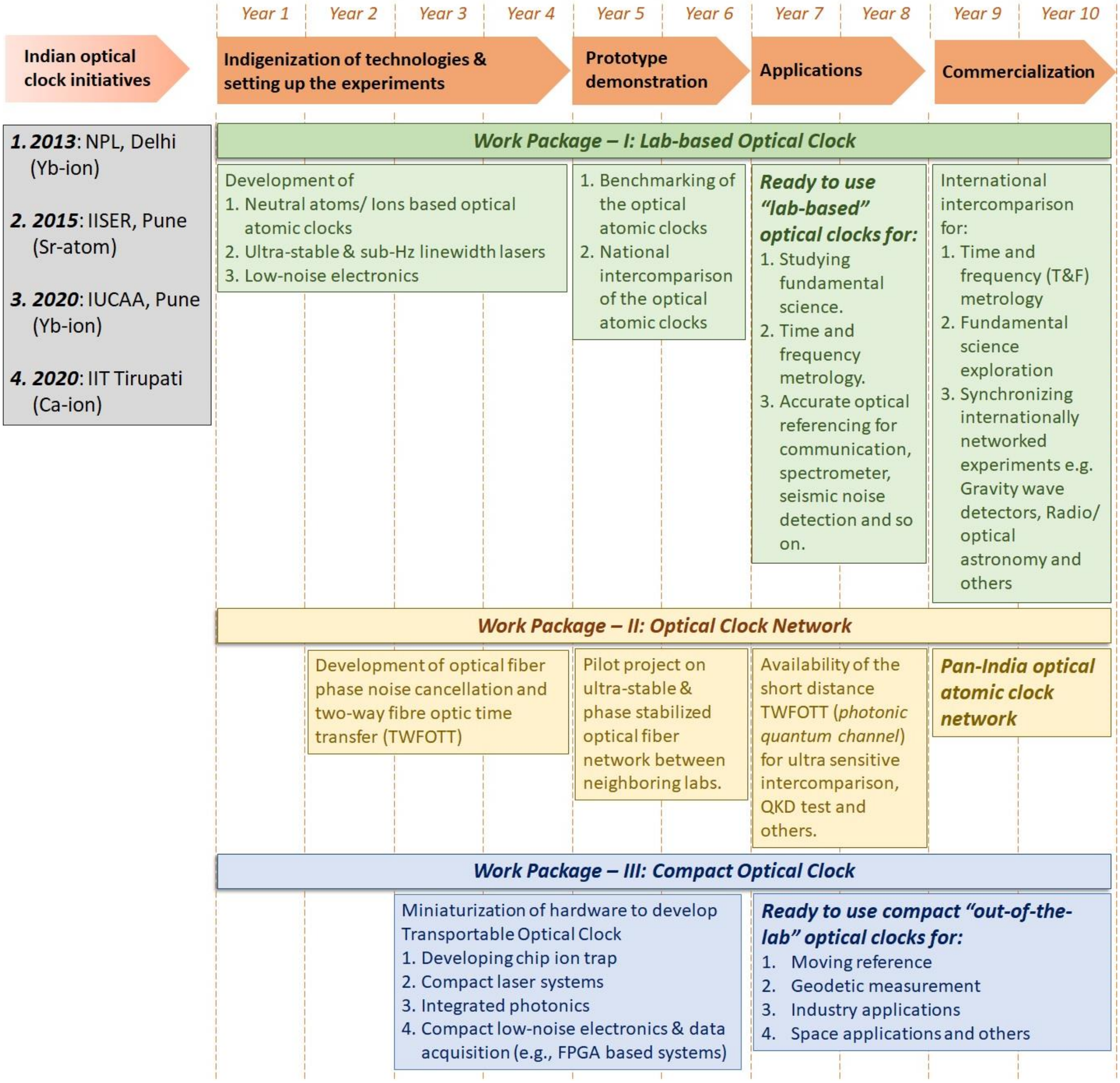

Figure 4. A proposed ten-year roadmap for indigenisation of optical clock technologies categorised into three distinct work packages: (**i**) lab-based optical clocks, (**ii**) optical clock networks, and (**iii**) compact optical clock developments.

4. Conclusions

Ultraprecise optical atomic clocks (sometimes referred to as quantum clocks) are identified as being among the indispensable pillars of the second quantum revolution (also known as quantum 2.0). Several countries have aptly recognised the importance of optical atomic clocks, and they have mandated developing such ultraprecise optical atomic clocks to establish and maintain their global leadership in time and frequency metrology and quantum technologies. A quantum clock is generally a part of the quantum sensing and quantum metrology aspects of the diverse quantum missions charted out by different nations. In India, the government has initiated the National Mission on Quantum Technology Applications (NM-QTA) for developing practical and useful applications of quantum technologies. Therefore, we need to focus on developing optical atomic clocks to make our own quantum missions successful. At present, NPL New Delhi, IISER Pune, IUCAA Pune, and IIT Tirupati are engaged in experimental programs to develop next-generation optical atomic clocks, and it is expected that more national initiatives shall arise in the near future, mainly for the development of nuclear or highly charged ion-based clocks, which will receive their impetus based upon the availability of adequate infrastructure and human resources within the country.

Optical clock initiatives by the aforementioned four Indian institutes have different technical and science motivations, e.g., maintaining the country's standard time, testing hypotheses of fundamental science, providing precision timings to the end users, and making valuable additions to quantum technologies by making India self-reliant. For those reasons, we are planning for (i) the development of ready-to-use "lab-based" optical clocks, (ii) the establishment of a pan-India optical clock network, and (iii) the building of mobile/transportable compact optical clocks. A network of optical clocks spread at various locations in the country, involving geographically distributed clocks with a phase-stabilised quantum link among them, is one of the primary requisites for fundamental science studies and testing quantum phenomena. Additionally, this phase-stabilised fiber optic network shall serve as a central test bed for quantum key distribution protocols and algorithms. In addition, the redefinition of the SI second based on optical transition(s) is likely to be enforced in international timekeeping standards in the near future. Keeping these developments and objectives in mind, there has been a global impetus to invest heavily in the relevant technologies and develop optical clocks based on atoms and ions.

Furthermore, China, Thailand, South Korea, and Australia are actively pursuing the development of optical atomic clock technology to maintain their global and regional supremacy in state-of-the-art precision metrology. Hence, India must make strong efforts to actively support, pursue, and sustain programs engaged in developing indigenous optical atomic clocks and related technologies to realise its global reputation as a growing leader in science and technology. To ensure that these national efforts progress in a suitable timebound manner, a prescribed roadmap has been outlined in this article, which shall be helpful for interorganisational collaboration, leading to the cross-fertilisation of ideas and the sharing of critical technology in various related aspects.

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