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Remote transfer of ultra-stable optical frequency reference using active cancellation of fiber induced phase noise

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Abstract

Comparison of ultra-stable frequency references located in geographically distributed areas require a transfer technique, which offers stability of 10^{-17} at 1 s over tens of kilometer. Such remote frequency transfer will allow comparing the optical frequency references of same or different atomic species (through a frequency comb bridge) for test of relativistic geodesy [1] or time variation of fundamental constants [2], and will contribute towards the database of frequency ratio measurements- an essential requirement for the re-definition of the SI second based on optical clocks [3]. It will also facilitate in creating an optical to microwave frequency link that can be used by various SI standards laboratory requiring stable microwave sources. In this paper, I discuss the modulated optical carrier wave based ultra-stable frequency reference transfer technique, and present a study of a laser interferometer based active fiber noise cancellation system and its applications.

1. Introduction

Over half a century, time and frequency have been decided by referencing the definition of the second based on the Cs atomic clocks operating at microwave frequency. But with recent advancement of optical atomic frequency standards which has been realized with 10^{-18} accuracy as well as stability [4] and are two orders of magnitude better compared to the present SI second definition, CIPM has recommended optical clocks to be adopted as the secondary representation of second. Such optical clocks are potential candidates for the re-definition of the SI second. A thorough road map has already been laid in the 23rd CCTF 2022 meeting to formally recognize optical frequency standard as the primary representation of the SI second by 2030 [3].

Optical clocks have demonstrated a quantum projection noise (QPN) limited stability of 10^{-16} $(\tau/s)^{-1/2}$ for an averaging time τ, by either operating two clocks synchronously [5] or by using stable clock lasers. Such a high clock stability can be used to monitor a temporal drift of the gravitational potential difference [1], time variation of fundamental constants like the fine structure constant α [2], long baseline radio telescope array [6].

The development of an optical clock requires time and resources, and multiple clocks based on different atomic species are typically built in different laboratories. A reliable transfer of a frequency reference is therefore critical for these comparisons. Development of optical frequency references itself will require optimum levels of stability for characterization. The laboratory based optical clocks are complex and are not always portable, so remote transfer of frequency references without introducing additional instability becomes an essential requirement. Also, comparison of optical frequency standard enables evaluation of their performance by measuring their relative instability and systematic bias, in the absence of other more stable frequency references.

Advancement in the development of ultra-stable and narrow linewidth laser using longer or cryogenic reference cavities has led to stabilities better than 10^{-16} at 1 s. Such lasers when used as clock oscillator for optical clocks results in better than QPN limited stability. Remote transfer of such stable frequencies require techniques which offers stabilities comparable or better than the frequency stability at the source.

Usually, the clock frequencies are routinely monitored globally using satellite based links, which guarantee the frequency measurements generated in distant laboratories and contribute towards the International Atomic time (TAI). There are two schemes- one scheme uses global navigation satellite system (GNSS) in common or all in view mode and can typically reach one part in 10^{14} over a day [7]. The second scheme uses frequency transfer using two- way satellite time and frequency transfer (TWSTFT) technique, giving stability few parts in 10^{15} over a day [8].

An alternative method for stable frequency reference distribution is transmission over optical fibers. The frequency reference, either optical or microwave is encoded onto an optical carrier for transmission over a fiber network. The end user at the remote site can recover the reference by decoding the modulated carrier signal. Optical fibers buried in earth can be considerably more stable than free space paths, especially over short time scales. They offer low loss and scalability, beneficial when designing a frequency distribution system.

One of the method of such optical fiber based frequency transfer is the direct transfer of optical frequency modulated carrier wave which will allow to reliably compare optical clocks with link stability from 10^{-15} to 10^{-17} at 1 s, limited by the time delay induced due to travel in the fiber [9,10]. A stability of $5x10^{-15}$ at 1 s has been achieved in Germany for a distance of 920 Km [11]. Recently two optical clocks in Tokyo separated by 30 Km, have been compared with a link stability of 10^{-17} at 1s [10].

In this paper, I will discuss the transfer of stable frequency references to remote places using optical fiber as the transmission channel. I will present a design of an active fiber noise cancellation system to compensate the phase noise accumulated over the length of the fiber.

2. Experimental Scheme

Direct transfer of optical frequency reference with a continuous wave (cw) laser

The technique for stable frequency transfer rely on the ability to detect and subsequently cancel the phase noise accumulated over the optical fiber. There are various sources of phase noise- both optical and electronic. The phase noise accumulated due to the fiber degrade the reference signal and hence needs to be compensated by giving a proper feedback. The transfer technique should employ a feedback loop with a large enough dynamic range to cancel the phase noise present in a typical fiber based network used in an urban environment.

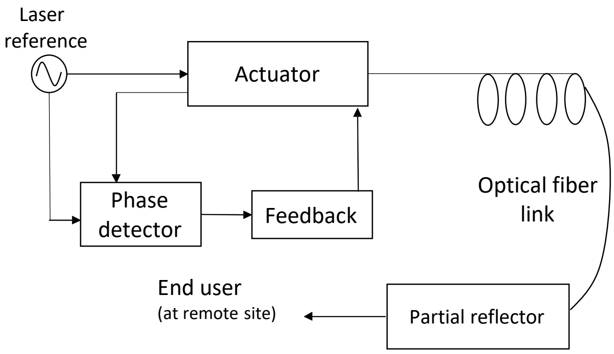

Figure 1. Operating principle of a typical actively compensated fiber network for distributing frequency and timing references.

Figure 1 shows the basic experimental scheme of active fiber-noise cancellation system. The ultra-stable frequency reference is a modulated cw optical carrier, in which the modulation frequency is the optical carrier frequency itself i.e, in 100's of THz range. In the optical clock experiments, this is the clock laser itself. The reference is to be transmitted to a remote end user using an optical fiber. At the remote end, a portion of the reference signal is reflected back and round trip signal phase is detected and compared with the reference signal using a phase detector at the reference end. A calibrated feedback based on the phase difference is then applied to an actuator for phase noise compensation.

The system works on the assumption that the feedback loop should have a bandwidth of $1/2\pi\ T_{\mathrm{rt}}$, and the coherence time of the reference should be greater than T_{rt}. T_{rt} is the round trip time delay. The main sources of fiber induced noise comes from mechanical and thermal perturbations to the optical length of the fiber.

Transfer of stable optical references to compare two optical clocks located at different locations

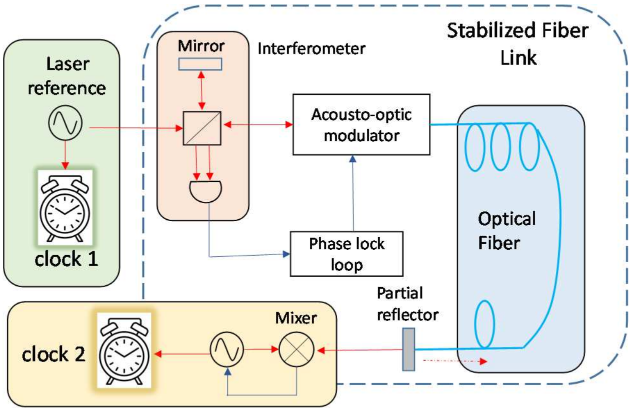

Figure 2. Comparison of two optical clocks located at different places using an interferometer based detection and AOM based actuation to actively cancel out the fiber induced noise. The red lines show optical path and the blue line shows the electrical path.

Figure 2 shows the details of such frequency transfer technique to compare two clocks at remote places. The phase detector is a laser interferometer, where a portion of the reference optical beam is used as the reference arm, while rest of the beam is frequency shifted by an acousto-optic modulator (AOM, actuator) and then transmitted through the fiber channel. Part of the transmitted light is reflected back (partial reflector) and then again channeled through an AOM and compared with the reference signal. An AOM has been used as actuator, because of its large dynamic range which can compensate large phase differences. At short distances, a stability of 10^{-17} at 1s can be achieved with this set-up [10].

Applications

Direct remote transfer of frequency find large number of applications. Some of them has been shown in Figure 3. Two clocks (clock 1 & clock 2) separated by a vertical height difference of Δh and connected by a stabilized optical fiber link, will have different rate of clock ticks. This is due to the gravitational shift of clocks operating at different heights. If we measure the clock frequency difference, it will be proportional to Δh, subject to precise information of the local acceleration due to gravity g. A common clock laser stabilized to a high finesse cavity maintained in vacuum and a temperature-controlled environment compare the clocks made of same species. The pre-stabilization to a cavity is necessary to achieve the required coherence time of the laser. The stability achieved for such a link depends on the time delay due to the fiber length. This will find applications in relativistic geodesy [1].

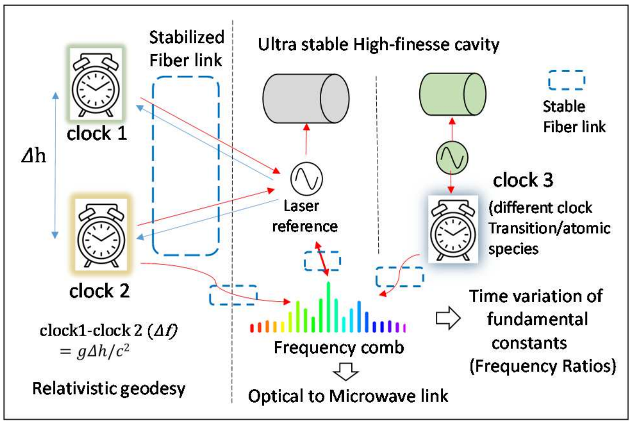

Figure 3. Various applications using remote transfer of stable laser reference. Two clocks at different height with a height difference Δh, will tick at different clock frequencies. A frequency comb stabilized to an ultra-stable reference laser cavity, can be used to measure the frequency ratio of optical clocks, consisting of different atomic species. The red line shows optical link and the blue ones the electrical link. The blue dashed box shows the stabilized fiber link.

Applications such as test of time variation of fundamental constants like the fine structure constant α depends on the comparison of two atomic clocks having different clock transitions/atomic species. If α were changing over time, the frequencies of the clock transitions based on different atomic systems would change with respect to each other [2]. The frequency link to connect two optical clocks made of different atomic species is usually realized using stabilized fiber combs [12]. Such fiber combs are stabilized using a laser generated from an ultra-stable cavity (See Figure 3).

The long baseline coherent radio telescope arrays requires frequency transfer with ultralow timing jitter (low phase noise at short time scales, approaching femtoseconds) for it to distribute a signal from a master oscillator to other telescopes in an array [6]. A low jitter component is important as it would enable all telescopes in the array to phase coherently add the signal data to emulate a single telescope with a large aperture.

Some measurements such as SI unit of standard length, phasor measurement unit in smart power grids, the next generation quantum pressure standard needs frequencies in the microwave domain. Stabilized fiber combs acts as a bridge between optical and microwave domain. Such combs when stabilized with laser which is disciplined with respect to an atomic clock can transfer the stability from optical domain to microwave domain [13].

Recently, frequency links created by using optical submarine cables lying on the ocean bed has been used as sensors to detect earthquake and tidal effects [14].

3. Conclusion

Remote transfer of modulated cw optical carrier to geographically distributed areas, offers various applications. I have discussed the operating principle of such transfer technique, a set-up for remote comparison of two optical clocks and various diverse applications possible with such setups.

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