New research trends on high-precision time transfer technology

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Abstract: High-precision time transfer plays an important role in the areas of fundamental research and applications. Accompanying with the remarkable improvements in the ability of generating and measuring high-accuracy time-frequency signal, seeking for new time-transfer techniques between distant clocks with much further improved accuracy attracts attentions world-widely. The time-transfer technique based on optical pulses has the highest precision presently, and the further improvement in the accuracy is heavily dependent on the time-domain properties of the pulse as well as the sensitivity of the applied measurement on the exchanged pulse. The application of optical frequency comb in time transfer for a precision up to femtosecond level are currently the focus of much interest, and has recently achieved many breakthroughs. Further investigations show that, utilizing quantum techniques, i.e. quantum measurement technique and quantum optical pulse source, can lead to a new limit on the measured timing information. Furthermore, it can be immune from atmospheric parameters, such as pressure, temperature, humidity and so on. Such quantum improvements on time-transfer have a bright prospect in the future applications requiring extremely high-accuracy timing and ranging. The potential achievements will form a technical basis for the future realization of sub-femtosecond time transfer system.

Keywords: High-precision time transfer; quantum improvement; pulse shaping; quantum frequency comb.

1 Introduction

Time is a fundamental physical quantity which characterizes the motion of matter. It provides an essential time base coordinate for all dynamical systems and measurements of timing processes. The measurement precision of time and frequency is five to six orders of magnitude higher than that of all the other fundamental physical quantities, and the measurement precision of those quantities can be improved indirectly through the measurement of time and frequency. Therefore, high-precision time and frequency has become a critical parameter representing the development levels of various areas of a nation ranging from science and technology, economic, military to social life, influencing the security and stability of a country.

Accompanying with the remarkable improvements in the ability of generating and measuring high-accuracy time-frequency signal[1-3], the application of high-precision time and frequency is playing an increasingly important role in areas of fundamental physics (e.g., tests of fundamental physical constants[4-7], general relativity verification[8-10], dark matter searching[11]), and many other areas of highly advanced technology and engineering infrastructure (such as long-baseline interferometry for radio astronomy[12], accelerator-based x-ray sources[13-16], mapping of the Earth's geoid[17], deep space exploration[18-20], precise distance ranging and timing[21-23], etc).

The breakthrough in all these applications will benefit from the capability of high-stability time and frequency transfer, therefore attempts to significantly improve the conventional time and frequency transfer accuracy and stability become a crucial subject. Accurate time transfer between two geographically distant sites is currently dominated by satellite-based navigation systems. A traditional method for transferring frequency and time standards over long distances has been the common-view global positioning system (GPS)[24]. By averaging for about a day it is possible to reach accuracies of one part in 1E-14[25]. Subsequently, the two way satellite time and frequency transfer (TWSTFT)[26-28] has pushed the frequency transfer instability to the low parts in E-15 in 1 day. With a much higher frequency and bandwidth of laser pulses than radio radiations, the time transfer by laser link (T2L2) was proposed and recently shown an synchronization accuracy of tens of picoseconds[29-30], which corresponds to a frequency stability of E-16 in 1 day. However, these techniques are far from enough to satisfy the growing requirement for comparison of the new generation of high-precision atomic clocks. An alternative for stable transferring of the time and frequency signal is transmission over optical fibers since an environmentally isolated fiber can be considerably more stable than free space paths. Currently, multiple research teams are oriented at ultrastable frequency transfer through optical fibers[31-34], and a frequency instability of 10^{20} after 10^3s averaging time has been demonstrated[34]. However, time scale comparisons are always necessary, therefore methods on time transfer through optical fibers (TTTOF) are also under investigation[35-42]. Among all the achieved results, a timing stability of the time transfer over 158 km long optical link with minimum value of 300 fs in terms of time deviation (TDEV) at averaging time of 10 s has been presented[37]. Moreover, it has been demonstrated that the long-term time transfer stability is less sensitive to the fiber length than the method accuracy[42].

The precision of the above time transfer measurement is classically limited by the available power and bandwidth[43]. To overcome the classical standard quantum limit (SQL), quantum clock synchronization (QCS) was proposed. By utilizing the nonclassical and nonlocal characteristics of quantum entangled and squeezing resources, QCS can result in enhanced accuracy compared with their classical analogues. By employing frequency entangled and squeezed pulses, it can break through the shot noise limit on the classical timing system, and finally reaches the fundamental Heisenberg limit. On the other hand, with the rapid development of optical frequency comb[44], using optical frequency comb and phase measurement technique for time transfer has revolutionarily improved the transfer accuracy into the femtosecond scale[22-23,45-46]. Utilizing the special property of the mode-locked femtosecond lasers, a new quantum-improved scheme is proposed[47] that lead to a new SQL in time transfer by combining homodyne detection, potentially reaching the yoctosecond range. Benefitting from the large number of photons and from the optimal choice of both the detection strategy and of the quantum resource, the proposed scheme represents a significant potential improvement in space-time positioning.

In addition, by shaping temporally the local oscillator in the homodyne detection scheme, the timing accuracy can be immune from environmental fluctuations such as pressure, temperature, humidity and other changes in dispersion[48]. Given its unique advantages in high transfer accuracy, to carry out quantum optimized pulse time transfer research has great prospects.

2 Review on research progress of high-precision long-distance time transfer

According to Einstein´s theory of timesynchronization[49], accurate time transfer between two observers A and B is dependent on measuring the arrival times of the incoming light pulses, which consists in repeatedly exchanging light pulses. The generic scheme of a one way time transfer is shown in Fig. 1. Observer A regularly emits light pulses at a rate synchronized to its local clock; B receives these pulses and determines their times of arrival by measuring the difference between the arrival times of the incoming light pulses and light pulses delivered by a source located in B and synchronized to a reference clock in B consider that the precision of the clocks in A and B is ideal, the accuracy of this measurement relies the sensitivity of the determination of the delay between two light pulses.

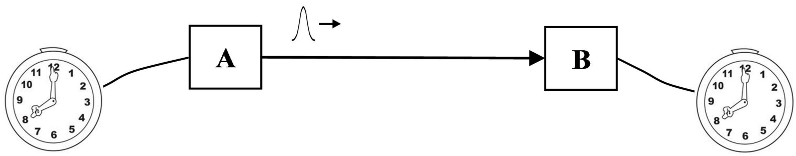

Fig. 1 General scheme of a one way time transfer

The conventional method is performed by measuring the arrival time of the maximum of the pulse envelope, which is called incoherent time of flight (TOF) measurement. Given a gaussian pulse of frequency spread $\Delta\omega$, then, according to the central limit theorem, the travel time of the pulses cannot be measured with an accuracy better than the classical shot noise limit[43]:

$$(\Delta u)^{tof} \geq (\Delta u)^{tof}_{SQL} = \frac{1}{2\Delta\omega\sqrt{N}} \cdot \quad (1)$$

Where N is the total number of photons measured in the experiment during the detection time. Due to the bandwidth limit of the photodetectors available today, the TOF measurement accuracy is in the picosecond range at best. By timing femtosecond pulses through phase-locking control of the pulse repetition rate using the optical cross-correlation technique that exploits a second-harmonic birefringence crystal and a balance photodetector, the time-of-flight precision was improved to the nanometer regime[50].

In quantum theory, the limit of time measuring accuracy comes from the quantum nature of light[51]. In order to break through the shot noise limit on the timing accuracy, researchers have proposed quantum time synchronization[43]: under ideal photon number squeezing and coincident-frequency entanglement conditions, the measurement accuracy of signal pulse travel delay will reach the fundamental limit set by natural physical principles —the Heisenberg limit.

$$(\Delta u)^{tof}_{QM} = \frac{1}{2\Delta\omega MN} \cdot \quad (2)$$

where M is the number of frequency entangled pulse. Currently, frequency entangled source with $M = 2$ generated by spontaneous parametric down conversion is the main light source of quantum time synchronization application[52-54]. In addition, quantum time synchronization protocols based on frequency entanglement have been shown capable of eliminating the dispersion effect on the achievable accuracy in transmission path[55-57]. Therefore, quantum time synchronization became widely studied.

The second method consists in the determination of the phase shift on a signal after traversing a given distance. This method will be referred to as a coherent phase (PH) measurement. For instance, the widely used continuous-wave (c.w.) laser interferometer measures the phase of optical wavelengths to achieve sub-nanometre resolution[58-60]. Suffering from quantum limits associated with the quantum nature of light, the measurement accuracy will be close to the corresponding shot noise limit[43]:

$$(\Delta u)^{ph} \geq (\Delta u)^{ph}_{SQL} = \frac{1}{2\omega_0\sqrt{N}} \cdot \quad (3)$$

Where ω_0 is the center frequency of the pulse. However, such measurements are limited to relative range changes as the ambiguity range equals half the laser wavelength. Therefore, multi wavelength interferometry (MWI), which combines measurements at several optical wavelengths to effectively generate a longer "synthetic wavelength", was applied to acquire a reasonable ambiguity range while maintaining sub-wavelength resolution. These systems are vulnerable to systematic errors from spurious reflections, and extending the ambiguity range beyond a millimeter can require slow scanning.

Femtosecond optical frequency combs offer an intriguing solution by combining the pulsed nature with the coherence of the carrier. Using two coherent frequency comb sources, a coherent laser ranging system was successfully implemented at NIST that combines the advantages of time-of-flight and interferometric approaches to provide absolute distance measurement and achieve a nanometer level of precision with an ambiguity range of 1.5 m and high immunity to spurious reflections [22]. Furthermore, optical time-frequency transfer over free space via two-way exchange between coherent frequency combs was demonstrated, which achieved 1 fs timing deviation across the 2 km link. With the development of phase-locking technology of optical frequency comb [23], the measurement precision is getting closer and closer to these quantum limits given by Eqn. (3).

In order to further reduce the limit of the measurement precision, Fabre's group proposed a new scheme combining homodyne detection and mode-locked femtosecond lasers that lead to a new SQL in time transfer, which is referred as the quantum improved measurement of time transfer [47]. The proposed scheme is shown in Fig. 2. According to the proposal, the pulses synchronized on the clock in A are measured in B by homodyne detection with the local oscillator pulses synchronized on the local clock.

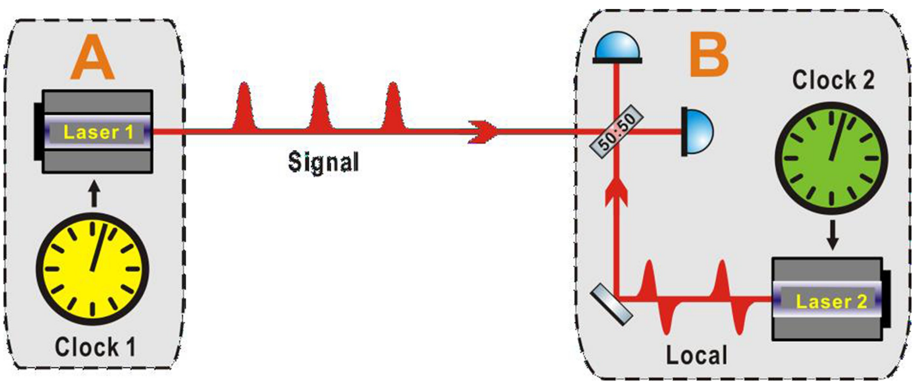

Fig. 2 Proposed balanced homodyne scheme to reach optimal detection in ranging measurement [47]

The key ingredient is the use of a mode-locked laser as a precise source for multi-wavelength interferometry in a homodyne detection scheme. Through balanced homodyne detection techniques and appropriate shaping of the local oscillator source in an adequate temporal mode, both the phase and time of flight information can be extracted simultaneously. The shot noise limit of time delay precision is expressed as:

$$(\Delta u)_{SQL} = \frac{1}{2\sqrt{\omega_0^2 + \Delta\omega^2}\sqrt{N}} \tag{4}$$

As can be seen, such scheme can lead to a new SQL in time transfer, potentially reaching the yoctosecond range (10^{-21}-10^{-24} s). Moreover, if squeezing of the input field modes is achieved, a new minimum precision of the measurable delay will be given[47].

$$(\Delta u)_{Sqz} = \frac{1}{2\sqrt{\omega_0^2 + \Delta\omega^2}\sqrt{N}} e^{-r} < (\Delta u)_{SQL}. \tag{5}$$

Where r represents the squeezing parameter of the incoming pulse. The already very low SQL given in Eqn. (4) can be even overcome using appropriately multimode squeezed light. Further study showed that, by shaping temporally the local oscillator, one can directly access the desired delay information without affected by the fluctuations induced by the environment [48].

Benefitting from the large number of photons and from the optimal choice of both the detection strategy and of the quantum resource, the proposed scheme represents a significant potential improvement in time transfer. The application of this quantum improved time transfer method in real system is still challenging, and the research attentions should be focused on the development of the key techniques, such as the efficient generation of quantum frequency comb, the adequate time shaping the local oscillator pulse, and suppression of phase noise in an optical frequency comb at the quantum limit to improve timing measurements.

3 Review on key techniques in quantum improved time transfer method

The application of this quantum improved time transfer method in real system is still challenging, and intensive research attentions can be classified into 3 main aspects of key techniques development, i.e., adequate time shaping the local oscillator pulse, efficient generation of quantum frequency comb, and phase noise suppression in an optical frequency comb at the quantum limit to improve timing measurements.

3.1 Progress on accurate pulse shaping of the local oscillator optical frequency combs

A great deal of scientific studies indicates that, for an ultrashort pulse with given phase and amplitude, accurate pulse shaping can be achieved through the phase and amplitude modulations of its spectrum. By employing the liquid crystal spatial light modulator (SLM) to a 4-f Fourier-transform configuration, a programmable pulse shaping technique was firstly proposed by Weiner et al.[61], and widely applied to varieties of precise pulse shaping [62-65]. However, due to the presence of space time conversion effect [66], the visibility of the optimum mode is decreased, and so does the relevant sensitivity. Verluise et al. experimentally accomplished the phase and amplitude reshapes of an ultrashort pulse by use of an acousto-optic programmable dispersive filter (AOPDF)[67], in which the original optical pulses pass through the acousto-optic crystal directly, without sophisticated 4-f structure. Because of the high dynamic range of the AOPDF, this method was thus extensively concerned. Based on the AOPDF, Ohno et al. demonstrated an adaptive control of both spectral phase and amplitude of pulses in experiment[68], where two-dimensional patterns obtained from frequency-resolved optical gating (FROG) were used for calculating cost functions in an adaptive control algorithm. Since the FROG measurement described the whole phase and amplitude profiles of the ultrashort pulse, there was no need of the pulse shape reconstruction during the control of pulse shape. Furthermore, Sato et al. performed arbitrary shaped ultrashort pulses by delivering through a single-mode optical fiber [69]. They numerically verified that, through the control of the input pulse spectrum to compensate the group delay dispersion and self-phase modulation, various desired time differential to the pulses could be acquired at the fiber output. Such method is the so-called all-optical pulse shaping protocol. In spite of a relatively low input peak power, it has been widely utilized in Ref. [70-72]. Recently Labroille et al. proposed a new all-optical time-space mode matching technique [73]. Base on a Babinet-Soleil-Bravais (BSB) compensator, the 1^{st} order time differentiation of both the pulse field and pulse envelop were fulfilled. When the pulse envelops of two optical frequency combs are approximately Fourier-transform limited, the required pulse shapes in Eqn. (1.3) could be generated using this method. Owing to the advantages of compact configuration, this method is free from the time-space conversion effect and has no need on active control, therefore is an ideal setup for 1^{st} order pulse shaping. In order to investigate the impact of the group velocity dispersion to the time delay measurement during the transmitting path, it is necessary for us to study the realization of the 2^{nd} order time differential to the local pulses.

3.2 Review on the generation of quantum light and quantum frequency comb

The optical parametric oscillator (OPO) based on the second order nonlinear effect is one of the most common methods to produce continuous variablenon classical light source with squeezing[74] and entanglement [75] characteristics. Due to the superiority of the nonclassical light in highly sensitive quantum measurement and quantum information applications, efforts have been made to optimize the parametric down conversion in order to obtain a greater degree of squeezing and entanglement, such as utilizing strong pump powers or optical resonant cavity to improve the nonlinear conversion efficiency. As we know, parametric down conversion is a transient process, nonlinear effect is proportional to the instantaneous power of the pump light and thus a mode-locked femtosecond pulse laser is best for pumping the parametric process. Furthermore, due to the short interaction time between the femtosecond pulse and the nonlinear crystal, the thermal damage to the crystal have been greatly reduced under high power condition. So far, a squeezing of as low as -6.8dB [76] has been obtained by using femtosecond pulse laser through single pass of a third-order nonlinear medium, such as the fiber. However, because of the inherent Rayleigh scattering and Brillouin scattering effect in the fiber, the coherence of the output light is destroyed. Employing a femtosecond pulse through a second-order nonlinear crystal is also used to produce the high performance squeezing light[77]. To obtain the ideal squeezing light, the pump peak power is supposed to be infinite. To increase the peak power, the Q modulation and the optical amplification method[78] are adopted at the expense of the loss of the coherence properties between the pump pulses. In addition, due to the influence of the spatial distribution deformation of the signal light produced in this process, the squeezing degree can be obtained is -6 dB. In order to break through the limit, the resonant cavity or waveguide is proposed[79]. The perfect quantum properties can be produced by using the high finesse resonant cavity under the finite pump power. To date, an amplitude squeezing up to -12dB[80] has been obtained by using continuous laser to pump an optical parametric down conversion crystal in a resonant cavity with high finesse. Therefore, in the experiments of producing quantum light source based on parametric down conversion, it is extremely attractive to combine the advantages of high peak power and resonant cavity. Such device is the so-called synchronously pumped optical parametric oscillator (SPOPO), in which the round-trip time of the pump or (and) signal should be coincident with the repetition cycle of the femtosecond optical pulse pump to ensure the coherent superposition of multi pump pulses' parametric effects and reduce the threshold output power. This SPOPO has been widely used to generate tunable ultrashort pulse light sources[81-83]. And their time domain characteristics are also analyzed deeply [84-86]. However, the theory of generating ultrashort pulse source based on SPOPO has not been proposed until 2006[87].

According to the theory, the generated quantum frequency comb based on the SPOPO can obtain a squeezing degree up to -25 dB [88], which therefore can reduce the measurement limit of Eqn. (1.3) by 2 orders of magnitude. The first experiment to generate the quantum frequency comb based on SPOPO technology was implemented in 2012 and an amplitude squeezing of -1.2 dB was reported[89]. Later on a similar experiment was carried out in Shanxi University, which reported a quadrature phase squeezing of -2.6 dB[90]. Though there is a large gap between the experiments and the theory, profound experiments will soon achieve breakthrough in improving the squeezing degree.

3.3 Research progress of CEO phase noise suppression technologies

It has been shown that the sensitivity of a highly sensitive homodyne timing measurement scheme with femtosecond lasers is limited by carrier-envelope-offset (CEO) phase noise[43]. Therefore, the CEO phase locking and noise suppression is one of the key technologies in quantum-improved time synchronization. The CEO phase locking technology, one of the key technologies of obtaining optical frequency combs (OFC), has been widely concerned from the beginning of the 20^{th} century when the OFC appeared, and thus become a critical piece of the Nobel Prize in physics 2005. The phase locking technique has been advanced from the initial use of direct coherent pulse detection [91] to the lately method based on measuring the phase shift induced by frequency drift [92]. While the control system has been evolved from feed-backward[92] to feed-forward technology[93]. Accompanying with the improvement of the CEO phase locking precision, the noise suppression capability becomes higher and higher. The most advanced feed-forward control technology ever reported used an acousto-optic frequency shifter (AOFS) placed in a femtosecond laser output to correct the CEO frequency in real-time. Compared with the feed-backward control technique which changes the CEO frequency by controlling the pump power of the femtosecond laser, the feed-forward control technology has a better performance in phase noise suppression as it can eliminate the effect of amplitude-phase noise conversion. With the feed-forward control technology, the residual timing jitter can be suppressed as low as 12-attoseconds, which is nearly an order of magnitude higher than the usual feed-backward control technique. But the disadvantage of feed-forward control technology is that the controllable range of frequency drift is small. Moreover, there will be small changes in beam direction. So this project will combine these two feedback technologies to optimize CEO phase locking thus obtain lower phase noise and sustained for a long time. For such CEO phase stabilized femtosecond optical pulses, a broadband passive optical cavity system in low vacuum was proposed and demonstrated to further filter the residual CEO phase noise to the shot noise limit[94].

In conclusion, although quantum optimized time synchronization based on OFC is a new concept in recent years and have a certain distance from application, but international researchers have made a deep study in the key technologies and have a breakthrough. In China, the research of QCS is still at the primary stage, Shanxi University, Institute of physics, Chinese Academy of Sciences have made prominent progress in the generation of quantum OFC and CEO phase locking respectively. However, there is no report about the work of quantum optimized time synchronization based on OFC in China. According to the strategic needs of the country and the research orientation, National Time Service Center, Chinese Academy of Sciences set quantum time synchronization as one of the important research contents of “135” science and technology planning and has taken the lead in establishing quantum time synchronization laboratory in 2011. The laboratory began to carry out the research of quantum optimized time synchronization based on femtosecond optical pulses in 2014. At present, progress has been made in the generation of quantum OFC and CEO phase noise suppression of optical pulse.

4 Conclusion

Accompanying with the remarkable improvements in the ability of generating and measuring high-accuracy time-frequency signal, researches on highly advanced time transfer techniques between distant clocks with much further improved accuracy have attracted widespread attentions. Though the time-transfer technique (e.g., T2L2) based on optical pulses has the highest precision presently, it cannot satisfy the time scale comparison requirement between two optical lattice clocks for fundamental physics law verification. The application of optical frequency comb in time transfer for is currently of much interest as it can achieve a precision up to femtosecond level. However, further breakthrough needs exploiting new ideas. Quantum improved time transfer was then proposed, utilizing quantum measurement technique and quantum optical pulse source, that can lead to a new SQL in time transfer, potentially reaching the yoctosecond range. Benefitting from the large number of photons and from the optimal choice of both the detection strategy and of the quantum resource, the proposed scheme represents a significant potential improvement in space-time positioning. Furthermore, such method can be immune from atmospheric influences. Such quantum improvements on time-transfer have a bright prospect in the future applications requiring extremely high-accuracy timing and ranging. The potential achievements will form a technical basis for the future realization of sub-femtosecond time transfer system.

Although the quantum improved time transfer based on OFC is a new concept in recent years and is still under investigated in laboratory, international researchers have numerous studies on the key technologies. In China, the research of quantum time transfer is still at the primary stage, and there is not yet report on the work of quantum improved time transfer based on OFC. However, many institutes, such as Shanxi University, Institute of physics (IOP, CAS), National Time Service Center (NTSC, CAS), have made lots of efforts in realization of individual aspects of key technologies, such as, generating quantum optical frequency comb and locking the CEO phase. Oriented by the strategic needs of the nation and the research direction, NTSC have set quantum time synchronization as one of the important research contents of "135" science and technology planning and has taken the lead in establishing quantum time synchronization laboratory in 2011. Since 2014, NTSC started the research of quantum improved time synchronization, and interim progress have been achieved in the generation of quantum OFC and CEO phase noise suppression of optical pulse.

References

[1] Bloom B J, Nicholson T L, Williams J R, et al. An optical lattice clock with accuracy and stability at the 10(-18) level[J]. Nature, 2014, 506(7486):71-5.

[2] Huntemann N, Okhapkin M, Lipphardt B, et al. High-accuracy optical clock based on the octupole transition in 171Yb [J]. Physical Review Letters, 2011, 108(9):186-191.

[3] Hinkley N, Sherman J A, Phillips N B, et al. An atomic clock with 10(-18) instability[J]. Science, 2013, 341(6151):1215-8.

[4] Peik E, Lipphardt B, Schnatz H, et al. Limit on the present temporal variation of the fine structure constant[C]. AIP Conference Proceedings. 2004:103-111.

[5] Fischer M, Kolachevsky N, Zimmermann M, et al. New limits on the drift of fundamental constants from laboratory measurements[J]. Physical Review Letters, 2004, 92(23):1773-1787.

[6] Fortier T M, Ashby N, Bergquist J C, et al. Precision atomic spectroscopy for improved limits on variation of the fine structure constant and local position invariance[J]. Physical Review Letters, 2007, 98(7):663 - 665.

[7] Lea S N. Limits to time variation of fundamental constants from comparisons of atomic frequency standards[J]. European Physical Journal Special Topics, 2008, 163(1):37-53.

[8] Holger M, Paul L S, Michael E T, et al. Tests of relativity by complementary rotating Michelson-Morley experiments[J]. Physical Review Letters, 2007, 99(5).

[9] CHOU C W, Hume D B, Rosenband T and Wineland, D J. Optical clocks and relativity[J]. Science, 2010(329): 1630-1633.

[10] Reynaud S, Satomon C. and Wolf, P. Testing general relativity with atomic clocks. Space Sci. Rev. 148, 233-247 (2009).

[11] Derevianko A, Pospelov M. Hunting for topological dark matter with atomic clocks[J]. Nature Physics, 2013, 10(12):933-936.

[12] Shillue B, Al Banna S and D'Addario L. Transmission of low phase noise, low phase drift millimeter-wavelength references by a stabilized fiber distribution system[J]. Proc. IEEE Int. Top. Meet. Microw. Photon. (MWP) 2004 IEEE, Ogunquit, Maine, U.S., 4-6 October 2004:201−204.

[13] Gnida M. SPEAR-heading X-ray Science for 40 Years[J/OL]. July 8, 2013, https://www6.slac.stanford.edu/news/2013-07-08-SPEAR-40.aspx

[14] Schoenlein R W, Shank C V. Femtosecond X-ray Pulses at 0.4 Å Generated by 90° Thomson Scattering: A Tool for Probing the Structural Dynamics of Materials[J]. Science, 1996, 274(5285):236-238.

[15] Decamp M F, Reis D A, Bucksbaum P h, et al. Coherent control of pulsed X-ray beams[J]. Nature, 2001,

413(6858):825-8.
[16] Cavalieri A L, Fritz D M, Lee S H, et al. Clocking femtosecond X rays [J]. Physical Review Letters, 2005, 94(11).
[17] Bondarescu R, Bondarescu M, Hetényi G, et al. Geophysical applicability of atomic clocks: direct continental geoid mapping[J]. Geophysical Journal International, 2012, 191(1):78-82.
[18] Krisher T P, Maleki L, Lutes G F, et al. Test of the isotropy of the one-way speed of light using hydrogen-maser frequency standards. [J]. Physical Review D Particles & Fields, 1990, 42(2):731-734.
[19] Calhoun M, Sydnor R and Diener W A. Stabilized 100-Megahertz and 1-Gigahertz reference frequency distribution for cassini radio science[J]. Interplanetary Network Progress Rep.2002(148):1-11.
[20] Calhoun M, Huang S, Tjoelker R L. Stable Photonic Links for Frequency and Time Transfer in the Deep-Space Network and Antenna Arrays[J]. Proceedings of the IEEE, 2007, 95(10):1931-1946.
[21] JUN Y. Absolute measurement of a long, arbitrary distance to less than an optical fringe[J]. Optics Letters, 2004, 29(10):1153-5.
[22] Coddington I, Swann W C, Nenadovic L, et al. Rapid and precise absolute distance measurements at long range[J]. Nature Photonics, 2009, 3(6):351-356.
[23] Giorgetta F R. Optical two-way time and frequency transfer over free space[J]. Nature Photon, 2013(7): 434-438.
[24] Levine J. Introduction to time and frequency-metrology[J]. Review of Scientific Instruments, 1999, 70(6):2567-2596.
[25] Lee S W, Schutz B E, Lee C B, et al. A study on the Common-View and All-in-View GPS time transfer using carrier-phase measurements [J]. Metrologia, 2008, 45(2):156-167.
[26] Kirchner D. Two-way satellite time and frequency transfer (TWSTFT): principle, implementation, and current performance [M]. Review of Radio Sciences 1996-1999 Oxford: Oxford University Press, 1999: 27-44 (1999).
[27] Hanson D W. Fundamentals of two-way time transfers by satellite [C]. Frequency Control, 1989., Proceedings of the 43rd Annual Symposium on. IEEE, 1989: 174-178.
[28] Bauch A. Results of the 2008 TWSTFT calibration of seven European stations [C]. Proc. of EFTF-IFCS 2009 IEEE, Besancon, France, April 2009: 1209-1215.
[29] Guillemot P, Samain E, Vrancken P. Time transfer by laser link-T2L2: An Opportunity to Calibrate RF Links[J]. Proceedings of Annual Precise Time & Time Interval Systems & Applications Meeting, 2008.
[30] Myrtille L B, Clément C, Etienne S, et al. Accuracy validation of T2L2 time transfer in co-location. [J]. IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control, 2015, 62(2):255-265.
[31] Lopez O, Amyklein A, Daussy C, et al. 86-km optical link with a resolution of 2×10^{-18} for RF frequency transfer [J]. European Physical Journal D, 2008, 48(1):35-41.
[32] Giuseppe M, Radan S, Margolis H S, et al. High-resolution microwave frequency transfer over an 86-km-long optical fiber network using a mode-locked laser [J]. Optics Letters, 2011, 36(36):511-3.
[33] Predehl K, Schnatz H. A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place[J]. Science, 2012, 336(6080):441-4.
[34] Olivier L, Adil H, Fabien K, et al. Cascaded multiplexed optical link on a telecommunication network for frequency dissemination. [J]. Proceedings of SPIE - The International Society for Optical Engineering, 2015, 9378(16):16849-16857.
[35] WANG B, GAO C, CHEN W L, et al. Precise and continuous time and frequency synchronisation at the 5×10^{-19} accuracy level. [J]. Scientific Reports, 2012, 2(2):556.
[36] Lopez O, Kanj A, Pottie P E, et al. Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network[C]. European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC), 2013 Joint. IEEE, 2013: 474-476.
[37] Lessing M, Margolis H S, Brown C T A, et al. Simultaneous time and frequency transfer over a 158-km-long fiber network using a mode-locked laser[C]. Lasers and Electro-Optics. IEEE, 2015.
[38] Ebenhag S C, Hedekvist P O, Jarlemark P, et al. Measurements and Error Sources in Time Transfer Using Asynchronous Fiber Network[J]. IEEE Transactions on Instrumentation & Measurement, 2010, 59(7):1918-1924.

[39] Ebenhag S C. Time transfer over a 560 km fiber link[C]. Proc. 22nd EFTF, 22-25 Apr. 2008, Toulouse, France.

[40] Piester D, Rost M, Fujieda M, et al. Remote atomic clock synchronization via satellites and optical fibers[J]. Advances in Radio Science, 2011(9):1-7.

[41] Rost M, Piester D, Yang W, et al. Time transfer through optical fibers over a distance of 73 km with an uncertainty below 100 ps [J]. Metrologia, 2012, 49(6):772-778.

[42] Smotlacha V, Kuna A, Mache W. Time transfer using fiber links[C]. EFTF-2010 24th European Frequency and Time Forum. 2010:1-8.

[43] Giovannetti V, Lloyd S, Maccone L. Quantum-enhanced positioning and clock synchronization.[J]. Nature, 2001, 412(6845):417-9.

[44] Hall J L. Nobel Lecture: Defining and measuring opticalfrequencies[J]. Review of Modern Physics, 2006, 78(4):1279-1295.

[45] Kim J, Cox J A, Chen J, et al. Drift-free femtosecond timing synchronization of remote optical and microwavesources[J]. Nature Photonics, 2008, 2(12): 733-736.

[46] Lee J, Kim Y J, Lee K, et al. Time-of-flight measurement with femtosecond lightpulses[J]. Nature Photonics, 2010, 4(10):716-720.

[47] Brahim, Lamine, Claude, Fabre, Nicolas, Treps. Quantum improvement of time transfer between remote clocks[J]. Physical Review Letters, 2008, 101(12).

[48] PU J, Olivier P, Claude F, et al. Real-time displacement measurement immune from atmospheric parameters using optical frequency combs.[J]. Optics Express, 2012, 20(24):27133-27146.

[49] Einstein A. The Collected Papers of Albert Einstein, Volume 3: The Swiss Years: Writings, 1909-1911[J]. Princeton University Press, 1994.

[50] Kim J, Chen J, Zhang Z, et al. Long-term femtosecond timing link stabilization using a single-crystal balanced cross correlator.[J]. Optics Letters, 2007, 32(9):1044-6.

[51] Jaekel M T, Reynaud S. Time-Frequency Transfer with Quantum Fields[J]. Phys. rev. lett, 1996, 76(14): 2407-2411.

[52] Giovannetti V, Maccone L, Shapiro J H, et al. Extended phase-matching conditions for improved entanglement generation[J]. Physical Review A, 2002, 66(4):519-531.

[53] Onur K, Marco F, Albota M A, et al. Two-photon coincident-frequency entanglement via extended phase matching[J]. Physical Review Letters, 2004, 94(8): 178-179.

[54] Nasr M B, Silvia C, Saleh B E A, et al. Ultrabroadband biphotons generated via chirped quasi-phase-matched optical parametric down-conversion[J]. Physical Review Letters, 2008, 100(18):1459-1469.

[55] Valencia A, Scarcelli G, Shih Y. Distant clock synchronization using entangled photon pairs[J]. Applied Physics Letters, 2004, 85(13):2655-2657.

[56] Giovannetti V, Lloyd S, Maccone L, et al. Clock synchronization with dispersion cancellation.[J]. Physical Review Letters, 2001, 87(11):265-286.

[57] Giovannetti V, Lloyd S, Maccone L, et al. Conveyor belt clock synchronization [J]. Physical Review A, 2004, 70(4):628-628.

[58] Badami V, Groot P D. Displacement Measuring Interferometry [J]. Measurement Science & Technology, 2013, 4(9):157-238.

[59] Nagano S, Yoshino T, Kunimori H, et al. Displacement measuring technique for satellite-to-satellite laser interferometer to determine Earth´s gravity field[J]. Measurement Science & Technology, 2004, volume 15(12):2406-2411(6).

[60] Pierce R, Leitch J, Stephens M, Bender P and Nerem R. Inter-satellite range monitoring using optical interferometry[J]. Appl. Opt, 2008(47): 5007-5019.

[61] Weiner A M, Heritage J P, Kirschner E M. High-resolution femtosecond pulse shaping[J]. Journal of the Optical Society of America B, 1988, 5(8): 1563-1572.

[62] Weiner A M. Femtosecond pulse shaping using spatial lightmodulators[J]. Review of Scientific Instruments, 2000, 71(5):1929-1960.

[63] Wilson J W, Philip S, Bartels R A. Ultrafast phase and amplitude pulse shaping with a single, one-dimensional, high-resolution phase mask.[J]. Optics Express, 2007, 15(14):8979-87.

[64] Monmayrant A, Weber S, Chatel B. PhD TUTORIAL: A newcomer´s guide to ultrashort pulse shaping and characterization[J]. Journal of Physics B Atomic Molecular & Optical Physics, 2010, 43(10).

[65] Weiner A M. Ultrafast optical pulse shaping: A tutorialreview [J]. Optics Communications, 2011,

284(15):3669-3692.

[66] Frei F, Galler A, Feurer T. Space-time coupling in femtosecond pulse shaping and its effects on coherent control[J]. Journal of Chemical Physics, 2009, 130(3):034302-034302-14.

[67] Verluise F, Laude V, Cheng Z, et al. Amplitude and phase control of ultrashort pulses by use of an acousto-optic programmable dispersive filter: pulse compression and shaping.[J]. Optics Letters, 2000, 25(8):575-7.

[68] Ohno K, Tanabe T, Kannari F. Adaptive pulse shaping of phase and amplitude of an amplified femtosecond pulse laser by direct reference to frequency-resolved optical gating traces[J]. Journal of the Optical Society of America B, 2002, 19(11):2781-2790.

[69] Sato M, Suzuki M, Shiozawa M, et al. Adaptive Pulse Shaping of Femtosecond Laser Pulses in Amplitude and Phase through a Single-Mode Fiber by Referring to Frequency-Resolved Optical Gating Patterns[J]. Japanese Journal of Applied Physics, 2002, 41(6A):3704.

[70] Preciado M A, Muriel M A. Design of an ultrafast all-optical differentiator based on a fiber Bragg grating in transmission.[J]. Optics Letters, 2008, 33(21):2458-60.

[71] Park Y, Aza A J, Slavík R. Ultrafast all-optical first- and higher-order differentiators based on interferometers[J]. Optics Letters, 2007, 32(6):710-2.

[72] Fangxin L, Yongwoo P, José A. Complete temporal pulse characterization based on phase reconstruction using optical ultrafast differentiation (PROUD)[J]. Optics Letters, 2007, 32(22):3364-6.

[73] Guillaume L, Olivier P, Nicolas T, et al. Pulse shaping withbirefringent crystals: a tool for quantum metrology[J]. Optics Express, 2013, 21(19):21889-21896.

[74] WU L A, Kimble H J, Hall J L, et al. Generation of squeezed states by parametric down conversion.[J]. Physical Review Letters, 1986, 57(20):2520-2523.

[75] DONG R, Heersink J, Corney J F, et al. Raman-induced limits to efficient squeezing in optical fibers[J]. Optics Letters, 2007, 33(2):116-118.

[76] Ruifang D, Joel H, Corney J F, et al. Experimental evidence for Raman-induced limits to efficient squeezing in optical fibers[J]. Optics Letters, 2008, 33(2):116-118.

[77] Hirano T, Kotani K, Ishibashi T, et al. 3 dB squeezing by single-pass parametric amplification in a periodically poled KTiOPO4 crystal[J]. Optics Letters, 2005, 30(13):1722-4.

[78] CHU S, ZHANG Y, WANG B, et al. High-Efficiency Intracavity Continuous-Wave Green-Light Generation by Quasiphase Matching in a Bulk Periodically Poled MgO:LiNbO3 Crystal[J]. Advances in Optoelectronics, 2008, 2008:4.

[79] La P A, Slusher R E. Squeezing limits at high parametric gains[J]. Physical Review A, 1991, 44(3):2013-2022.

[80] Moritz M, Stefan A, Tobias E, et al. Squeezed light at 1550 nm with a quantum noise reduction of 12.3dB[J].Optics Express, 2011, 19(25):25763-72.

[81] Marzenell S, Beigang R, Wallenstein R. High Repetition Rate Mid-Infrared Femtosecond Optical Parametric Oscillator[J]. Springer Series in Chemical Physics, 1998, 63:63-65.

[82] Maker G T, Ferguson A I. Doubly resonant optical parametric oscillator synchronously pumped by a frequency-doubled, mode-locked, and Q -switched diode laser pumped neodymium yttrium lithium fluoridelaser[J]. Applied Physics Letters, 1990, 56:17(17):1614-1616.

[83] Butterworth S D, Mccarthy M J, Hanna D C. Widely tunable synchronously pumped optical parametric oscillator[J]. Optics Letters, 1993, 18(17):1429-31.

[84] Kafka J D, Watts M L, Pieterse J W J, et al. Synchronously pumped sub-picosecond optical parametric oscillator: US, US5365366[P]. 1994.

[85] Maker G T, Ferguson A I. Doubly resonant optical parametric oscillator synchronously pumped by a frequency-doubled, mode-locked, and Q -switched diode laser pumped neodymium yttrium lithium fluoridelaser[J]. Applied Physics Letters, 1990, 56:17(17):1614-1616.

[86] Bryan D A, Rice RR, Gerson R, et al. Magnesium-Doped Lithium Niobate For Higher Optical Power Applications[J]. Optical Engineering, 1985, 24(1):138-143.

[87] de Valcarcel, G.J, Patera, G, Treps, N, et al. Multimode Squeezing of frequency combs[C]. European Conference on Lasers and Electro-Optics, 2007 and the International Quantum Electronics Conference. Cleoe-Iqec. IEEE, 2007:061801(R).

[88] Patera G, Treps N, Fabre C, et al. Quantum theory of

synchronously pumped type I optical parametricoscillators: characterization of the squeezed supermodes[J]. European Physical Journal D, 2009, 56(1):123-140.

[89] Araújo R M D, Pinel O, Jian P, et al. Generation and characterization of multimode quantum frequency combs[J]. Physical Review Letters, 2012, 108(8):1.

[90] LIUH Y, CHEN L, LIU L M. State Key Laboratory of Quantum Optics and Quantum Optics Devices, Electronics I O O, University S, et al. Generation of femtosecond pulsed quadrature phase squeezed light[J]. Acta Physica Sinica, 2013, 62(16):581-586.

[91] XU L ,Spielmann C, Poppe A, et al. Route to phase control of ultrashort light pulses.[J]. Optics Letters, 1996, 21(21):2008-10.

[92] Telle H R, Steinmeyer G, Dunlop A E, et al. Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation [J]. Applied Physics B, 1999, 69(4):327-332.

[93] Jones D J,Diddams S A, Ranka J K, et al. Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis[J]. Science, 2000, 288(5466):635-40.

[94] Koke S, Grebing C, Frei H, et al. Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise. Nat. Photonics 4, 462[J]. Nature Photonics, 2010, 4(7):462-465.

[95] Roman S, Valerian T, Clément J, et al. Analysis and filtering of phase noise in an optical frequency comb at the quantum limit to improve timing measurements[J]. Optics Letters, 2014, 39(12):3603-3606.

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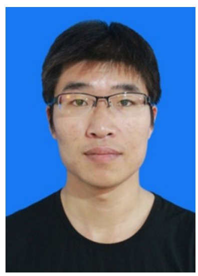

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