High Resolution Measurement with Asynchronous Optical Sampling

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Abstract: Asynchronous optical sampling is an emerging new measuring technique that exploits the frequency resolution, frequency accuracy of frequency combs for ultrahigh-resolution, high-sensitivity broadband spectroscopy and time-offset measurement. This review describes principles and applications of Asynchronous optical sampling and summarizes the current state of the art. As laser technology progresses, Asynchronous optical sampling will continue to mature and could surpass conventional frequency and time measurement technology for a wide range of laboratory and field applications.

1. Introduction:
Asynchronous optical sampling (AOS) has some advantages compared with other electronic methods in high-resolution measurements. Its optical pulses are able to be demonstrated by electric fields of a test pulse before and after the sample. In the earlier work, NIST exploited the high bandwidth and the speed of AOS for precision ranging [1], and they exploited the high frequency resolution of its frequency-domain counterpart, multi-heterodyne spectroscopy, for precision molecular spectroscopy [2]. And asynchronous optical sampling has been known as application of the dual-comb technique, which utilizes it as a scanner in the pump–probe method. AOS enables the rapid acquisition of transient responses with a considerably wide temporal dynamic range and has been applied in the detection of coherent phenomena[3,4] and terahertz time-domain spectroscopy[5], among others. The dual-comb configuration can be treated as a rapid scanning method, able to carry out new measurements with an unprecedentedly wide dynamic range. Therefore, an extension of the dual-comb for multi-dimensional measurements can naturally be reminded as one of the further applications. In the following parts, we introduce the principle of AOS to make it better understand in the first place, and then we give a clue to three fields of application of AOS, which has been presented or used. At last, it would be the potential fields that AOS would be applied in the future.

2. Principle:
The AOS principle can be comprehended more particularly in different ways, here using the explanation which presented by the Newbury team, the basic methods of AOS is illustrated in Figure1. As a simple demonstration, the signal and the local oscillator (LO) are two fiber frequency combs, phase locked together such that the LO pulse advances past the signal pulse by $\Delta T$ every pulse. For start, the signal comb pulse generates reference pulses, and after that, a test pulse, and then transfer through the fiber spool. The two pulses are then combined with a separation which is much longer than the pulse duration. Second, the LO pulses samples the electric fields and femtosecond level jitter.
Fig. 1. In the top part of the schematic of the setup. The link lines are fiber optics, the dashed lines are electrical paths, and the filled ovals are fiber couplers. For the demonstration here, using a spool of optical fiber as the test sample and using the window by interleaving the “reference” and the “test” signals with offset instead of testing them respectively. Balanced detection is to make the close to shot-noise-limited heterodyne detection come true. And in the bottom, schematic of AOS assuming zero carrier-envelope offset phase for the LO pulse train.

The signal comb source produces a train of pulses, $E_S$, and the LO comb owe the same form. Both combs share a common tooth at same optical frequency $v_0$, when the two combs are mixed, it generates the resulting detected heterodyne signal that is $V_t$, which makes the treatment simpler. The waveform $V(\tau)$ repeats every $T$ second in an equivalent time and the signal electric field sampled by $S(t)$ at a spacing of $\Delta T$. As with sampling in any equivalent time, the laboratory time scale is magnified by a factor $M = T_L / \Delta T$. As the LO pulse train pass across the signal pulse train, it will eventually sample a full pulse repetition period $T_S$ (or “frame”), where points the sampling effectively cycles around and begins again. According to the previous information, obtaining a frame takes $T_S / \Delta T = M - 1$ pulses or a period $T_{\text{update}} = (M - 1)T_L$ in the laboratory. [6]

3. Applications:
In the following section, some key applications of LOS will be introduced, includes the field of time-synchronization, tomography, distance measurement.

3.1. Detection the instability of the fiber link in time offset system
For the various application of the AOS, the detection of diminutive instability is essential because high precise time and frequency dissemination is of major importance for many scientific applications such as basic physical principle of tests, X-ray free electron lasers (XFELs), deep space exploration, Atacama Large Millimeter Array (ALMA), especially navigation and atomic clock comparison. As the better stability of the atomic clock, the more exacting request of the accuracy of the time synchronization. During the past decades, the progress in atomic/optical clocks has driven the frequency instability to $10^{-16}/s - 10^{-19}/100s$ level[7]. Yet the accuracy of transferring these frequency standards under conventional schemes based on free-space microwave propagation did not meet the requirement for comparison and distribution of such high quality frequency standard. To ameliorate the problem, the existing fiber optic network has become an attractive option in such ultrahigh precision applications with its advantages of low attenuation, high reliability, and continuous availability.

Based on the present fiber optical technique, there are three main ways to meet the frequency transfer and time synchronization: Light loading radio frequency and timing signal, direct optical frequency transmission, and the signal transmission of femtosecond optical comb. In the Table.1, as we can see, according to the UP13/SYRTE, MPQ/PTB, NPL, Peking University, Frequency transfer has made a huge success. In the fig.2. from the fiber link of 120 kilometers in 2014-2015 years expand to the fi-
ber link of 440 kilometers, which is the longest frequency transfer methods with the carrier of optical combs and the medium of fiber link at the present. [8]

| Institution       | Carrier Wave Type | Time Delay Accuracy | Time Deviation/100s | Experiment Year |
|-------------------|-------------------|---------------------|---------------------|-----------------|
| UP13/SYRTE        | Optical Frequency | 100ps               | 7ps                 | 2013            |
| AGH.Univ.         | Radio Frequency   | 20ps                | 1.6ps               | 2012            |
| TSU               | Optical Frequency | 50ps                | 0.6ps               | 2012            |
| PKU               | Optical Comb      | 100ps               | 1.6ps               | 2015            |

Fig.2. The schematic diagram of precise time synchronization and frequency transfer. At the remote end, the atomic clock can be reproduced. DWDM: dense wavelength division multiplexing.

However, as for the technique of time synchronization nowadays as the Table.2, it could limit the development of application. In the field of time synchronization and precision measurement, etc. traditional electronic measuring resolution confined to the instrumental limit approach ~20 ps, which is a barrier for further high precise time synchronization. But if changing the methods of time interval measurement from the principle to obtain the time delay with dual-comb asynchronous optical sampling, which can detect the deviation to femtosecond.
Table 2. Comparison of different synchronous resolution in unit interval

| Organization                  | Carrier          | Fiber Length (km) | Fractional Frequency Stability-1 | Time Jitter (TDEV)-2 | Year |
|-------------------------------|------------------|-------------------|----------------------------------|----------------------|------|
|                               |                  |                   | 1S                              | 1000S                |      |
|                               |                  |                   | 100S                            | 1000S                |      |
| MPQ/PTB                      | Optical frequency| 540               | $-2 \times 10^{-14}$             | $-3 \times 10^{-17}$ | 2013 |
| NPL                          | Optical frequency| 1840              | $2.7 \times 10^{-15}$            | —                    | 2013 |
| AGH Univ. Sci. & Techno.     | Comb             | 86                | $5 \times 10^{-15}$              | $-6 \times 10^{-17}$ | 2011 |
| PKU                          | Radio frequency  | 60                | $-6 \times 10^{-14}$             | $-9 \times 10^{-16}$ | 2012 |
| UP13/SYRTE                    | Comb             | 120               | $8.21 \times 10^{-18}$           | $1.48 \times 10^{-19}$| 2015 |

Dual-comb asynchronous optical sampling has been used in free-space ranging metrology and timing synchronization. But, which has not been applied to fiber link yet. The potential difficulty is the dispersion and random birefringence of the fibers, which significantly broaden the pulse and reduce the interference contrast. This will result in uncertainty in center of curve determination. To overcome these potential problems, the PKU team limit the spectral bandwidth to 100GHz (0.8nm) by use DWDM, and add the dispersion compensation fiber to limit pulse width. And the biggest problem of the free-space ranging metrology is that it can not transfer over a long distance, therefore, present the synchronization via fiber link that have low attenuation and high stability.

For testing the feasibility of AOS in fiber link system, the fiber link AOS system with translation stage is constructed as the figure 3. Two comb were used as light source. Their repetition rate, $f_{rep}$, were approximately 100 MHz. The frequency difference, $\Delta f_{rep}$, was adjustable. Both the master and the transfer comb are locked to an Rb clock respectively. On each side, the laser pulses passed through the DWDM, filtered and split into channel#33 and channel#34 and propagated to the other site. There are two linear cross correlation setups. In channel#33, transfer comb went through translation stage and then linear cross-correlated with master comb. In channel#34, transfer comb directly cross-correlated with master comb. Each channel’s cross-correlation signal was observed by using balanced photo detector (BPD) respectively. The signals were low-pass filtered and sampled by a data acquiring card (DAQ).
Fig. 3. Schematic of the fiber link linear optical sampling system with translation stage. DWDM: dense wavelength division multiplexing; BPD: balanced photo detector; LPF: low pass filter; DAQ: data acquisition.

Table 3. Result of time resolution measurement

| Parameter      | Timing error  | Node             |
|----------------|---------------|------------------|
| Time delay 0.1 ps | 0.012 ps      | 10 times average |
| Time delay 0.5 ps | 0.049 ps      | 10 times average |
| Time delay 1.0 ps | 0.078 ps      | 10 times average |

This Table 3 shows the time resolution results, the average timing error (or time offset) is sub-picosecond level.

AOS over 100km fiber as figure 4 shows, compared to first experiment, translation stage was replaced by the combination of single mode fiber (SMF) and dispersion compensation fiber (DCF), which is 100km long lab spooled fibers. Amplifying the laser pulses with EDFA (erbium doped fiber amplifier). There are also two asynchronous optical sampling setups, one is the transfer comb passed through the 100km fiber and cross-correlated with the master comb, the other is master comb directly with the transfer comb.

Fig. 4. Schematic of the linear optical sampling system over 100 km fiber. EDFA: erbium doped fiber amplifier; SMF: single mode fiber; DCF: dispersion compensation fiber

According to the results, the optical sampling is sufficiently high without control of the polarization. When observe the simultaneously recorded optical sampling traces, with the local and the one after the
100 km fiber propagation, dispersion of the fibers significantly broaden the pulse and reduce the interference contrast. And the result of the experiments also shows the optical sampling trace over 100km long fiber link with dispersion compensation. Surprisingly, over 100km fiber the optical sampling signal is sufficiently clear and high with dispersion compensation and without control of the polarization.

And AOS’s precision in the fiber delay measurement was not possible with an electronic TIC (time interval counter). Sub-picosecond time offset measurement over fibers using asynchronous optical sampling. The narrow spectrum and the dispersion compensation, because of using DWDM and DCF, ensure clear optical sampling trace. The time offset from the curve fitting proves the feasibility of this AOS measurement of in the long fiber link.

By demonstrating sub-picosecond time-offset measurement over 100 km spooled fibers with linear optical sampling technique. The implementation of the dual-comb asynchronous linear optical sampling in the time offset measurement offers the sub-ps precision. The narrow spectrum and the dispersion compensation ensure clear optical sampling trace. The time offset from the curve fitting proves the feasibility of this dual-comb measurement of in the long fiber link.

3.2. Tomography:
In optical sampling, a transient waveform under study is gated with time delayed laser pulses, sampling this waveform with high time resolution. This technique is commonly employed for exploiting nonlinear optical effects [9] and for pump probe studies [10,11]. However, in these approaches the overall measurement time and scanning range is strongly limited by mechanical scanning of the time delay of the probe pulses. the scanning range is limited to a few centimeters and the signal to noise ratio can degrade due to mechanical instabilities [12–14]. These limitations can be overcome by asynchronous optical sampling (AOS), where two pulsed lasers with slightly detuned repetition rates are employed [15,16]. A constant difference $\Delta f_{\text{rep}}$ between the repetition rates of two lasers leads to an increasing mutual time delay. Thus, the pulses of the first laser sweep the pulses of the second laser, performing a non-mechanical scan of the time delay. In the coherent AOS implementations, the electric fields of the first laser pulse train sweep the electric field of the second laser pulse train. In LCI, a sample under investigation is probed with light of low temporal coherence and interfered with a second, time delayed low coherence beam [17]. The extension to OCT imaging is achieved by two-dimensional scanning. Cross-sectional images of the sample are obtained by displaying the logarithmic amplitude of the depth dependent correlation signals [18].

In coherent asynchronous optical sampling, the electric field of a light source is interferometrically overlapped with a second, time delayed electric field. This sweep of the electric fields generates correlations signals. Although this technique does not require pulsed lasers, these light sources are commonly employed due to their low noise operation and low coherence lengths resulting from the broad spectral bandwidths. However, the discrete nature of the laser pulse timings can limit the generation of the correlation signals in time domain systems significantly. A new approach is needed to bridge the gap between time domain systems based on rapid scanning optical delay lines, which cover only small scanning ranges, and AOS based systems covering only a fixed large scanning range. Figure.5. sketch the optical setup for electronically controlled coherent asynchronous optical sampling.
Fig. 5. Optical setup of the experiment. DC: dispersion compensation, ND: neutral density filter, BS: beamsplitter.

Two commercial femtosecond fiber lasers are arranged within an interferometer setup. Each laser contains a ring oscillator with an erbium doped fiber amplifier [19]. An essential part of the oscillator is a free-beam section comprising several wave-plates and a polarizer, serving as artificial saturable absorber. Hence, mode-locking is achieved by nonlinear polarization evolution via the optical Kerr effect [20]. Laser 2 (the master oscillator) runs freely with a repetition rate of 100MHz, laser 1 (the slave oscillator) can be tuned in repetition rate by varying the length of the free-beam section. A stepper motor and a piezoelectric transducer within the cavity of this laser are used for coarse and fine adjustment, respectively. The change in cavity length results in a modified repetition rate and thus in different timing delays of the laser pulses. A master slave lock is realized by matching the repetition rate of the slave oscillator to the free running master oscillator, using a phase locked loop (PLL) circuit. The phase difference of both pulse trains is determined by measuring the laser pulses with internal photodiodes. The phase difference serves as error signal, which is coupled back to the piezoelectric transducer. The stepper motor is only activated for compensation of larger drifts of the cavity length. Varying the delay between the two pulse trains is achieved by electronically sweeping the set point of the locking electronics: an additional input signal \( \phi(t) \) is added to the determined phase difference before the feedback loop is closed (see [21] for details). A linearly sweeping phase- and time delay is accomplished by applying a triangular function as input signal. The amplitude, offset and frequency of the sweeping time delay scales with \( \phi(t) \). In the ideal case of no external disturbances of the cavity length, an increasing time delay relative to the master laser results from a constant, slightly higher cavity length of the slave laser. When the maximum time delay is reached, the cavity length of the slave laser has to be switched below the cavity length of the master laser for achieving a decreasing time delay. Thus, the main advantage of ECOPS beyond ordinary mechanical scanning results from the fact that mechanical action is only required for changing the slope of the time delay. Only slight mechanical movements in the range of some micrometers are necessary for appropriate changes of the cavity length. In this manner the electronically controlled delay can be used for fast and flexible optical sampling.

The setup of this technique for application in coherent linear optical sampling is also shown in Fig.9. The output of laser 1 is guided to the sample by beamsplitter 1. A galvanometer scanner deflects the beam for two-dimensional scanning; a lens is used for focusing the light onto the sample. The backscattered light of the sample arm is interferometrically overlapped at beamsplitter 2 with the light of laser 2. The dispersion of both lasers is matched by an optical windows applied as dispersion compensation DC, the reference arm intensity is reduced by a neutral density filter ND. The interferometric signal is detected with a balanced receiver, bandpass filtered and optionally demodulated by an analog logarithmic amplifier. The received signal and the phase control signal are measured by a multichannel transient recorder. A subsequent numerical post processing step renders the data to images.
Electronically controlled coherent asynchronous optical sampling is a novel technique for virtually non-mechanical low coherence interferometry and optical coherence tomography. The technique allows scanning ranges beyond the limitations of time and spectral domain methods and scanning rates beyond the limitations of AOS applied to low repetition rate lasers. The limitation of equal repetition rate difference frequency and scanning rate of AOS is broken by applying a user adjustable phase signal to directly control the mutual time delay of two pulsed lasers. The parameters scanning range, rate and offset can be selected individually by full electronic control. The advantages of time domain systems, such as flexible scanning parameters and high dynamic range by analog logarithmic amplification, are exploited without having to accept the disadvantages of non-mechanical spectral domain methods with autocorrelation noise, mirror artifacts and scanning range vs. axial resolution limitations. Regions of interest can be defined within the samples under investigation, allowing the user to perform a time and memory efficient analysis of specific structures within a large scanning range. Applications ranging from penetration depth limited OCT imaging to remote sensing analysis of subsurface structures in three dimensions are possible with this flexible scanning scheme. This feature is especially important for the analysis of known structures, where a priori knowledge of the object might be exploited for quickly skipping unnecessary parts of the scanning range with high speed, before the region of interest is scanned in detail. The new approach scales with the laser repetition rate and permits the use of long-cavity fiber lasers, which are highly stable and commercially available. Hence, operation beyond laboratory setups is realizable, pushing the technique to a valuable tool for precise interferometric metrology, optical coherence tomography, enface tomographic imaging and future applications exploiting non-linear or time-dependent effects.

3.3. Measuring the estimated distance:
In the first place, the absolute distance is calculated by synthetic wavelength method with continuous wave (CW) lasers as the light source. The optical frequency comb is adopted as frequency standard for CW wavelength calibration [22–25]. In a simplified measurement, synthetic wavelengths are considered to be directly generated by heterodyne beatings among optical frequency components within the comb bandwidth and the absolute distance is measured through phase analysis of these heterodyne frequencies [26]. Nevertheless, an estimated distance serves as the prerequisite for the establishment of an effective synthetic wavelength chain. To overcome this disadvantage, the second approach is proposed to measure absolute distances without auxiliary estimations. Based on time-of-flight principle, periodic train of pulses emitted by the frequency comb can be utilized for absolute length measurement. Thus, an idea was proposed by Ye [17], that time intervals between pulses were used to determine the estimated distance based on time-of-flight principle and interference fringes were analyzed to obtain an enhanced resolution.

An incoherent scheme based on asynchronous optical sampling AOS [28,29] is proposed with the particular aim of performing absolute length measurement and simplifying distance calculation. This scheme can be divided into two parts: dual-comb temporal optical scanning and second harmonic generation (SHG). Dual combs, with a tiny difference in their repetition rates, are involved to fulfill temporal optical scanning among pulses and guarantee the measurement of arbitrary distances.

The experimental setup is shown in Fig. 6. The light sources are two Er-doped fiber lasers: one for the signal laser (SL) and the other for the local oscillator (LO). The fiber laser for the SL emits pulses with a spectral bandwidth of 30 nm centered at 1550 nm. The repetition rate can be tuned using a PZT actuator coupled to a motorized stage inserted in the laser cavity. The pulses are amplified and compressed by an Er-doped fiber amplifier (EDFA). The LO fiber laser shares the same characters with the SL except the fixed repetition rate. The repetition rates of the two femtosecond lasers are locked to an Rb atomic clock with a difference and the offset frequencies of the two lasers are not actively controlled.
Fig. 6. Experimental setup for dual-comb nonlinear asynchronous optical sampling. EDFA: erbium-doped optical fiber amplifier, HWP: half wave plate, QWP: quarter wave plate, PBS: polarization beam splitter, L: lens, PD: photodetector, CLK: Rb atomic clock.

The pulses from the SL are split into the reference and measurement arms of a Michelson interferometer by a polarization beam splitter (PBS). The retro-reflector in the reference arm is fixed while that in the measurement arm is on a linear translation stage. The exit beam of the reference retro-reflector propagates through the PBS because of the quarter wave plate (QWP). Meanwhile, the retro-reflector in the Michelson interferometer is used to reflect the exit beam of the target retro-reflector. It is represented by a dotted line since the input and output beams are at different heights. The pulses reflected by the two retro-reflectors are combined with the LO pulses respectively and focused onto two type II barium borate (BBO) crystals for the SHG. The exit beams of the two retro-reflectors are separated to minimize polarization crosstalk caused by the low extinction ratio of one PBS. The resulting signals from the two BBO are digitized and acquired individually by a 14 bit 250 MHz data acquisition card synchronized to the repetition rate of the LO. Meanwhile, curve-fitting algorithm, using 9 points near the maximum value, is employed to get peak positions of the resulting signals. The waveform in Fig. 10 is a screen shot of the resulting signals from the two BBO, acquired by an oscilloscope. A third retro-reflector for the heterodyne interferometer is also mounted on the translation stage for comparison.

The performance of the system is tested by measuring an actual distance in air and compared with the heterodyne interferometer. The stability of the dual-comb system is evaluated with different averaging times while the target fixed at ~39.2 mm. In the experiment of TSU[30], absolute distances are measured by the proposed nonlinear AOS utilizing dual-comb optical scanning and type II SHG. Dual combs, with a tiny difference in their repetition rates, are involved to fulfill pulses overlap at arbitrary distances. Several experiments are conducted and the results are compared with a heterodyne interferometer. The residuals are scattered from 74.1 nm to 100.6 nm and the stability of the system is demonstrated with an uncertainty of 1.48 μm for a single measurement, corresponding to an averaging time of 0.5 ms. Moreover, the uncertainty can be reduced to 166.6 nm for 50 ms and 82.9 nm for 500 ms. The NAR is also extended by adjusting the repetition rate of the signal laser and a mechanical range of 693.7 mm is proved by a series of tests.
4. Prospect and Conclusion:

In summary, asynchronous optical sampling can provide a high-resolution measurement, so this kind of system will have application for precision measurements, especially in those fields which high frequency resolution or accuracy is demand. The instability detection of the fiber link in time offset system, the calculation of absolute distance and the tomography are all the very important applications of AOS. And besides these applications I mentioned in the previous, AOS still has a lot of prospects in the future. For example, dual comb optical spectrometer has more superior performance in spectral resolution, sampling time and signal-to-noise ratio. With the progress in AOS theoretical and experimental study and the reduce of optical frequency comb system cost, the dual comb optical spectrometer based on AOS will be more and more widely used in atmospheric pollution monitoring, breath gas detection and other important field. Because asynchronous optical sampling has the extraordinary resolution of transmission, the time synchronization technique based on AOS shows a potential application in the fields of basic physical quantities measurement, atomic clocks time comparison, high-qualified radio interferometry and deep space exploration. The asynchronous optical sampling not only has plenty of application in the physics, chemistry and biology, but also shows a huge potential potency in frontier engineering technology.[31]

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