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# A NEW OPTICAL FREQUENCY TRANSFER METHOD VIA FIBRE BASED ON ACTIVE PHASE NOISE COMPENSATION WITH SINGLE ACOUSTO-OPTIC MODULATOR

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**Abstract**

In this paper, we propose and experimentally demonstrate a new method for optical frequency transfer over fibre. Instead of dual acousto-optic modulators (AOMs) as adopted in the traditional fibre phase noise compensation setup, here an active fibre phase noise compensation scheme with a single acousto-optic modulator (AOM) is used. The configuration simplifies the equipment of the user end while maintaining a high-performance optical frequency transfer stability. We demonstrate an actively stabilized coherent transfer at an optical frequency of 193.55THz over 10-km spooled fibre, obtaining a relative frequency stability (Allan deviation) of $3.84 \times 10^{-16}$/1 s and $4.08 \times 10^{-18}/10^4$ s, which is improved by about 2~3 orders of magnitude in comparison with the one without any phase noise compensation that achieves a relative frequency stability of $1.81 \times 10^{-14}$/1 s and $2.48 \times 10^{-15}/10^4$ s.

Keywords: acousto-optic modulator, optical frequency transfer over fibre, phase noise compensation, relative frequency stability.



## 1. Introduction

High-precision time and frequency are widely used in satellite navigation, deep space exploration, military strikes, space science, mobile communication, power transmission and other fields [1, 2]. It is an important strategic resource for a country, related to scientific and technological development, economic construction and national security.

In recent years, the accuracy of atomic frequency standards has been continuously improved, and the uncertainty of optical clocks has been even reduced to the order of $10^{-18}$ [3–5]. The uncertainty of the optical clocks has surpassed that of the caesium atomic fountain clock, and the redefinition of second has become a hot spot in current metrology [6–7]. Currently, the definition of second is most likely defined on the optical clocks. If this is the case, the time-frequency laboratories must have the optical clocks. It will inevitably involve the time-frequency transfer between the optical clocks. Therefore, there is an urgent requirement to develop a time-frequency transfer technology based on the optical clocks.

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At present, satellite common-view and *two-way satellite time and frequency transfer* (TWSTFT) technologies are mainly used to achieve remote international time comparison [8]. The relative frequency stability of TWSTFT is the highest in the traditional time-frequency transfer method based on microwaves, and its stability is about $10^{-15}$~$10^{-16}$/day [9, 10]. Conventional time-frequency transfer accuracy based on microwaves cannot meet the requirement satisfied by the optical clocks.

Fibre has advantages of low loss and strong anti-interference ability, and can perform long-distance and high-precision time-frequency transfer. Therefore, time-frequency transfer over fibre is one of the ideal methods for solving the time-frequency transfer between the optical clocks, and has become the current research hot spot of time-frequency transfer. The core problem of optical time-frequency transfer over fibre is the compensation of phase noise. At present, the research teams in France [11, 12], Germany [13], Poland [14, 15], China [16–20] and other countries [21–24] have adopted the active phase noise compensation method to achieve high-precision optical frequency transfer over fibre.

In 2012, University Paris 13, Observatory of Paris and other institutions transferred optical frequency signals over a 540 km fibre network, using a laser with a linewidth less than 5 kHz, with a relative frequency stability of $5 \times 10^{-15}$/1 s and $2 \times 10^{-19}$/30000 s [11]. In 2015, an optical frequency transfer was performed on a 1100 km cascaded fibre link, with a relative frequency stability of $4 \times 10^{-16}$/1s, falling down to $1 \times 10^{-19}$/2000 s [12].

In 2013, *Max-Planck-Institut für Quantenoptik* (MPQ) and *Physikalisch-Technische Bundesanstalt* (PTB) performed an optical frequency transfer over a single-span 1840-km fibre link using a laser with a linewidth of about 1 Hz, obtaining a relative frequency stability (modified Allan deviation, MADEV) of $2 \times 10^{-15}$/1 s, $4 \times 10^{-19}$/100 s [13]. AGH University of Science and Technology in Poland accomplished an optical frequency transfer over a 100 km spooled fibre using a 1 Hz narrow linewidth laser, obtaining a relative frequency stability of $1.2 \times 10^{-16}$/1 s, falling down to $1.5 \times 10^{-19}/10^3$ s [14].

National Time Service Center of the Chinese Academy of Sciences uses a cavity-stabilized ultra-narrow linewidth laser with a linewidth of 1.9Hz as the transfer-coherent optical source. A relative frequency stability of the optical carrier frequency transfer over a 112 km fibre link is $2.5 \times 10^{-16}$/1 s and $7.5 \times 10^{-20}/10^4$ s [16], using a laser with a linewidth of about 200 Hz as the transfer-coherent optical source, a relative stability of the optical carrier frequency transfer over a 210-km fibre is $1.51 \times 10^{-14}$/1 s, falling down to $5 \times 10^{-17}/10^4$ s [17]. East China Normal University uses a 0.36 Hz linewidth ultra-stable laser to obtain the optical carrier frequency transfer with a relative frequency stability of $3.5 \times 10^{-17}$/1 s and $3 \times 10^{-19}/10^4$ s over an 82 km fibre (including a 32-km urban fibre link) [18], in which the optical frequency transfer over a 50 km spooled fibre gives a fibre-induced frequency instability of $2 \times 10^{-17}$/1 s, and reaches $8 \times 10^{-20}$ after 16 hours [19].

The above-mentioned active phase noise compensation scheme usually uses one AOM at the source end and another one at the user end of the optical path, and an additional signal source is needed at the user end for the AOM to work normally. In this paper, a new fibre optical frequency transfer method based on active phase noise compensation is proposed. This method needs to use only one AOM at the source end, which not only saves one AOM, but also saves a signal source that provides signals for the AOM at the user end. The structure of the user end is simple, so it is cost-effective for the user. Based on this method, an optical frequency transfer system based on a 10 km fibre was designed. We demonstrated a single-AOM phase noise compensation method at the source end for optical frequency transfer over a 10 km fibre link, achieving a relative frequency stability of $3.84 \times 10^{-16}$/s. Moreover, for similar laser linewidth and transfer distance, the measured results are comparable to those achieved with the dual-AOM frequency transfer scheme [17, 20].

The remainder of the paper is organized as follows. In Section 2, the theory and principles of the proposed method are given. The composition of optical frequency transfer system is described, and the active phase noise compensation scheme is presented. In Section 3, we verify effectiveness of the proposed method by comparison of the phase noise compensation scheme with free running via 3-m/10-km fibre. The experiment results are shown in terms of relative frequency stability and phase noise. Conclusions are summarized in the last section.

## 2. Theory and principles

### *2.1. System composition*

Based on the optical frequency transfer experiment performed recently, an optical frequency transfer system with a compensation method applied at the source end, based on single AOM was proposed. Based on the system, the optical frequency transfer experiments were performed over a 10 km spooled fibre. The principle of active phase noise compensation in optical frequency transfer is shown in Fig. 1. The experimental system is mainly composed of a narrow linewidth laser (linewidth < 100 Hz), an AOM, a 10-km spooled fibre, two *photodetectors* (PDs), two optical *circulators* (Cs), five *optical couplers* (OCs), a *voltage-controlled oscillator* (VCO), a measure system and so on.

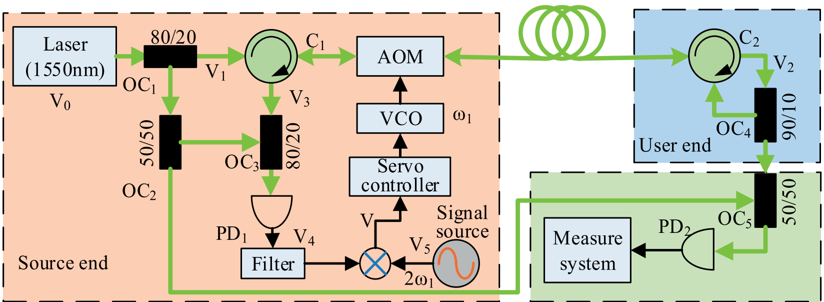


Fig. 1. A schematic diagram of the optical frequency transfer experiment via fibre.

The fibre used in the experiment is a G652D single-mode communication fibre of Yangtze Optical Fibre and *Cable Joint Stock Limited Company* (YOFC), with a maximum attenuation of 0.2 dB per kilometre. The laser is an NKT Photonics E15 commercial fibre laser with a centre wavelength of 1550 nm and a free-running line width of about 100 Hz. The power is 40 mW. This experiment has a 20 km round-trip fibre, so it is possible to ignore the influence of the laser phase noise on optical frequency transfer.

The AOM is a Gooch & Housego's Fiber-Q type with +1 order diffraction, that is to say the laser output frequency of the AOM is increased by $f_1$ (80 MHz) compared with the laser input frequency. The photodetector is a device that apply the photoelectric effect to detect the laser intensity and convert it into the corresponding current. The phase noise of the in-loop beat signal at the $PD_1$ represents the phase noise introduced by the transmitting fibre (twice through), and the phase noise of the out-of-loop beat signal at the $PD_2$ represents the relative frequency/phase change of the transmitted optical signal through the fibre. The low-noise and high-gain InGaAs high-speed amplified photodetector is used in the experiment, with a maximum bandwidth of 250 MHz and a wavelength response range of 800–1700 nm.

The source-end optical path structure is as follows: a laser signal generated by the narrow linewidth laser is split into two beams (80:20) through the optical coupler 1($OC_1$); one beam (80%) passes through the fibre circulator ($C_1$) and is frequency-shifted by 80 MHz with the AOM. Then, the beam reaches the user end via the 10-km fibre link. The other beam (20%) output signal of $OC_1$ is split into two beams (50:50) via the optical coupler 2($OC_2$); one of them reaches the optical coupler 3 (80:20) as a local reference signal to beat frequency with the return light from the user end, and then reaches the $PD_1$. The other signal (50%) of $OC_2$ reaches the optical coupler 5($OC_5$) and is beaten with an output signal (10%) of the optical coupler 4($OC_4$) to evaluate the relative frequency stability of the signal transmitted to the user end.

The structure of phase noise compensation is as follows: the returning light and the local reference signal pass through $OC_3$, then are detected by the $PD_1$ to generate a 160 MHz signal. The band-pass filter is used to filter clutter; then, the signal and another 160 MHz signal generated by the frequency source are phase-detected by the phase detector, and the phase detector is a double balanced structure. The obtained phase-detection signal is used as an error signal. The error signal is filtered by our own-construction narrowband RC low-pass filter before passing the New Focus's LB1005 high-speed servo controller. Then, the error signal is fed back to the VCO. The VCO generates an 80 MHz signal, and then this signal drives the AOM for phase noise compensation via a 2 W power amplifier.

### 2.2. Basic principles

In this paper, a narrow linewidth laser with a linewidth < 100 Hz is selected as the optical frequency source. The frequency signal transmitted by the laser source can be described by:

$$V_0 = A\cos(\omega_0 t + \varphi), \tag{1}$$

where $A$, $\omega_0$ and $\varphi$ represent amplitude, angular frequency and phase of the optical frequency signal, respectively. As the amplitude information $A$ is not relevant to the experimental results, $A$ is ignored in the following expressions.

The light emitted by the laser is coupled with a part of the optical signal $V_1$ via the $OC_1$, and $V_1$ is:

$$V_1 = V_0 = \cos(\omega_0 t + \varphi). \tag{2}$$

After passing through the optical circulator ($C_1$), it goes through the AOM driven by the VCO, and then enters the fibre link and is transmitted to the user end. The optical signal $V_2$ is given by:

$$V_2 = \cos(\omega_0 t + \omega_1 t + \varphi + \varphi_p + \varphi_1), \tag{3}$$

where $\omega_1$ and $\varphi_1$ represent angular frequency and phase of the VCO, respectively; and $\varphi_p$ is phase noise introduced by the fibre link.

After arriving the optical signal to the user end, it is split by the optical coupler, part of the signal is taken as a stable optical frequency signal that can be used by the user end, and other parts are returned to the source end according to the original path. The returned optical signal derived from the optic circulator 1($OC_1$) is expressed:

$$V_3 = \cos(\omega_0 t + 2\omega_1 t + \varphi + 2\varphi_p + 2\varphi_1). \tag{4}$$

Since the return signal passes through AOM again, the phase introduced by the AOM is also doubled. After the optical signals $V_1$ and $V_3$ are beaten by the detector, the beat frequency of the two signals can be obtained as:

$$V_4 = \cos(2\omega_1 t + 2\varphi_p + 2\varphi_1). \tag{5}$$

Mixing $V_4$ with the microwave signal source $V_5$ ($V_5 = \cos(2\omega_1 t)$), we obtain an error signal for controlling the VCO:

$$V = \cos\left(2\varphi_p + 2\varphi_1\right). \tag{6}$$

This error signal is used to control the phase $\varphi_1$ of the VCO so that the equation $2\varphi_p + 2\varphi_1 = \mathrm{C}$ always holds, where C is a constant. Obviously, there is also $\varphi_p + \varphi_1 = \mathrm{D}$, D is a constant. In this way, the signal received by the user can be expressed as:

$$V_2 = \cos(\omega_0 t + \omega_1 t + \varphi + \varphi_p + \varphi_1) = \cos[(\omega_0 + \omega_1)t + \varphi + \mathrm{D})]. \tag{7}$$

We can see that when the phase-locked loop is stabilized, it can ensure that $\varphi_p + \varphi_1$ is equal to a constant D. Therefore, the effect of $\varphi_p$ on the phase noise of the signal received at the user end is cancelled. The signal stability at the user end is the same as the stability of the signal $V_1$ at the source end.

## 3. Experiment and results

In order to fully verify effectiveness of the fibre phase noise compensation, the specific scenario of this experiment is as follows:

1. Measure the noise floor of the transfer system by connecting the source end and the user end with a 3 m fibre.
2. Add a 10 km spooled fibre to the transfer system to free run, without adding a phase noise compensation unit and measuring the relative frequency stability in uncompensated conditions.
3. Add the phase noise compensation unit to the optical frequency transfer system to measure the relative frequency stability of the phase noise compensation at a round-trip distance of 20 km. Finally, compare and analyse the above measurement results to evaluate the effect of phase noise compensation on the optical frequency transfer.

Firstly, the 3 m fibre is used for connecting the source end and the user end. The voltage control port of the VCO is disconnected, that is, phase noise compensation is not performed. Then, the optical frequency transfer via 3 m fibre is measured. The relative frequency stability was measured using a counter (Agilent 53230) for about 60000 s, and calculated by Stable32 software.

Figure 2 shows that the relative frequency stability of the free running over 3-m fibre is $8.62 \times 10^{-16}$/s, falling down to $1.17 \times 10^{-16}/10^4$ s, when the integration time is from 10 s to 1000 s, *Allan Deviation* (ADEV) shows a downward trend of $1/\tau^{1/2}$, indicating that the residual noise comes mainly from the *frequency modulation* (FM) white noise. The slope of ADEV changes after 1000 s and begins to upturn. The main reason may be temperature fluctuations.

The voltage-control terminal of the VCO is connected to the output terminal of servo controller to form a closed loop. In the closed-loop condition, the system's relative frequency stability was measured after 3 m fibre phase noise compensation; the counter (Agilent 53230) continuously made measurements for 60000 s. The ADEV calculated by the Stable32 software is shown in Fig. 3.

Figure 3 shows that, after the phase noise compensation, the relative frequency stability of 3-m fibre link is $1.01 \times 10^{-16}$/s, falling down to $3.46 \times 10^{-19}/10^4$ s. During the integration time from 10 s to 4000 s, ADEV shows a downward trend of $1/\tau$. It indicates that the phase noise mainly consists of phase-modulated white noise and phase-modulated flicker noise.

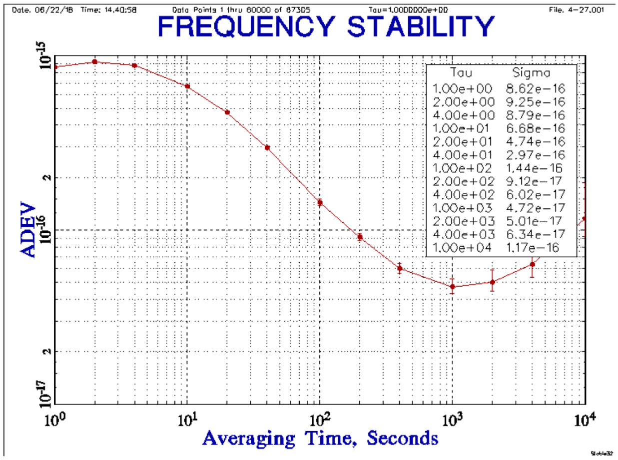


Fig. 2. The relative frequency stability of 3 m fibre free running.

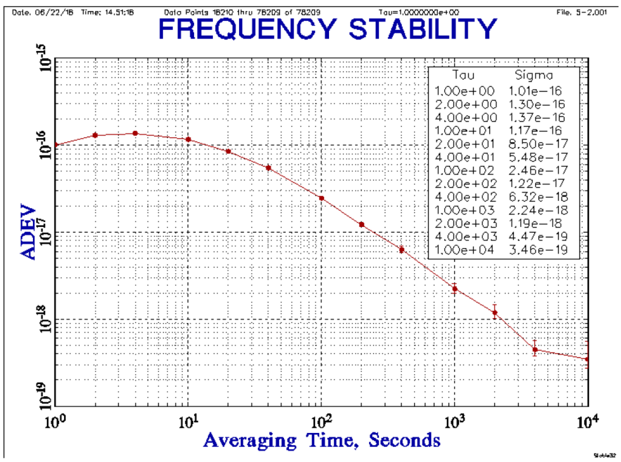


Fig. 3. The relative frequency stability after the phase noise compensation via 3 m fibre.

After the experiment with 3 m fibre optical frequency transfer had been completed, the optical frequency transfer experiment was carried out over a 10 km spooled fibre. The 10 km spooled fibre connected the source end with the user end. Then, the relative frequency stability of the open-loop free-running system was measured, and the uncompensated relative frequency stability of 10 km was calculated. The counter (Agilent 53230) continuously made measurements for 60000 s. The ADEV calculated by the Stable32 software is shown in Fig. 4.

As seen from Fig. 4, the relative frequency stability of the free-running optical frequency transfer over the 10 km fibre at an averaging time of 1s and $10^4$ s are $1.81\times10^{-14}$ and $2.48\times10^{-15}$, respectively. In addition, the downward trend of ADEV with free running over 10 km fibre does not conform to any of five kinds of phase noise, indicating that it contains multiple noise components.

Next, the voltage-control terminal of the VCO was connected to the output terminal of servo controller to form a closed loop. The system relative frequency stability was measured after 10-km

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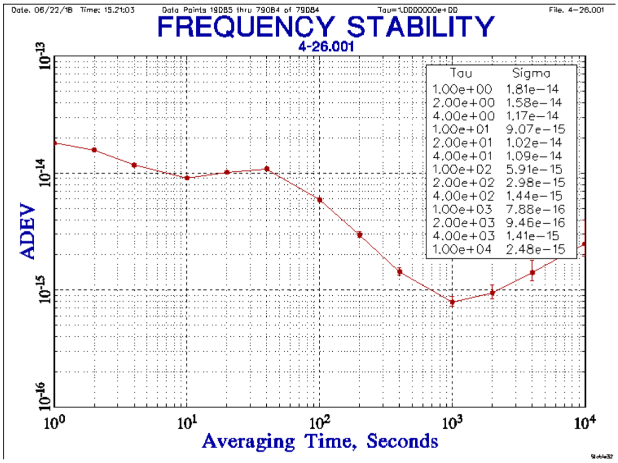


Fig. 4. The relative frequency stability after the phase noise free running via 10 km fibre.

fibre phase noise compensation, the counter (Agilent 53230) continuously made measurements for 60000 s. The ADEV calculated by the Stable32 software is shown in Fig. 5.

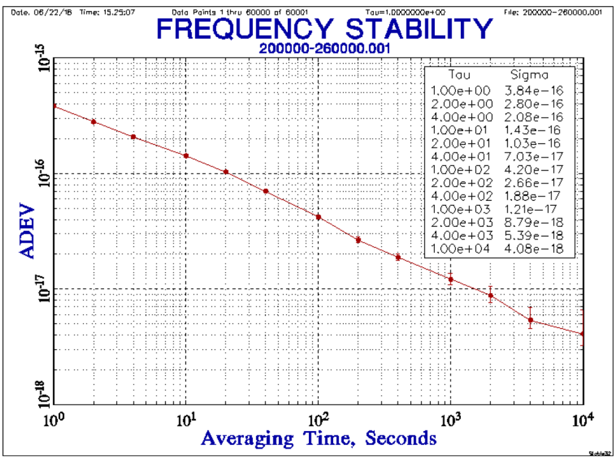


Fig. 5. The relative frequency stability after the phase noise compensation via 10 km fibre.

Figure 5 shows that the relative frequency stability after the phase noise compensation via 10 km fibre is $3.84 \times 10^{-16}$/s, falling down to $4.08 \times 10^{-18}/10^4$ s. During the integration time from 1 s to $10^4$ s, ADEV shows a downward trend of $1/\tau^{1/2}$, indicating that the residual noise consists mainly of the FM white noise.

To further show the effects of compensation and free running, we compared the relative frequency stability of the above experiments, as shown in Fig. 6. The relative frequency stability after the phase noise compensation via 10 km fibre decreases from $1.81 \times 10^{-14}$/s and $2.48 \times 10^{-15}/10^4$ s to $3.84 \times 10^{-16}$/s and $4.08 \times 10^{-18}/10^4$ s, respectively, compared with that obtained for 10 km free running. The relative frequency stability is improved by about 2∼3 orders of magnitude.

The relative frequency stability after 10 km fibre phase noise compensation is close to the relative frequency stability after 3 m fibre phase noise compensation, which greatly compensates the phase noise caused by the fibre.

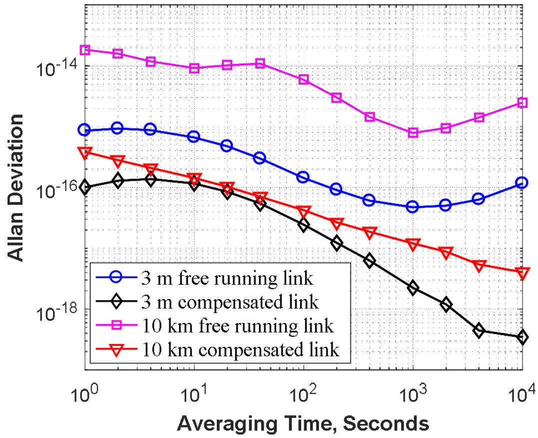


Fig. 6. The relative frequency stability after the phase noise compensation/free running via 3 m/10 km fibre.

Moreover, we also measured the phase noise of the 80 MHz beat signal using the phase noise test set 5125 A for each experiment, as shown in Fig. 7. It can be seen that the phase noise of the 80 MHz beat signal at 10-km free running is about: 59 dBc/Hz@0.01 Hz, 38 dBc/Hz@0.1 Hz and 8 dBc/Hz@1 Hz. The phase noise of the 80MHz beat signal at 10-km fibre phase noise compensation is about: 34 dBc/Hz@0.01 Hz, 14dBc/Hz@0.1Hz and −15 dBc/Hz@1 Hz. Compared with the 10 km free running, the phase noise of the 10 km fibre phase noise compensation experiment is greatly improved (by about 24 dB) at the near end.

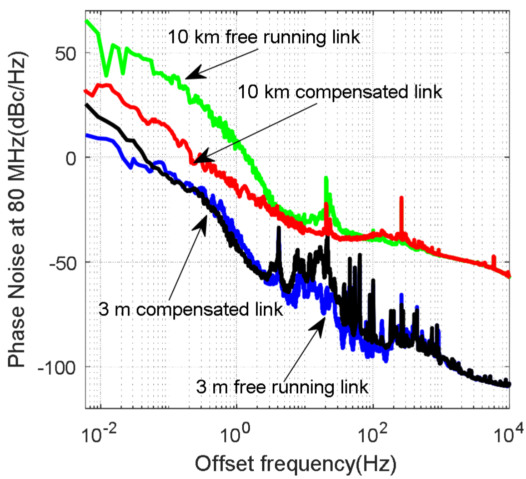


Fig. 7. The phase noise after the phase noise compensation/free running via 3 m/10 km fibre.

## 4. Conclusions

In conclusion, a new fibre optical frequency transfer method with a single AOM was proposed and experimentally demonstrated in China Academy of Space Technology(Xi'an). In comparison with the existing dual-AOM scheme, the main contribution of the proposed scheme is transferring the optical frequency via fibre based on active phase noise compensation with a single AOM at the source end. The method simplifies the equipment of the user end while maintaining the frequency stability of frequency transfer. The results demonstrated that the relative frequency stability of optical frequency transfer over a 10 km fibre was improved by about 2~3 orders of magnitude – from $1.81 \times 10^{-14}$/s and $2.48 \times 10^{-15}/10^4$ s without the fibre noise cancellation setup to $3.84 \times 10^{-16}$/s and $4.08 \times 10^{-18}/10^4$ s with the fibre noise cancellation setup, respectively.

In the subsequent work this method will be applied to a urban communication link by using ultra-narrow linewidth lasers with linewidths better than 1 Hz to support the ultra-long-range optical frequency transfer and its use in high-tech applications.

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