

Polarization Scramblers to Solve Practical Limitations of Frequency Transfer

Dan Xu , Olivier Lopez , Anne Amy-Klein , and Paul-Eric Pottie 

Abstract—Polarization variations in optical fibers are complex and would severely affect the performances of polarization-sensitive signal distribution systems. Owing to advances in experimental techniques and theoretical tools, we observe the effect of polarization variations in the optical fibers and we demonstrate that polarization mode dispersion (PMD) dominates the free-running fiber noise. Ultrahigh correlation, over 99%, is found between the phase fluctuation induced by polarization variation and the temperature fluctuation impacted on the optical fibers. By means of a polarization scrambling technique, the polarization variations in the optical fiber are averaged and the phase perturbations are minimized. It provides a promising solution for suppressing the random disturbances of polarization in the fiber-based optical frequency transfer system and quantum key distribution (QKD) system.

Index Terms—Optical fiber link, polarization mode dispersion, polarization scrambler, two-way noise compensation, ultrastable frequency transfer.

I. INTRODUCTION

THE physics of optical fibers has been explored in depth because of its importance for fiber-optic communication. One attractive feature of optical fibers is that an environmentally isolated fiber can be considerably more stable than free-space paths, especially in urban environments. The optical fiber link have demonstrated outstanding capabilities to transfer time and frequency signals, which enables the comparison of remote atomic clocks [1]–[4]. It also attracts much attention in offering the possibility to implement long-distance quantum communication protocols like quantum key distribution (QKD). By applying quantum entanglement to pairs of photons, these QKD systems can be naturally integrated into existing wavelength-division-multiplexed (WDM) networks, thereby taking advantage of the

vast fiber-optic infrastructure, which is ubiquitously deployed around the globe [5]–[13].

The transmission distance of a fiber-optic communication system has traditionally been limited by fiber attenuation and by fiber distortion. Fiber attenuation is caused by a combination of material absorption, Rayleigh scattering, Mie scattering, and connection losses. Polarization dependent gain and polarization dependent losses introduce also a rotation of the state of polarization (SOP) that needs to be compensated for. In the frequency metrology domain, it can be simply compensated with optical amplifiers and optical repeater techniques with automatic polarization control [14]–[16]. In the quantum communication domain, QKD system has been verified over distances up to 100 km in combination with existing fiber telecommunication networks using polarization-entangled photons [13]. In addition, recent developments relying on active fiber noise stabilisation to lock two independent laser wavelengths and with a single photon detector, demonstrate twin field quantum key distribution (TF-QKD) over 300 km optical fiber spools [17]. Further, with the implementation of quantum repeaters, it will enable transmission distance beyond the metropolitan length scale.

Comparatively, the random birefringence evolution in optical fibers can be affected and accumulated by numerous environmental factors such as temperature variations and mechanical perturbation. Polarization mode dispersion (PMD), due to the birefringence, defines a fast and a slow polarization mode orthogonal to one another, and slight imperfections or distortions in a fiber core can alter the propagation velocities for these two polarizations and alter the propagation delay [18]. Moreover, the directions of both fast and slow axes of the link move randomly in time. Therefore, the final output polarization may change randomly in optical networks. Passive optical components can also alter the SOP of the light travelling through the fiber, so it is a combination of SOP change and PMD change that introduce time-varying delay propagation. With mid-range dedicated fiber and without Dispersion Compensation Fiber (DCF) spools we demonstrated optical frequency transfer with relative frequency stability in the low- 10^{-17} [19]. But the situation is worse for in-field implementation of 2-fiber unidirectional frequency transfer where DCF spools are used as they introduce supplementary asymmetry. Recent studies show limitation for optical and radio-frequency (RF) transfer at the level of 10^{-16} relative frequency stability in such 2-fiber uni-directional architectures [20].

For RF transfer, to reduce the sensitivity to PMD in the fibre, a polarization scrambling technique was proposed and demonstrated in the RF and hyper-frequency (HF) domain [21],

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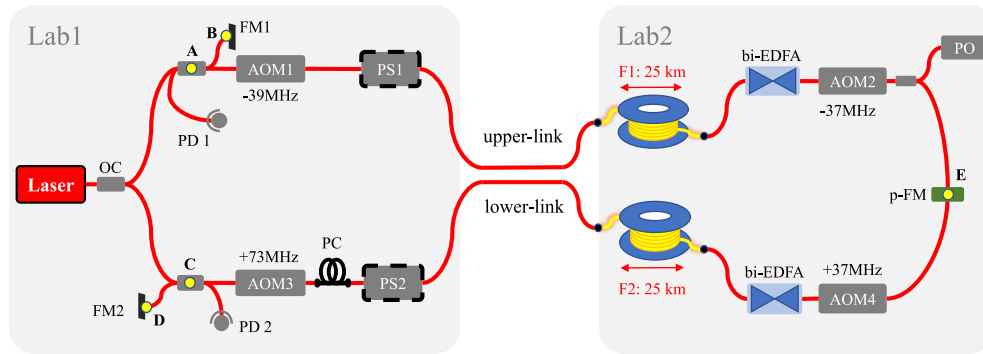


Fig. 1. Experimental setup. OC, Optical Coupler; FM, Faraday Mirror; AOM, Acousto-Optic Modulator; PD, Photo-diode (PD1 on fiber 1, PD2 on fiber 2); bi-EDFA, bi-directional Erbium-Doped Fiber Amplifier; p-FM, partial Faraday Mirror; PC, Polarization Controller; PS, polarization Scrambler; PO, in-line polarimeter. Labels A to E are used to describe the various light propagation paths in the text.

[22]. For optical frequency comparison the polarization-induced propagation delay fluctuations are (partially) correlated for the forward and backward signals and this asymmetry degrades the effectiveness of the noise compensation and introduce possible frequency bias.

For polarization entanglement-based QKD, sufficiently large PMD could severely deteriorate the entanglement between two photons [23], [24]. The fluctuations in the polarization state over optical fibre result in an increased quantum bit error rate (QBER) and therefore a reduction of the key rate. The most common solution is to use the polarization feedback system for automatic polarization stabilization [25], [26]. This active compensation approach, however, will either be time-consuming or increase the complexity of the system, which may compromise the practical security of QKD.

Here we isolate experimentally the effect of PMD on the propagation delay fluctuations and investigate the time evolution of PMD in spooled fiber links, where temperature fluctuations are larger than in in-field buried links. We demonstrate strong correlation between delay variations of an optical frequency signal and temperature variations impacted on the optical fibers. We show the physical process of polarization mode dispersion supported by the direct recording of unitary Stokes parameters representing the output SOP after propagation. We are further able to reduce the sensitivity to this polarization effect by scrambling the polarization state of the optical frequency signal before it injects into fiber link without altering the optical detection, thereby improving the resilience of fiber links to their environmental variations. The effectiveness of this polarization scrambling technology is confirmed for the first time in optical frequency domain, for uncompensated and compensated 2-fiber links operated uni-directionally, solve practical limitations of frequency transfer on unidirectional architectures that enables very attractive possibilities in respect of future implementation on active telecommunication networks. Moreover, it provides a promising solution for removing the random disturbances of polarization in the QKD system.

II. EXPERIMENTAL SETUP

Our system is schematically shown in Fig. 1 and is intended to analyse propagation delay fluctuations properties in single-mode

fibers [27], [28]. The laser source located in Lab1 is a narrow bandwidth laser emitting at 1542.14 nm, phase and frequency locked to an ultra-stable laser with a bandwidth of about 100 kHz. The line width of the ultra-stable laser, and therefore of the slave laser, is about 1 Hz [29]. The coherence time of the slave laser largely exceeds the propagation time into the fiber. Chromatic dispersion is also very negligible. The laser has a stable linear output polarization state. Light beams carrying frequency reference or other types of quantum information are splitted in two with a 50-50 Optical Coupler (OC) and injected into two distinct 25-km spooled fibers located in Lab2. The two fiber spools have approximately the same optical length, within a few meters. The fibers are Corning SMF-28e fiber type. The attenuation is ~ 0.2 dB/km, and the PMD is specified as < 0.2 ps/ $\sqrt{\text{km}}$. For each link, a coupler and a Faraday Mirror (FM) are used to build a strongly unbalanced Michelson interferometer and measure optical phase fluctuation of the long arm as compared to the short arm [14].

By using a partial Faraday mirror (p-FM) in Lab2 [30], the upper link (from A to E in Fig. 1) and lower link (from C to E) are connected. The light sent to Lab2 via the upper-link can be reflected back to Lab1 via the upper-link, or can be transmitted back to Lab1 via the lower-link. In the same way, the light sent to Lab2 via lower-link are partly reflected and partly transmitted. Two bi-directional Erbium-Doped Fiber Amplifiers (bi-EDFAs) are used to compensate for the transmission losses.

We used four Acousto-Optic Modulators (AOMs) set at the extremity of each fiber spools to shift in frequency the light propagating through the fibers. The heterodyne detection enables to distinguish the signals coming from the stray reflections and to distinguish the beat notes carrying on different segments of fiber noise. The set of driving frequencies applied to the four AOMs (see Fig. 1) is such that we have unambiguous determination of all possible fiber paths. This set-up allows us to measure simultaneously frequency fluctuations for light that travels either bidirectionally or uni-directionally, only in spool 1, only in spool2, or any combination of both. More details and performances assessment and noise floor limits were reported in [28].

For this experiment we will focus on two beat notes we denote RT1 (Round-Trip1, at 152 MHz) and LP1 (Loop1, at 34 MHz) on photo-diode PD1. RT1 is the beat note between light propagating forth and back on the AB fiber path and on the AE fiber path

(see Fig. 1 for labels A, B and E). LP1 is the beat note between light on the AB fiber path and light propagating on the fiber path CE-EA. We detect two other beat notes that we denote RT2 (Round-Trip2, at 220 MHz) and LP2 (Loop2, at 34 MHz) on photo-diode PD2. RT2 is the beat note in C between light propagating forth from the OC and the light that propagates along the path CE-CDC. LP2 is the beat note between light propagating forth from the OC and the light that propagates along the fiber path AE-EC-CDC. RT1 and RT2 exhibit the free running round-trip fiber noise on the upper-link (AE) and lower-link (CE), respectively. LP1 and LP2 exhibit the free fiber noise on the loop link (upper link + lower link). They can be used to correct the phase noise of either the upper- or lower-link, for bi-directional or uni-directional set-up [19].

All the beat notes are then filtered, tracked, and simultaneously recorded by a multi-channel dead-time free frequency counter operated in Π -type and Λ -type with 1 s gate time. At the same time, the temperature and humidity data are logged both in Lab1 and Lab2.

For this experiment we added a 50-50 fiber coupler and a polarization analyzer (General Photonics POD-201) at the output port in Lab2, so that the SOP of the light upcoming from the upper-link and that reaches the p-FM can be recorded and analyzed. We record one point per 10 s. A Polarization Controller (PC) is used to optimize the amplitudes of the beat notes without polarization scrambling in a first stage. Note that the amplitudes of the RT1 and RT2 beat notes are automatically optimized thanks to the p-FM [14], [31]. Two commercial 3-axis polarization scrambling units (PS) are added at the input points of the upper- and lower-link to produce scrambled polarization states before the light injects into the fiber links (see Fig. 1). As our measurement are based on heterodyne detection for which the amplitude of the beat note depends on the polarization match between the beating waves, the experimental challenge is to scramble the polarization while keeping the amplitude of the beat note constant.

To solve this issue, we use a phase conjugation technique to achieve the self-demodulation of the scrambling, implemented as follow. The two polarization scramblers (General Photonics Polarite III), acting on three fiber squeezers based on piezoelectric ceramics (PZT), are fed using RF synthesizer (Rigol DG4000) to generate low-frequency waves. We set sinusoidal frequencies at 1 kHz for the X_1 -axis, and 59 kHz for the X_2 - and X_3 -axis of the PSs. The modulation periods were chosen to be short enough as compared to the acquisition time of the beat-note (that is 1 s) and the round-trip propagation delay of the light, so that the polarization is averaged enough over one measurement sample. The higher is the modulation frequency, the better the technique should work. However, the rate is limited by the finite bandwidth of the polarization scramblers. The 59 kHz drive frequency applied to X_2 - and X_3 -axis is chosen to match the resonant frequency of the PZT driver of the polarization scramblers, so that the half-wave voltage V_π is only 4.8 V and that no additional voltage amplification is needed after the wave generator. The low frequency waves at 1 kHz are amplified with a high voltage amplifier to about 50 V. It results in an imperfect but effective scrambling of the polarization as seen in Fig. 2(b) after propagation. Similar pictures are obtained before propagation.

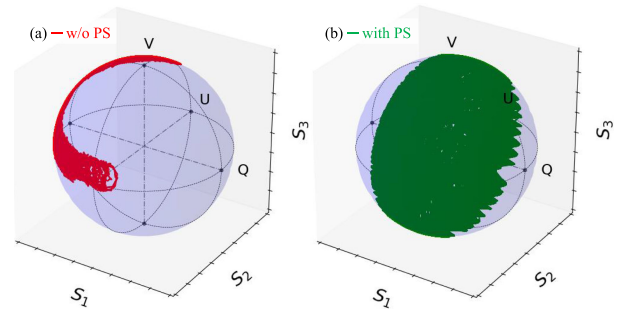


Fig. 2. Polarization states on a Poincaré Sphere, (a) without polarization scrambling (1 point per 10 s over 9 days) and (b) with polarization scrambling (10 points per 1 s over 10 000 s).

In order to conjugate the phase of the two scramblers, we use an additional trick based on the propagation delay and binary phase shift keying. The propagation delay τ of the loop (LP1) from A to C is about 250 μ s. RT1, RT2 and LP2 experience roughly the same delays. A binary π -phase shift keying modulation with a duty cycle of 50% and with a period of $2\tau = 500 \mu$ s, that we set such as to correspond to twice the propagation time, is applied on the driving signals of the two polarization scramblers.

By searching for the minimum amplitude variation of the beat notes of the loop signals LP1 and LP2, we adjusted roughly the phase offset of the scrambling between the forth and back signals. With such experimental set, the polarization scrambler at end C demodulates the received signal from A and vice-versa. The polarization scrambler at end C demodulates also itself, demodulating at time $t + \tau$ the light that was emitted in C at time t (and the same is valid in A). It guarantees that the polarization is scrambled along the link but the beat note detection on PDs are not affected. As a result no amplitude-to-phase modulation is observed during the experiment and the short-term stability at one second remains constant (see explanations below). Note that as the propagation delay variations are in the scale of ns, that are much smaller than the time period of the scrambling, the set-up needed to be adjusted once and is stable afterwards over long integration time.

III. RESULTS AND LIMITATIONS

The phase evolution of the free running one-way propagation delay fluctuations (e.g. $\frac{1}{2}$ RT1) is shown in Fig. 3(a) (left axis, red curve). We checked that $\frac{1}{2}$ RT2, $\frac{1}{2}$ LP1 and $\frac{1}{2}$ LP2 exhibit similar fluctuations. When the phase is translated into a time error, the free running propagation delay fluctuations are at the level of ~ 1.8 ns over 16 days, which is too much for high accuracy signal transmission. To find out its limiting factors and reduce the large one-way propagation delay fluctuations, we analyze and estimate its correlation coefficients with the temperature and humidity variations measured simultaneously both in Lab1 and Lab2. The results show high correlation (99.7%) between the free running fiber noise and the temperature variation in Lab2, as shown in Fig. 3(a) (right axis, black curve). It means that the key limiting factor for free running propagation delay fluctuations arises from the temperature variations of the spooled fiber. The temperature variations introduce birefringence. Birefringence in the fiber causes severe effects on the polarization

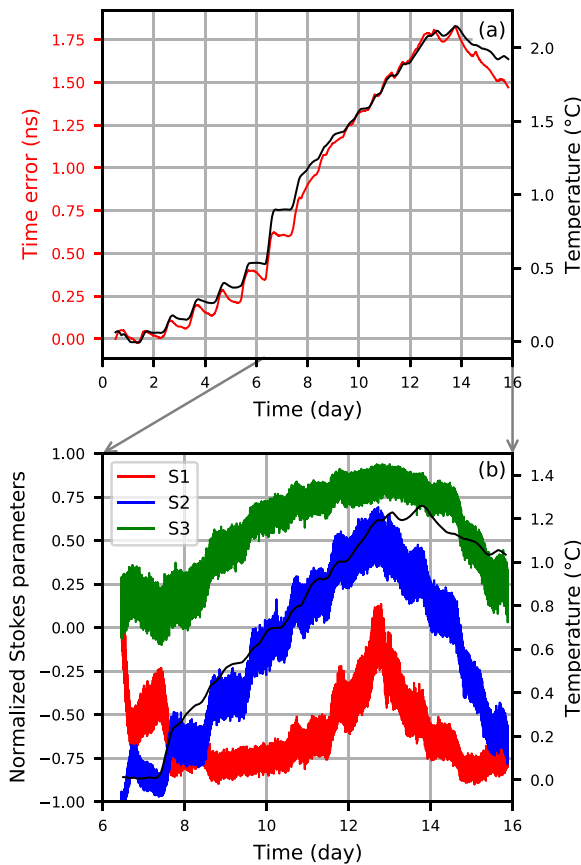


Fig. 3. (a) High correlation between the free running one-way fiber noise (left axis, red line) and the temperature variations of the optical fibers (right axis, black line) over about 16 days, (b) the normalized Stokes parameters (S1, S2, S3) of a polarimeter (left axis) measured over the last ~ 10 days.

state, in particular polarization mode dispersion. Due to PMD, the propagation delay along the fiber link changes with its temporal polarization state. Therefore, PMD effects of the fiber are believed to hinder long-distance transmission. Note that passive and active components along the fiber have a negligible PMD below 1 ps.

The polarization states were measured by a polarimeter at the output of upper-link (see in Fig. 1), overlapping the last ~ 10 days in Fig. 3(a). The long-term polarization tracking is shown in Fig. 3(b) expressed by three normalized Stokes parameters (S1, S2, S3) with sampling rate of 0.1 Hz. The long-term polarization drifts during ~ 10 days is obvious. In addition we see interestingly some daily variation in the Stokes parameters. So we investigate all the places that go through along the link, some temperature cycling going on during the day-night in Lab2 accounts for it, shown in Fig. 3(b). The temporal polarization state variation in a real-time graphic display is also provided and shown in Fig. 2. During the ~ 10 days, the polarization state moves slowly and randomly on the Poincaré Sphere.

This PMD effect will cause nonreciprocal noise in our frequency transport in the optical fiber and results in a degraded stability. The directions of both fast and slow axes of the link move randomly in time due to temperature variations along the fiber. As a consequence, the random variation of the propagation

delay are not the same for the forward signal and the backward signal, especially for two adjacent fibers. Thus the polarization of the upper-link and lower-link transmitted signals changes and leads to phase fluctuation asymmetry, which cannot be compensated in the closed-loop stabilization system.

To show this asymmetry, we introduce a two-way unidirectional (TWU) observable, $TWU = \frac{1}{2}(RT1 - RT2)$. Since the phase noise along a single fiber is strongly reciprocal, the TWU observable measures the phase difference between light propagation in the upper-link and lower-link. It was previously shown that the observation does not depend on the direction of propagation at least at the level of 10^{-18} [19]. With this combination, the symmetrical noise on upper- and lower-link are suppressed and the residual asymmetrical noise is shown in Fig. 4(b)(red). It amounts around 50 ps on 16 days, which is 3% of the total noise 2 ns. We checked that other TWU observables, such as $\frac{1}{2}(LP1 - LP2)$, exhibit the same behaviour.

When PMD starts to dominate the frequency stability, RF frequency transfer experiments carried years ago solved the issue with rapid polarization scrambling to average out the PMD effect [21], [22]. Such a solution is possible for an optical frequency transfer as well, provided that one preserves the amplitude stability of the heterodyne beat notes. This is what our set-up demonstrates for the first time, to the best of our knowledge. Thanks to the phase conjugation between the two polarization scramblers, no amplitude-to-phase modulation is observed and, as a matter of fact, the short-term stability at one second remains constant with polarization scrambling.

Figure 2(b) displays the rapid polarization state variation with scrambling in a time scale of 10 000 s with sampling rate of 10 Hz. Compared to the situation without polarization scrambling, the Poincaré Sphere is mostly covered rapidly. In this situation, the polarization state of the signal is averaged and the effects of random polarization rotation are minimized.

Figure 4(a) shows the free running one-way noise without (red) and with (green) the polarization scrambled. The propagation delay fluctuation is significantly reduced, just ~ 0.15 ns over 10 days. Fig. 4(b) shows the TWU observable without (red) and with (green) the polarization scrambled. For comparison, their phase noises are suppressed significantly and the signature of diurnal temperature variation disappears for both of one-way and TWU when the polarization states are scrambled. Their fractional frequency stability in terms of modified Allan deviation (MDEV) are shown in Fig. 4(c). Typically, the free-running one-way (red solid line) displays a plateau after 100 s integration time and afterwards following a bump around 20 000 s integration time which we attribute to the diurnal temperature fluctuations acting on the fibers. Fig. 4(c) (red dashed line) shows typical MDEV of TWU observable which displays the characteristic flat dependence on integration time. In contrast, when scrambling the polarization, the long-term stability of the free-running one-way is improved to the mid- 10^{-16} level and the bump around 2×10^4 s is suppressed about one magnitude, as shown in Fig. 4(c) (green solid line). For TWU, its long-term stability is also improved, as shown in Fig. 4(c) (green dashed line). It demonstrates that the polarization effects are strongly cancelled out. The relative frequency stability is below 6×10^{-17} for

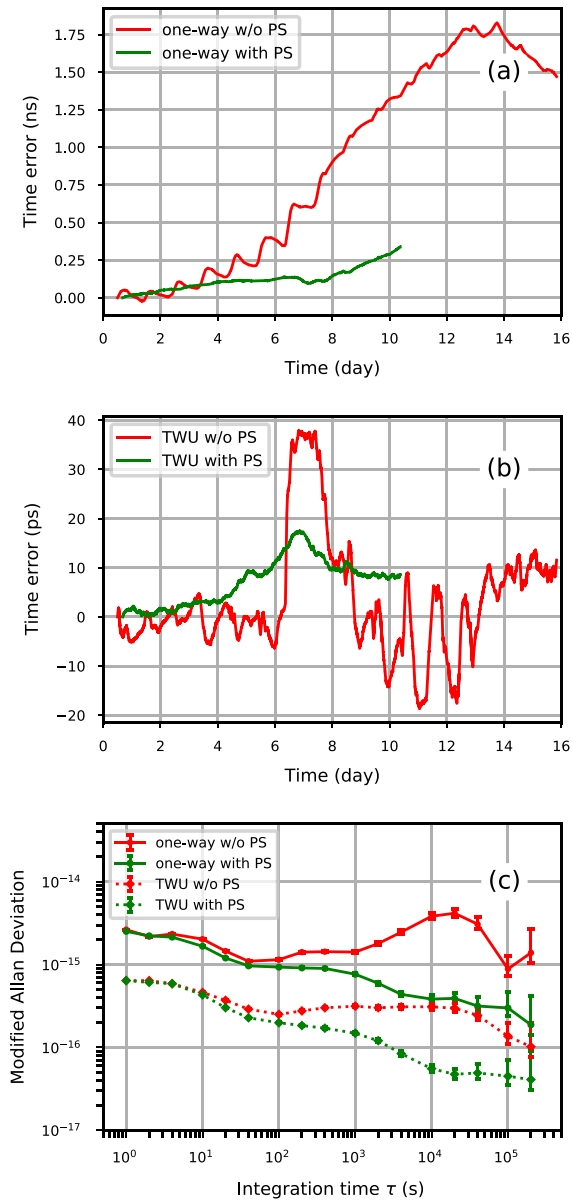


Fig. 4. (a) Free running one-way fiber noise without (w/o) and with polarization scrambler(PS), (b) two-way unidirectional phase noise without and with polarization scrambler(PS), (c) fractional frequency stability of the one-way and TWU without and with polarization scrambler(PS).

integration time $> 10\,000$ s, which is the best performances reported so far using spools, and overcomes limitations foreseen for in field fibers where dispersion compensation spools are used as in [20].

IV. CONCLUSION

We observe polarization states variations in the fiber link due to temperature changes, which leads to propagation delay fluctuations in optical frequency transfer. Since the polarization drift will cause degraded long-term stability for free-running fiber noise, we proposed and realized a polarization scrambling scheme to eliminate by averaging the propagation delay fluctuations induced by polarization mode dispersion and their

sensitivity to temperature. In this work, we demonstrate its effectiveness for uncompensated and compensated 2-fiber unidirectional optical frequency transfer. The polarization effect is effectively reduced and the periodical phase fluctuations induced by the daily temperature variations are cancelled out. Moreover, the corresponding long-term instabilities are significantly improved: The free-running one-way is improved to mid- 10^{-16} for the first time. TWU reaches the mid- 10^{-17} level after one day's integration time.

The positive results of the proof-of-concept experiment demonstrate the feasibility of our polarization scrambling scheme valid in a general case and we show results in the particular case of fiber spools, where the PMD is also expected to be high due to constraints of the spool. In the future, our experimental set-up can be improved with a 6-channel wave generator and a fully independent voltage amplifiers set, which will allow us to optimize much more carefully the experimental parameters. Indeed we believe that the performance can be further enhanced with optimized polarization modulation frequencies and optimized self-conjugate modulation-demodulation.

For installed buried fibers, the polarization variations couple more weakly to external environment, so we inspect little influence on polarization-sensitive systems deployed on field fibers. This gives the explanation for no obvious bump on the long-term stability with uni-directional two-way measurement deployed on the 43-km SYRTE-LPL link [30].

Beside being of fundamental interest for understanding fiber-based time and frequency transfer in metrology domain, our study also has practical implications as it directly applies to polarization-sensitive quantum key distribution system. The improved ability against external environmental variations reveal its prospective application more generally to any fiber-based communications.

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