All-passive multiple-place optical phase noise cancellation

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We report on the realization of delivering coherent optical frequency to multiple places based on passive phase noise cancellation over a bus topology fiber network. This technique mitigates any active servo controller on the main fiber link and at arbitrary access places as opposed to the conventional technique, in which an active phase compensation circuit has to be adopted to stabilize the main fiber link. Although the residual fiber phase noise power spectral density (PSD) in the proposed technique turns out to be a factor of 7 higher than that of the conventional multiple-access technique when the access place is close to the end of the fiber link, it could largely suppress the phase noise introduced by the servo bumps, improve the response speed and phase recovery time, and minimize hardware overhead in systems with many stations and connections without the need of the active servo circuits including phase discriminators and active compensators. The proposed technique could considerably simplify future efforts to make precise optical frequency signals available to many users, as required by some large-scale science experiments. © 2021 Optical Society of America

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Atomic optical clocks have rapidly grown in the last decade and are proving to be a powerful tool for investigation of fundamental and applied physics [1–5]. Precision clock networks are of particular interest in precision measurements and fundamental physics tests, such as general relativity, temporal variation of the fundamental constant [6], searching for dark matter, gravitational waves and physics beyond the Standard Model [7–10], as well as providing innovative quantum technologies for other branches of science [11]. Most of the applications mentioned above require high-precision clock networks with multiple places over fiber links. To achieve this aim, active compensation schemes as first demonstrated in 1994 by Ma et al. have been proposed to cancel the fiber-induced phase drift and implement highly stable optical frequency distribution [12], which generally utilizes the phase error from a round-trip probe signal to achieve the feedback control of a voltage-controlled oscillator (VCO) via a servo controller [12]. One intriguing question is how to distribute a reference optical frequency to many users simultaneously in a cost-effective and robust way.

In the past years, many works have demonstrated that coherence optical phase can be delivered to multiple users with the help of servo controllers. Grosche et al. have first proposed and demonstrated to extract the ultrastable signal for multiple users along the active phase stabilized main link [13], enabling to tap the fiber anywhere with the same precision level as that achieved at the main link output. Alternatively, a branching optical fiber network with phase noise correction at each output end has been proposed and experimentally demonstrated [14, 15]. All these existing demonstrators for the multiple-access applications have to adopt at least one active servo controller for the main fiber link [13, 16–18] or for each branch fiber link [14, 15, 19]. Consequently, the overall performance of the above mentioned techniques is mainly dependent on whether the servo controller’s parameters set properly [20]. For example, there will be occasional interruptions where a phase lock temporarily loses lock, corresponding to unpredictable jumps in the optical signals. These interruptions will reduce the effective averaging time to bias the measurement [12]. Moreover, the effect of the servo bumps on the main fiber link will pass to each access place and corrupt the spectral purity received by each place.

In our previous work, we have demonstrated optical frequency transfer with passive phase stabilization over a bus or a ring fiber network [19, 21]. The technique possesses the advantages of an unlimited compensation precision and a fast compensation speed and free from the effect of servo bumps on the spectral purity [19, 21]. However, the feasibility and adaptability of the passive phase noise cancellation technique for the multiple-access application needs to be theoretically and experimentally studied. Therefore, the investigation of the novel multiple-access optical frequency transfer scheme which implement alternative phase correction techniques other than the more commonly used conventional, active, phase correction technique is seeing increasing demand. Improving the robustness and sensitivity of multiple-access optical frequency transfer devices, as well as understanding and characterizing the limitations of the novel multiple-access optical frequency transfer scheme with passive phase correction is an important step towards the goal of heralding a new generation of viable precision optical frequency
transfer devices. These devices could be employed in the above mentioned applications [1–11].

In this article, we extend the study of the optical frequency transfer technique based on our previous passive phase correction technique [19, 21], demonstrating its application as a multiple-access optical frequency transfer technique. We experimentally study the optical frequency transfer stabilities, phase noise power spectral densities (PSDs) and accuracies for the two access places at the most symmetric 50/50 km ($L_a/L_b$) one and the relative asymmetric 70/30 km one, over a total fiber link of $L = 100$ km. In comparison with our previous work [19, 21, 22], in which we have demonstrated multiple-place optical frequency transfer over the star and ring fiber networks with the passive phase noise cancellation technique, here we demonstrated that a high performance multiple-place optical frequency transfer over the widely adopted bus fiber topology with all-passive phase noise cancellation at the access places and the main fiber link. The proposed technique could increase the adaptability to incorporate the optical frequency transfer technique into any existing communication networks with different topologies.

Figure 1 shows the schematic diagram of multiple-place optical frequency transfer with a simple extraction along the passively stabilized main link. The main optical link aims at regenerating a coherent optical phase at the output end of the fiber [21] and at any places along the fiber as the input end of the fiber. The principle of passively stabilizing the main fiber link can be found in [19, 21]. In brief, an ultrastable reference $\nu_s$ at the local site is upshifted by frequency of $\omega_1$ with an acousto-optic modulator (AOM) denoted as AOM1 and then injects into the fiber. At the output, the light is downshifted by frequency of $\omega_r$ with the AOM2 (here $\omega_1 > \omega_r$), and part of light is sent back with a Faraday mirror (FRM). The round-trip signal is mixed with the input ultrastable laser using an interferometer consisting of an optical coupler (OC) and another FRM. The beatnote radio frequency (RF) signal is twice the sum of the AOMs’ frequencies and exhibits the round-trip phase noise, $2\phi_p$, with $\phi_p = \phi_a + \phi_b$, where $\phi_a$ and $\phi_b$ are the noise of the fiber spans of length of $L_a$ and $L_b$, respectively. Afterwards, we divide the beatnote with a factor of 2 and then mix the divided signal with an assistant frequency of $\omega_s$. The lower sideband of the mixed signal, $\omega_s - \omega_1 + \omega_r$, is used. Afterwards, the mixed signal together with $\omega_1$ is fed into the electrical port of the AOM1. Finally at the output end, the phase fluctuations of the optical frequency $\nu + \omega_s - \omega_1$ are automatically cancelled.

At each access place, the configuration is similar with the one presented in [13], at a distance $L_a$ from the input end and $L_b$ from the output end, a $2 \times 2$ optical coupler is adopted to extract both the forward and backward signals from the main fiber. The forward signal can be expressed as,

$$S_F(\omega) \propto \cos((\nu + \omega_1)t + \phi_a) + \cos((\nu + \omega_s - \omega_1 + \omega_r)t - \phi_p + \phi_b).$$

(1)

Similarly, the backward signal has a form of

$$S_B(\omega) \propto \cos((\nu - 2\omega_r + \omega_1)t + \phi_p + \phi_b) + \cos((\nu + \omega_s - \omega_1 - \omega_r)t + \phi_b).$$

(2)

The beatnote frequencies between $\nu + \omega_1$ and $\nu - 2\omega_r + \omega_1$ and between $\nu + \omega_s - \omega_1 + \omega_r$ and $\nu + \omega_s - \omega_1 - \omega_r$, result in the same frequency of $2\omega_r$ with the phase fluctuation $2\phi_p$. The signal is divided by a factor of 2, filtered, and drives an AOM (AOM3) in order to correct for the frequency and phase fluctuations of the forward signal. The forward signal after passing through the AOM3, is thus downshifted to,

$$S_F(\omega) \propto \cos((\nu - \omega_r + \omega_1)t + \phi_p) + \cos((\nu + \omega_s - \omega_1)t).$$

(3)

A similar phase noise cancelled signal can be obtained on the backward extracted signal with an opposite frequency shifter. Thus, the phase noise of the remote site and the access sites are automatically cancelled.

As demonstrated by Williams et al., the phase noise rejection capability is limited by the propagation delay [23]. The residual phase noise PSD, $S_{access}(f)$, at each access place in terms of the single-pass free-running phase noise PSD, $S_{fiber}(f)$, and the
single-pass fiber link $L$ propagation delay, $\tau_0$, by compensating
the forward optical signal can be expressed as [22, 23],

$$S_{\text{access}}(f) \simeq (2\pi f \tau_0)^2 \left[ 1 + \left( \frac{2L_d}{L} - \frac{2}{3} \left( \frac{L_d}{L} \right)^2 \right) S_{\text{fiber}}(f) \right]. \quad (4)$$

Note that, in comparison with the conventional multiple-access
scheme, the phase noise rejection capability of both the
conventional and proposed techniques is proportional to $S_{\text{fiber}}(f)$
and the uncompensated single-pass fiber phase noise PSD, $S_{\text{fiber}}(f)$.
Although, the residual fiber phase noise PSD in the proposed
technique turns out to be a factor of 7 worse than that of in
the conventional multiple-access scheme at the output of the fiber
link ($L_d = L$) [16, 19], it could largely suppress the phase
noise introduced by the servo bumps (see Fig. 2), which could
significantly increase as the increase of the fiber link [24], and
simplify the hardware overhead in systems with many stations
and connections [21].

![Fig. 2. Measured phase noise PSDs of (a) the 70/30 km free-running access place (blue curve), (b) the 50/50 km free-running access place (orange curve), (c) the compensated 70/30 km access place (black curve), (d) the compensated 50/50 km access place (magenta curve), and (e) the 70/30 km theoretical delay-limited value (gray curve). Strong servo bumps can be effectively removed in the proposed scheme.](image)

![Fig. 3. Measured fractional frequency instability, calculated from $\Pi$-type data with the overlapping Allan deviation (ADEV), of the 100-km free-running main link (red triangles), the stabilized 70/30 km access place output (black squares), the compensated 50/50 km access place output (blue circles), and the noise floor, in which the fiber links are replaced by the short fibers, of the access place output (gray diamonds).](image)

Figure 2 shows the phase noise power spectral densities
(PSDs) of the stabilized 70/30 km access place (c, black curve) and
the stabilized 50/50 km access place (d, magenta curve), respectively.
The phase noise PSDs of the free-running 70/30 km access
place (a, blue curve) and the 50/50 km access place (b, orange curve) are also shown. The free-running curve is typical for
optical fiber links, with a noise of approximately 100 rad$^2$/Hz at
1 Hz for the 70/30 km access place, scaling down with a slope
of about $f^{-2}$, and reaching around $10^{-5}$ rad$^2$/Hz after 100 Hz.
Their noises of the free-running 70/30 km (a, blue curve) and
50/50 km access places (b, orange curve) slightly differ because the
two measurements are performed at different times. At the
same time, both passive phase stabilized cases are also very
similar with the phase noise PSDs about $10^{-5}$ rad$^2$/Hz between 1
and 100 Hz. We can clearly see that the noise correction is
limited by the main fiber propagation delay approximately $\sim 150$
Hz, which is compatible with the theoretical bandwidth of 189
Hz given by $1/(4\sqrt{\tau_0})$. This limit is the same for both access
places because the bandwidth of the extraction is limited by the
longer delay, namely the main fiber link delay [16]. More
importantly, we can clearly see that compared with the conventional
multiple-access optical frequency transfer technique [13–15],
the strong servo bumps are effectively suppressed in our passive
phase noise suppression technique as observed in our previous
work [19, 21, 22].

Figure 3 displays the fractional frequency stability of the
free-running and passively stabilized configurations, calculated from II-type data with overlapping Allan deviation (ADEV). The stability of the 70/30 km (50/50 km) access place is $3.1 \times 10^{-15}$ ($2.0 \times 10^{-15}$) at 1 s averaging time, decreases as a slope of approximately $\tau^{-1}$ and reaches a floor of approximately $4.1 \times 10^{-19}$ ($3.3 \times 10^{-19}$) at $10^4$ s. As calculated by Eq. 4, the ratio of the stability of the 50/50 km and 30/70 km places should be $R = 0.64$. In our experiment, we also obtain the ratio of $R \approx 0.64$ ($2.0 \times 10^{-15}/3.1 \times 10^{-15}$). As a comparison, we also measured the noise floor for the access output as displayed in Fig. 3. The long-term stability is mainly attributed to the thermal noise on uncompensated fibre paths, due to imperfect length adjustment and thermal stabilisation in the extraction optical set-up, or in the main fiber link [22, 25]. Compared with our previous work in which we characterized the system performance at the output of the main fiber link [21], the ultrastable laser can be thus transferred through the secondary and main links without significant degradation.

![Figure 4](image_url)

**Fig. 4.** Frequency comparison between input and access place frequencies after 70 km over the 100 km fiber. (b) 84,014 data points were taken with dead-time free II-type frequency counters with a 1 s gate time (green points, left axis). We calculated unweighted mean (II-type) values for all cycle-slip free 1,000 s long segments, resulting in 84 data points (black dots, right frequency axis, enlarged scale). Histograms (brown bars) and Gaussian fits (red curves) for (a) frequency values taken with one second gate time and (c) 84 phase coherent 1,000-second frequency averages.

Complementary to the characterization of the stability and phase noise, the accuracy has to be throughout-fully examined by calculating the mean value of the end-to-end beatnote frequency offset. Figure 4(b) shows the frequency deviation of the beatnote’s data for the 70/30 km access place, recorded with a 1 s gate time and II-type counters, over successive 84,014 s (green point, left axis) and the arithmetic mean of all cycle-slip free 1,000 s intervals (black dots, right axis). Histograms (brown bars) and Gaussian fits (red curves) of the frequency deviation for the access place after 70 km are also illustrated in Fig. 4(a) and (c). According to the Gaussian fit in Fig. 4(c), the calculated results demonstrate that the mean frequency is shifted by $-28.9 \mu$Hz ($-1.5 \times 10^{-15}$). The standard deviation of the 1,000 s data points is $493 \mu$Hz ($2.5 \times 10^{-18}$), which is a factor of 1,000 smaller than the ADEV at 1 s as expected for this II-type evaluation. Considering the long-term stability of frequency transfer as illustrated in Fig. 3, we conservatively estimate the accuracy of the transmitted optical signal as shown in the last data point of the ADEV, resulting in a relative frequency accuracy of $4.1 \times 10^{-19}$.

Adopting the same procedure, the mean frequency offset and the standard deviation for the 50/50 km place were calculated using the 1000 s point with the total 89,690 II-type counter data to be $52.2 \mu$Hz ($2.7 \times 10^{-19}$) and $454 \mu$Hz ($2.3 \times 10^{-18}$), respectively. Taking into account the long-term ADEV at 10,000 s of the data set for the 50/50 km access place of $3.3 \times 10^{-19}$, we conservatively estimate that the mean frequency offset is $2.7 \times 10^{-19}$ with a statistical uncertainty of $3.3 \times 10^{-19}$ for the 50/50 km access place. We can conclude that there is no systematic frequency shift arising in the all-passive multiple-place phase noise cancellation setup at a level of a few $10^{-19}$.

In summary, we have presented a new method, making a stable optical frequency available at any arbitrary access places along the fiber link with passive phase noise cancellation. In comparison with previous work, here we demonstrated that a high performance multiple-place optical frequency transfer over the widely adopted bus fiber topology with the open-loop design, mitigating some technical difficulties in conventional active multiple-access phase noise cancellation. We experimentally demonstrate transferring of optical frequency to two different access places. After being compensated, delivering an optical frequency to different places with the relative frequency instability in terms of ADEV measured by the II-mode frequency counter can be as low as $3.1 \times 10^{-15}$ at 1 s and $4.1 \times 10^{-19}$ at $10,000$ s. The frequency uncertainty of the light after transferring through the fiber relative to that of the input light is a few $10^{-19}$ for the access places over the 100 km fiber link.

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