Passive phase noise compensation for fiber-optic radio frequency transfer with a nonsynchronized source

Tiancheng Lin (林天成)[1], Guiling Wu (吴龟灵)[1,2,*], Hongwei Li (李洪伟)[1], Guoyong Wang (王国永)[3], and Jianping Chen (陈建平)[1,2]

[1]*State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Shanghai Key Laboratory of Navigation and Location-Based Services, Shanghai 200240, China*
[3]*China Academy of Space Technology (Xi'an), Xi'an 710000, China*
**Corresponding author: wuguiling@sjtu.edu.cn*

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We propose a passive compensation fiber-optic radio frequency (RF) transfer scheme with a nonsynchronized RF stable source during a round-trip time, which can avoid high-precision phase-locking and efficiently suppress the effect of backscattering only using two wavelengths at the same time. A stable frequency signal is directly reproduced by frequency mixing at the remote site. The proposed scheme is validated by the experiment over a 40 km single mode fiber spool using nonsynchronized common commercial RF sources. The influence of the stability of nonsynchronized RF sources on the frequency transfer is investigated over different length fiber links.

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Fiber-optic radio frequency (RF) transfer has been widely adopted in radio astronomy, deep space networks, and long-distance-distributed radio telescopes[1] due to the advantages of wide bandwidth, low attenuation, and better reliability in fiber links. Considering that it is superior in terms of complexity, compensation range, and compensation speed, passive compensation schemes based on frequency mixing have been regarded as a promising way to suppress the phase fluctuations induced by the temperature, variation, and mechanical vibration of fiber links. Several varieties of passive compensation schemes[2–9] have been proposed and demonstrated. One kind of them employs the signal frequency-dividing[2–5] from phase-locking[6] to the standard frequency signal as the probe signal. In these schemes, triple transmission over the fiber link is needed for one-time compensation, which will reduce the compensation bandwidth and increase the complexity of systems. Another kind of scheme can finish the compensation within one round-trip transmission by employing the signal from an RF source at the remote site as the probe signal[7–9]. The RF source only needs to be stable during a round-trip time (RTT), so the oscillator equipped at the remote site for the operational robustness in practical applications[10] can be directly utilized. In Ref. [7], a high-precision phase-locking control is needed to synchronize the RF source at remote site with the signal from the local site. In Refs. [8,9], the RF source at the remote site does not need to be phase-locked. However, the undistinguished backscattering noises still cannot be avoided, even though two wavelengths have been employed, since the probe signal is still bidirectionally transmitted over the same wavelength.

In this Letter, we propose a passive compensation fiber-optic RF transfer scheme with a nonsynchronized RF source at the remote site, which can avoid high-precision phase-locking and efficiently suppress the effect of backscattering only using two wavelengths at the same time. At the remote site, a signal from a nonsynchronized RF source is sent to the local site as a probe signal. At the local site, the received probe signal is mixed with the local standard signal to obtain a phase-conjugated signal, which is transmitted back to the remote site over the same fiber link with another wavelength. A stable frequency signal is directly reproduced by mixing the received phase-conjugated signal with the signal from the nonsynchronized RF source at the remote site. The proposed scheme is validated by the experiment over a 40 km single mode fiber spool using nonsynchronized common commercial RF sources. The influence of the stability of nonsynchronized RF sources on the frequency transfer is investigated over different length fiber links.

The diagram of the proposed scheme is illustrated in Fig. 1. At the remote site, the RF signal generated by an RF source is set to be half of the standard RF signal in frequency and split into two branches by a power splitter. The signal on one branch is modulated on an optical carrier (λ_1) to be transmitted to the local site as the probe signal. At the local site, the probe signal is detected by a photodetector and then mixed with the standard RF signal to generate a phase-conjugated RF signal. Then, the phase-conjugated RF signal is modulated on another wavelength (λ_2) and transmitted back along the same fiber link. The signal over λ_2 is photodetected at the remote site and then mixed with the RF signal from the other branch of the power splitter to get a stable frequency signal. We can see that the proposed scheme can perform the phase noise compensation within one round-trip and efficiently suppress the effect of backscattering by only employing

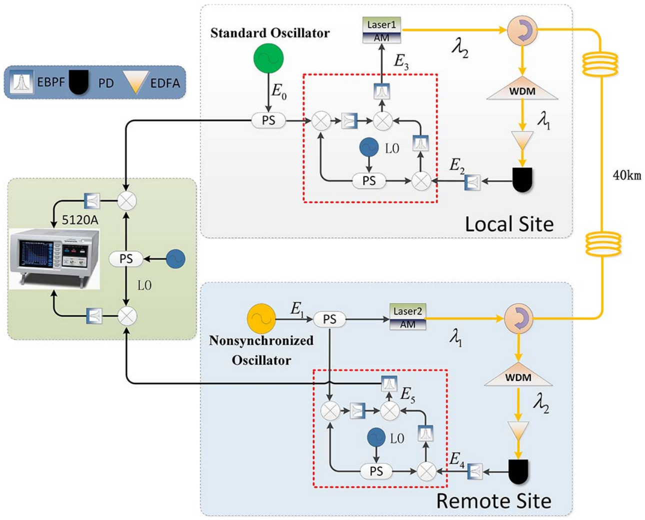


Fig. 1. Schematic of the proposed fiber-optic frequency transfer scheme. EBPF, electric bandpass filter; PD, photodetector; EDFA, erbium-doped fiber amplifier; LO, local oscillator; PS, power splitter; AM, amplitude modulator.

two wavelengths without frequency-dividing or phase-locking. In this way, the proposed scheme can reach a higher compensation bandwidth than triple transmission schemes by performing the phase noise compensation within one round-trip and, therefore, can support longer distance. At the same time, the simplicity of the system can avoid the noises induced by extra devices and processing, besides reducing the cost and complexity.

The standard frequency signal at the local site can be denoted as

$$E_0(t) \propto \cos(\omega_s t + \phi_s), \tag{1}$$

where ω_s and ϕ_s represent the angular frequency and initial phase of the standard signal.

The RF signal from the nonsynchronized RF source at the remote site can be expressed as

$$E_1(t) \propto \cos\left[\left(\frac{1}{2}\omega_s - \Delta\omega\right)t + \phi_1(t)\right], \tag{2}$$

where $\Delta\omega$ is the frequency deviation to ideal $\omega_s/2$, and $\phi_1(t)$ is a function of time t considering the worse stability of the nonsynchronized source than the standard frequency source.

At the local site, the received probe RF signal can be expressed as

$$E_2(t) \propto \cos\left[\left(\frac{1}{2}\omega_s - \Delta\omega\right)(t - \tau_{RL\lambda_1}) + \phi_1(t - \tau_{RL\lambda_1})\right], \tag{3}$$

where $\tau_{RL\lambda_1}$ is the fiber link propagation delay for wavelength λ_1 from the remote site to the local site. Then, E_2 is mixed with the standard signal E_0 to generate the phase-conjugated RF signal;

$$E_3(t) \propto \cos\left[\frac{1}{2}\omega_s(t + \tau_{RL\lambda_1}) + \Delta\omega(t - \tau_{RL\lambda_1}) + \phi_s - \phi_1(t - \tau_{RL\lambda_1})\right]. \tag{4}$$

At the remote site, the photodetected RF signal on λ_2 can be expressed as

$$\begin{aligned} E_4(t) \propto \cos\Big[&\frac{1}{2}\omega_s(t + \tau_{RL\lambda_1} - \tau_{LR\lambda_2}) + \Delta\omega(t - \tau_{RL\lambda_1} - \tau_{LR\lambda_2}) \\ &+ \phi_s - \phi_1(t - \tau_{RL\lambda_1} - \tau_{LR\lambda_2})\Big], \end{aligned} \tag{5}$$

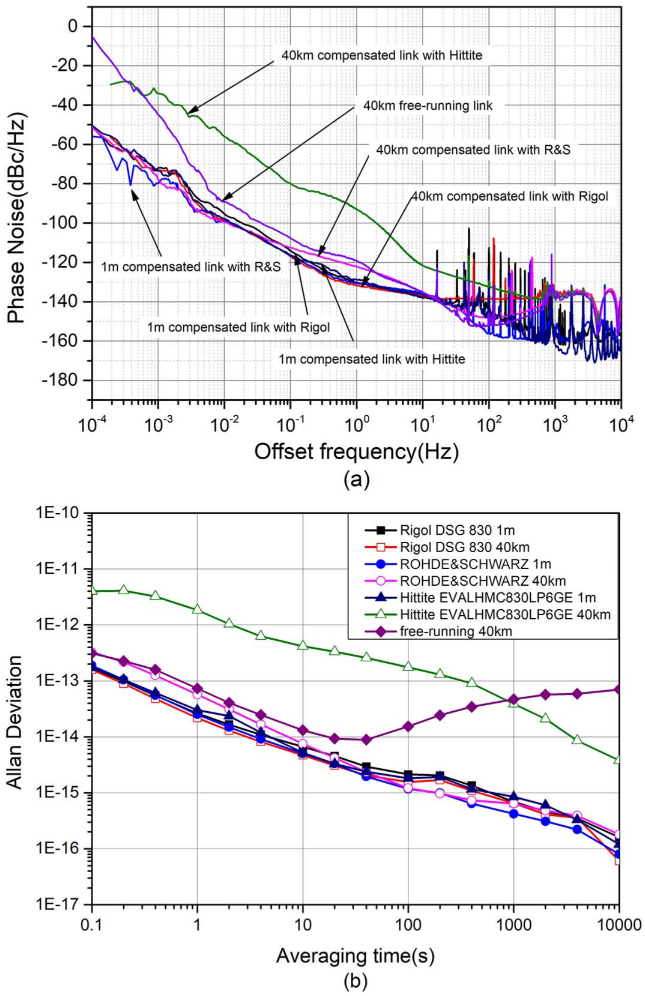
where $\tau_{LR\lambda_2}$ is the fiber link propagation delay for wavelength λ_2 from the local site to the remote site. By mixing E_4 with the other branch of the power splitter, we have

$$\begin{aligned} E_5(t) \propto \cos\Big\{&\omega_s t + \frac{1}{2}\omega_s(\tau_{RL\lambda_1} - \tau_{LR\lambda_2}) - \Delta\omega(\tau_{RL\lambda_1} + \tau_{LR\lambda_2}) \\ &+ [\phi_1(t) - \phi_1(t - \tau_{RL\lambda_1} - \tau_{LR\lambda_2})] + \phi_s\Big\}. \end{aligned} \tag{6}$$

In Eq. (6), the second term in the bracket is the residual phase noise caused by the asymmetry propagation delay of different wavelengths along the same fiber link, and it can be ignored when the wavelength gap is small enough[11]. The third term results from the frequency deviation to ideal $\omega_s/2$ of the nonsynchronized RF source. It is easy to show by simulation that the fractional instability induced by a relative frequency deviation of under 2×10^{-5} per year can be less than $2 \times 10^{-18}/3 \times 10^4$ s for the transfer of less than 1000 km with a temperature fluctuation of 10°C/day. It indicates that the influence of $\Delta\omega$ can be neglected for most common commercial oscillators [about 3.6×10^{-8} per year of relative frequency deviation for Rigol's and Rohde & Schwarz's (R&S's) sources used in our experiment]. The fourth term is induced by the instability of the nonsynchronized RF source, i.e., the variation of $\phi_1(t)$ with t. When the nonsynchronized RF source is stable enough during an RTT, the residual phase noise can also be ignored[7]. Then, we can get a stable frequency signal at the remote site. It is worth noting that at an arbitrary point along the fiber link, a stable frequency signal, can also be obtained by tapping and mixing the phase-conjugated signal and the probe signal[12–14].

The proposed scheme in Fig. 1 is experimentally evaluated. At the local site, a 1 GHz RF signal is generated from a signal generator as the standard frequency signal. The local and remote sites are connected by a 40 km single mode fiber spool. At the remote site, three different RF sources from Rigol, Hittite, and R&S are used as the nonsynchronized RF source, respectively, for comparison. The wavelengths of the launched light from two sites are 1550.12 and 1550.92 nm, respectively. Two $LiNbO_3$ Mach–Zehnder modulators are used for intensity modulation. The dual-mixing method[6] (as shown within the red dotted box in Fig. 1.) is used to efficiently suppress the effect of leaked signals and their harmonics in frequency mixing. The 1 GHz standard frequency signal and the reproduced signal at the remote site are converted to 10 MHz and then input to a phase noise test set (Symmetricom Inc., TSC5120A) for frequency transfer performance evaluation.

Figure 2(a) shows the measured phase noise spectra of the proposed fiber-optic RF transfer at 10 MHz using three different nonsynchronized RF sources. The results over a 1 m fiber illustrate the phase noise floors, which are mainly determined by RF signal processing, optical transmitting, and receiving at each site. As can be seen, the system floors with different RF sources are almost the same due to the negligible propagation delay. As the fiber link extends to 40 km, the phase noise is significantly deteriorated, relative to the floor, without phase noise compensation (free running link). After the proposed compensation using Rigol's or R&S's RF source, the phase noise of 40 km compensated link almost approaches the floor at the offset frequency of less than 0.1 Hz. It indicates that the fluctuation mainly induced by the ambient variations is efficiently suppressed, and the performance is mainly restricted by the system floor, which can be improved by using high-performance RF devices. However, when using the source of Hittite, the phase noise of the 40 km compensated link is much higher than its floor and even worse than the 40 km free running link at the offset frequency less than 100 Hz. It mainly attributes to the worse instability of Hittite's source, whose impact on the phase noise has exceeded that of propagation delay variation induced by ambient variation. The phase noises of the 40 km compensated link at a higher offset frequency using three different sources are almost the same, since this part is dominated by the amplified spontaneous emission noise of an erbium-doped fiber amplifier[15]. We also find that the phase noise of the proposed scheme using Rigol's or R&S's RF source is very close to that using the scheme in Ref. [3] over the 40 km link. It is mainly because Rigol's or R&S's RF source is stable enough during an RTT, and hence, the residual phase noise determined by the instability of the RF source in an RTT [the fourth term in Eq. (6)] can be ignored. The corresponding stability (Allan deviation) with a 5 Hz measurement bandwidth is shown in Fig. 2(b). One can see that the Allan deviation of about 10^{-14}/s and $10^{-16}/10,000$ s can be achieved over a 40 km compensated link with Rigol's or R&S's RF source, respectively.



(a)

(b)

Fig. 2. (a) Measured phase noise spectra at 10 MHz with different nonsynchronized RF sources. (b) The corresponding fractional frequency stabilities.

In Ref. [11], the overlapping Allan deviation at 10^4 s for a 50 km frequency transfer with 0.8 nm wavelength difference is lower than 3×10^{-18} and near 2×10^{-17} for the temperature variation of below 5°C/day and 30°C/day, respectively. Therefore, the influence of wavelength difference of 0.8 nm over the 40 km fiber link can be ignored in our experiment relative to the system floor noise of around 2×10^{-16} at 10^4 s. Moreover, since the Allan deviation will degrade one order of magnitude for a 10-times distance extension[11], the influence of the 0.8 nm wavelength difference will be close to the system floor when the fiber length extends to 500 km and has a temperature variation of 30°C/day in our experiment. In order to achieve higher precision and longer distance, smaller wavelength differences or frequency transfer schemes utilizing the same wavelength[4] should be employed. It is worth noting that the transfer distance is also limited by transmission loss, dispersion, phase compensation range and bandwidth, and the coherence of the RF source in an RTT. The transmission loss and the effect of dispersion can be compensated by a bidirectional optical amplifier and dispersion compensation[16]. The proposed scheme has an unlimited phase compensation range as a passive compensation scheme and a higher compensation bandwidth than triple transmission schemes. Therefore, the long-term drift caused by a longer fiber in the loop bandwidth can also be compensated sufficiently, as long as it employs a nonsynchronized stable source in the corresponding RTT.

The measured phase noise spectra of 500 MHz probe signals from the three RF sources are shown in Fig. 3. One can see that Rigol's and R&S's (∼ −65 dBc/Hz @1 Hz and ∼ −49 dBc/Hz @1 Hz) sources are more stable

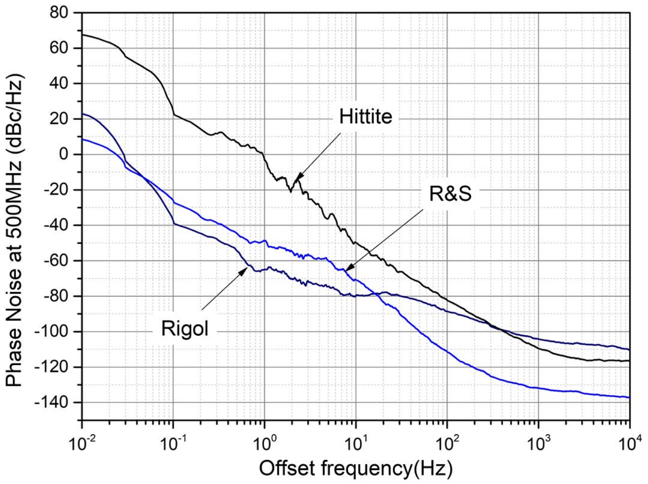


Fig. 3. Measured phase noise spectra of RF sources at 500 MHz from Rigol, Hittite, and R&S.

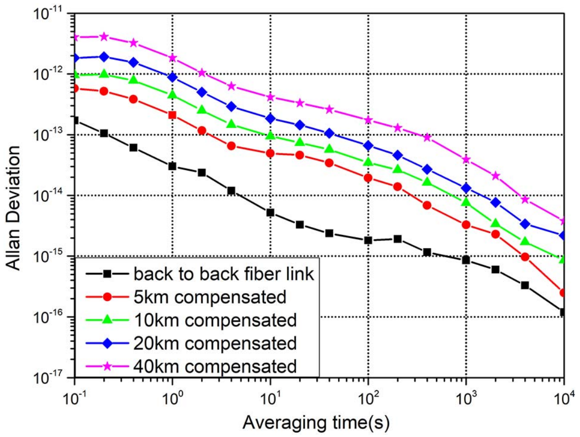


Fig. 4. Measured fractional frequency stabilities with Hittite's source over different length fiber links.

than Hittite's (∼0 dBc/Hz @1 Hz), which is consistent with the frequency transfer stability of the proposed scheme in Fig. 2. Two crossing points between the spectra of Rigol's and R&S's sources at about 0.06 and 20 Hz are also observed in Fig. 2(a) in 1 m and 40 km compensated links for the influence of the stability of the nonsynchronized RF source on the phase noise of the RF transfer.

The frequency transfer stability with the worse Hittite's source is measured over different length fiber links, shown in Fig. 4. It can be seen that the frequency transfer stability decreases with the increase of the fiber link length. This is mainly because the RF signal from Hittite's source is incoherent after an RTT delay, and the correlated phase noise between the probe signal and its round-trip signal increases with the growth of the propagation delay (fiber length). On the other hand, for Rigol's or R&S's source, the phase noise of 40 km compensated link is almost equal to that of the 1 m fiber link at the offset frequency of less than 0.1 Hz. It indicates that the impact of the source on the proposed scheme can be neglected as long as the nonsynchronized source is stable enough in an RTT.

In summary, we propose a passive phase noise compensation scheme for fiber-optic RF transfer with a nonsynchronized RF source to avoid high-precision phase-locking. Passive phase noise compensation without the effect of backscattering is realized by only employing two wavelengths without the requirement of electrical frequency-dividing. The RF transfer performances of the proposed scheme are experimentally evaluated using nonsynchronized sources with different stabilities. The impact of the nonsynchronized source under different fiber lengths is also investigated. The results show that the ambient variations that induced phase noise over a 40 km fiber link can be efficiently suppressed by the proposed scheme with common oscillators often equipped at the user site in practical applications.

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