Stable fiber delivery of radio-frequency signal based on passive phase correction

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A novel passive phase correction method for stable fiber transfer of radio-frequency (RF) signal is proposed and demonstrated. By employing only one local oscillator and two frequency mixers in the local station, an RF signal received by an optical remote antenna unit is transmitted to the local station with very small phase jitter. An experiment is performed. When a 6 GHz RF signal is delivered through a 20 km single-mode fiber, effective cancellation of the RF signal's phase jitter induced by environmental perturbations is achieved. The residual jitter is less than 1.33 ps (about 0.05 rad). The proposed scheme requires no active mechanism to compensate the fiber-length fluctuations, and is thus compact, cost-effective, and easy to implement.

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In applications such as radio astronomy [1], deep space network [2], distributed synthetic aperture radar systems [3], high-precision clock standards distribution [4], particle accelerators [5], and global navigation satellite system, where multiantenna receivers using carrier phase for positioning and navigation [6], radio-frequency (RF) or local oscillator (LO) signals are required to be transferred to another station with least phase variation. Due to low loss, light weight, low cost, immunity to electromagnetic interference, and many other advantages, optic fiber is one of the best media for RF phase transfer, especially for long-distance transmission. However, the length of the optic fiber would be changed randomly because of environmental vibrations and temperature variations. To realize highly stable RF phase transfer via an optical fiber, the phase vibration induced by the fiber length variation should be corrected in real time. Previously, there were two main methods to achieve this goal. One was to apply a feedback loop. The phase error extracted from a round-trip signal was used to control a parameter of the fiber link to actively compensate the phase jitter induced by fiber transmission. Up to now, optical/electrical delay lines [7,8], tunable lasers [9], fiber stretchers [10,11], optoelectronic modulators [12], and voltage-controlled oscillators (VCOs) [5] have been used to implement the compensation. The main drawback related to the active approach is the need of complex circuits to extract the phase error and drive the devices for phase correction in real time. In addition, the compensation range is restricted by the achievable range of the device's parameter for phase correction. When the environments change severely, the fiber length variation may be beyond their compensation range. Although the method based on VCOs principally has an endless compensation range, it is hard to achieve precise compensation because of the high voltage sensitivity of the VCOs. The other kind of method is to passively remove the phase jitter by electrical frequency mixing [13–15], which avoids the complicated phase error detection and feedback circuits. However, the schemes reported by electrical frequency mixing usually need two or three synchronized microwave sources and three or even more stages of frequency mixing. The major problem associated with the large-number-stage frequency mixing is the complicated operation, large conversion loss, and serious intermodulation distortion.

In this Letter, we propose and demonstrate a novel approach for highly stable RF phase transfer via an optical fiber by frequency mixing-based passive post phase correction. Only one LO source with an arbitrary initial phase and two frequency mixers are needed, making the proposed approach compact, cost-effective, and easy to implement.

Figure 1 shows the schematic diagram of the proposed stable RF phase transfer scheme with post phase correction. The LO signal generated at the local station has half the frequency of the signal received in the remote antenna unit (RAU), which modulates an optical carrier at a Mach–Zehnder modulator (MZM1). The optical microwave signal is then transmitted to the RAU through a certain length of standard single-mode fiber (SMF). In the RAU, the received signal, which needs to be transmitted to the local station, modulates another optical carrier at a second MZM (MZM2). The signal is then combined with the optical microwave signal from the local station using an optical coupler. After being boosted by an erbium-doped fiber amplifier (EDFA), the combined signals are transmitted back to the local station. Since the signal to be transmitted in the RAU is a single-frequency RF signal, it can be expressed as

$$A_1 = \cos(\omega_r t + \varphi_r), \quad (1)$$

where ω_r and φ_r are the frequency and phase of the RF signal to be transmitted, respectively. In writing Eq. (1), it is assumed that the phase variation of the RF signal ($d\varphi_r/dt$) is much smaller than ω_r. The LO signal in the local station can also be written as

$$A_2 = \cos(0.5\omega_r t + \varphi_0), \quad (2)$$

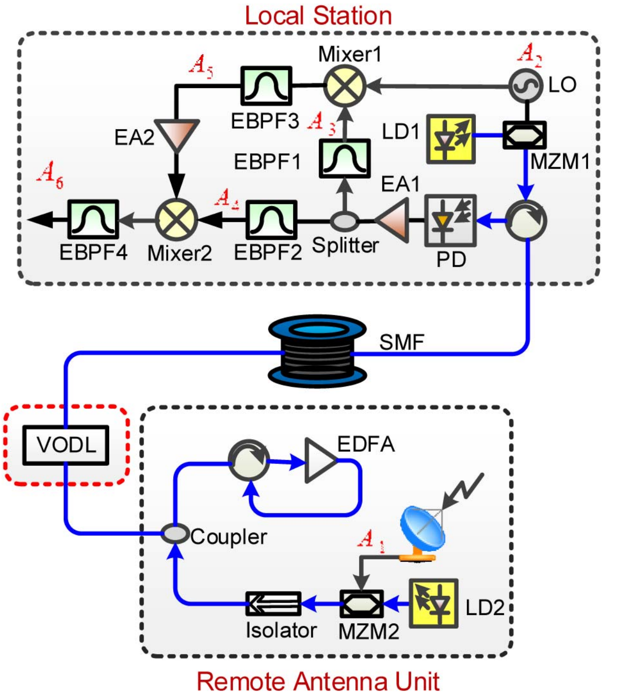

Fig. 1. Schematic diagram of the proposed scheme for highly stable RF phase transfer based on frequency mixing. EBPF, electrical bandpass filter; MZM, Mach–Zehnder modulator; EDFA, erbium-doped fiber amplifier; LD, laser diode; LO, local oscillator; PD, photodetector; VODL, variable optical delay line; EA, electrical amplifier.

where φ_0 is the phase of the LO signal. Since the LO signal is a locally generated frequency standard, φ_0 is considered as a constant.

In the local station, the combined signal is detected by a photodetector (PD). If the transmission delay of the SMF is τ, A_1 travels one way in the SMF, so it is delayed by τ, and A_2 undergoes a round trip so the time delay should be 2τ. The ω_r component and the $0.5\omega_r$ component in the detected signal are expressed as

$$A_3 = \cos[\omega_r(t - \tau) + \varphi_r], \tag{3}$$

$$A_4 = \cos[0.5\omega_r(t - 2\tau) + \varphi_0]. \tag{4}$$

The signal detected is first amplified by an electrical amplifier (EA) and then split into two parts by a power splitter. In the upper branch, A_3 is selected by an electrical bandpass filter (EBPF), which is mixed with A_2 at Mixer 1. The output signal of EBPF3 is given by

$$A_5 = \cos(1.5\omega_r t - \omega_r\tau + \varphi_r + \varphi_0). \tag{5}$$

In the lower branch, another EBPF (EBPF2) is incorporated to select out A_4, which is then mixed with A_5 at Mixer 2, generating a signal with a frequency of ω_r. It is filtered out by EBPF4 and the signal obtained is

$$A_6 = \cos(\omega_r t + \varphi_r). \tag{6}$$

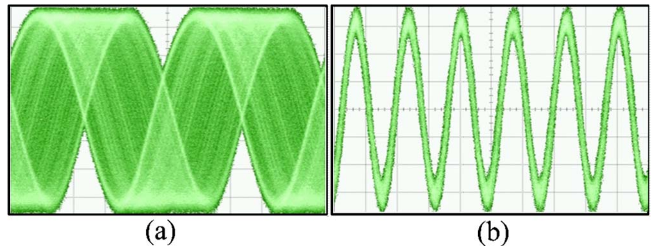

Fig. 2. Eye diagrams of the signal received at the local station (a) without and (b) with the proposed post phase correction scheme.

As can be seen from Eq. (6), the RF signal received at the local station has the same frequency and phase as that received in the RAU. Therefore, highly stable RF phase transfer via an optical fiber is achieved by using only one LO source and two-stage frequency mixing. Since the phase of the LO signal is removed automatically by frequency mixing, the proposed method has no requirement of the initial phase of the LO signal.

A proof-of-concept experiment is carried out based on the setup shown in Fig. 1. In the experiment, ω_r is set to be 6 GHz (generated by Agilent 8267D) and the frequency of the LO signal is 3 GHz (generated by Agilent N5181A). The two microwave sources are not synchronized. The wavelengths of the two laser diodes are 1550.496 and 1550.896 nm, respectively. MZM1 is a 40 Gb/s $LiNbO_3$ modulator and MZM2 is a 10 Gb/s intensity modulator. In the experiment, a variable optical delay line (VODL) is inserted before the 20 km SMF to introduce length vibration of the transmission link. The PD (Picometrix P-18A) has a bandwidth of 19 GHz and a responsivity of 0.85 A/W. The eye diagrams of the signals were monitored by a 40 GHz digital sampling oscilloscope (Agilent 86100A). A 43 GHz electrical spectrum analyzer (Agilent E4447A) was used to measure the root-mean-square (RMS) timing jitter.

Figure 2 shows the eye diagrams of the RF signal received at the local station with and without the proposed post phase correction scheme, corresponding to A_6 and A_3 in Fig. 1. As can be seen, the signal received before the

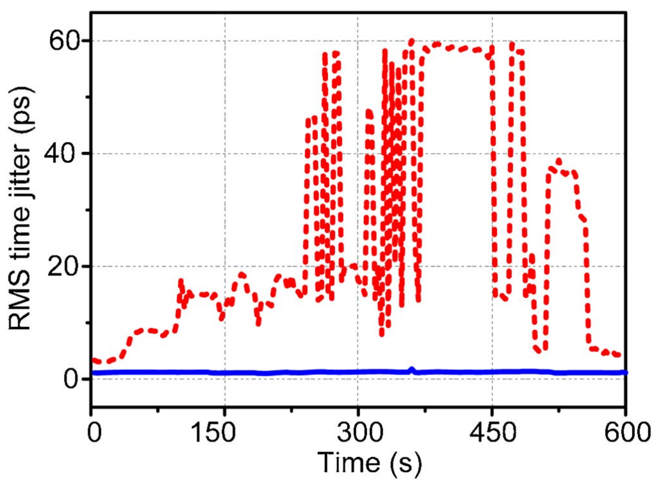

Fig. 3. RMS timing jitter of the signal after 20 km SMF transmission with (solid line) and without (dashed line) post phase correction.

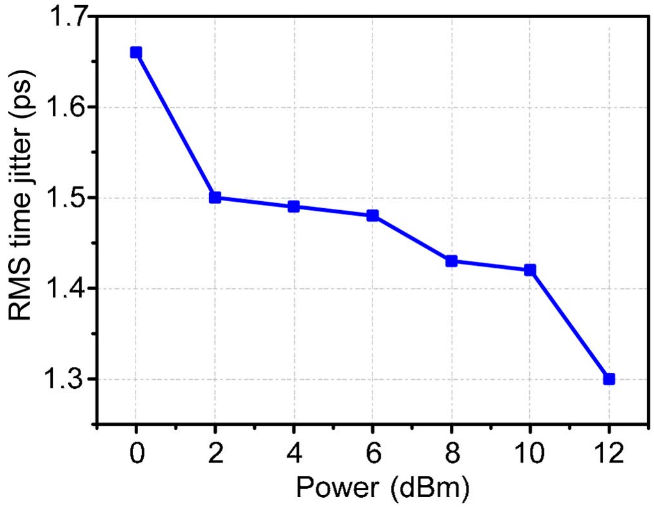

Fig. 4. Relationship between the power of the electrical signal received in the RAU and the RMS time jitter of the signal after transmission through the fiber link with the proposed post phase correction scheme.

proposed correction scheme has a large timing jitter due to adjustment of the VODL, whereas after phase correction the vibration of the RF phase is effectively reduced. In Fig. 2(b), we can still observe some amplitude noise, which is mainly originated from the EDFA, PD, EAs, and the noise floor of the oscilloscope.

Figure 3 shows the measured RMS timing jitter of the received RF signal within 600 s. The dashed line shows the RMS timing jitter of the free-running signal A_3 without post phase correction. As can be seen, the RMS timing jitter could reach 60 ps when adjusting the VODL randomly. With the proposed post correction scheme, the RMS timing jitter of the signal A_6 is reduced dramatically to less than 1.33 ps, corresponding to about 0.05 rad, as shown by the solid line in Fig. 3.

Figure 4 shows the relationship between the electrical power of the signal received in the RAU and the RMS time jitter of the signal after transmission through the fiber link with the proposed post phase correction scheme. When the power of the signal received increases from 0 to 12 dBm, a better signal-to-noise ratio can be obtained, and the RMS time jitter decreases slightly from 1.66 to 1.33 ps.

It should be noted that the performance of the proposed post phase correction scheme can be improved by taking into account many factors that are not considered in Eqs. (1)–(6), e.g., fiber dispersion. Because of the wavelength difference between the two optical carriers, the fiber dispersion would introduce a fixed time delay to the output signal (A_6). If there are wavelength drifts of the laser sources, evident timing jitter may be presented. This problem can be solved by replacing the SMF by a dispersion compensated fiber link, or using highly stable laser sources. Besides, the proposed scheme is quite suitable for applications where a low-frequency RF signal should be transmitted, considering that transfer of high-frequency RF (e.g., 60 GHz) needs wide band electrical mixers and filters.

In summary, a novel post phase correction method for stable fiber transfer of RF signals is proposed and demonstrated. Only two-stage frequency mixing and one LO source were used, and no active mechanism was involved, making the fiber RF phase transfer system compact, cost-effective, and easy to implement. An experiment was carried out. The 60 ps timing jitter of a 6 GHz RF signal after transmission over a 20 km SMF was reduced dramatically to less than 1.33 ps (about 0.05 rad).

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