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Passive phase correction for stable radio frequency transfer via optical fiber

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Abstract The transfer of radio frequency (RF) signal via optical fiber is widely adopted in distributed antenna systems and clock standard disseminating networks. To suppress the phase variation caused by fiber length fluctuation, passive phase correction technique based on frequency mixing has been proved as a promising approach due to its significant advantages over the traditional active compensation technique in terms of complexity, compensation speed, and compensation range. The phase correction can be done either in the transmitter or in the receiver, but it usually requires many stages of electronic mixing and auxiliary microwave signals, which not only increases the cost of the link but also degrades the quality of the transmitted signal. In addition, the effect of chromatic dispersion, polarization mode dispersion, and coherent Rayleigh noise in the optical fiber will further deteriorate the phase noise of the signal after transmission. In this paper, an analytical model for the stable RF transfer system based on passive phase correction is established, and the techniques developed in the last few years in solving the problems of the method are described. Future prospects and perspectives are also discussed.

Keywords Stable RF transfer · RF delivery · Phase correction · Pre-phase distortion · Microwave photonics

1 Introduction

In applications such as radio astronomy, deep space network, distributed synthetic aperture radar systems, high-precision clock standard distribution, and particle accelerators, radio frequency (RF) signals are required to be transferred between different stations via optical fiber with the least phase variation [1–6]. Taking advantages of low loss, high stability, large bandwidth, and immunity to electromagnetic interference, optical fiber has been proved as the best medium for long-distance RF transfer with the frequency stability several orders of magnitude better than the technique based on satellites [7,8]. The research on disseminating RF reference signals through optical fibers can date back to 1970s for the Deep Space Network built by the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) [1]. After that, many optical fiber links were established for stable RF transmission. For example, a fiber link with a length of 642 km was built in Italy (the Italian Link for Time and Frequency, LIFT) to transmit RF standard signals from the Italian metrological institute to several Italian scientific poles with high stability [9]. Besides, optical fiber links were also built in the Atacama Large Millimeter Array (ALMA) to transfer two phase-correlated optical waves from the control center to each antenna in order to obtain stable RF references [10].

Since the environmental perturbations, such as the temperature changes and mechanical vibrations, would change the effective refractive index and length of optical fiber, a random phase variation will be introduced to the transmitted RF signal. To realize stable RF transfer, many schemes have been proposed, which can be generally classified into three categories. One method is to actively adjust the optical path by changing the length of the fiber link or the wavelength of the laser source [11–22]. The second approach is to

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pre-compensate the phase variation by introducing a conjugate phase to the RF signal before transmission via a phase shifter, a frequency shifter, or a voltage-controlled oscillator (VCO) [23–35]. In practical implementations of these methods, the phase variations caused by the changes in the fiber link should be extracted and used to drive the tunable device for phase variation compensation. An active phase-locked loop (PLL) is always required. However, the PLL bandwidth is usually limited by the response speed of the tunable device, so the active methods cannot effectively deal with the fast variations in the fiber link. Besides, due to the finite tunable range of the compensation devices, schemes in the first category can only work under the case where the time delay variation is very small (usually $<100\,\mathrm{ps}$). Recently, passive phase correction schemes based on frequency mixing, which can be classified as the third way to realize stable RF transfer via optical fiber, were proposed. Compared to the active schemes applying PLLs, the passive phase correction schemes would have a simple structure, a fast compensation speed, and an infinite compensation range. In addition, the passive phase correction method can be achieved by both pre-phase distortion in the transmitter and post-phase correction in the receiver.

In this paper, an analytical model for photonic stable RF transfer system based on passive phase correction is established, which describes the principle of the method and reveals several performance limitation factors. Techniques developed in the last few years to address the issues of the method are reviewed. The pros and cons of each scheme and the future development of the method are discussed.

2 Principle of the passive phase correction method

The principle of the passive phase correction methods applying pre-phase distortion and post-phase correction is schematically shown in Fig. 1.

Mathematically, the single-frequency RF signal to be transmitted is expressed as

$$S_\mathrm{t}(t) = \cos\left[\omega_0 t + \varphi_0 + \Delta\varphi_0(t)\right] \tag{1}$$

where ω_0 and φ_0 stand for the angular frequency and the initial phase of the RF signal, respectively. $\Delta\varphi_0$ represents the random phase noise of the RF signal.

To realize phase stable transmission of the RF signal, an auxiliary signal with a half frequency of the RF signal is needed,

$$S_\mathrm{a}(t) = \cos\left[0.5\omega_0 t + \varphi_\mathrm{a} + \Delta\varphi_\mathrm{a}(t)\right] \tag{2}$$

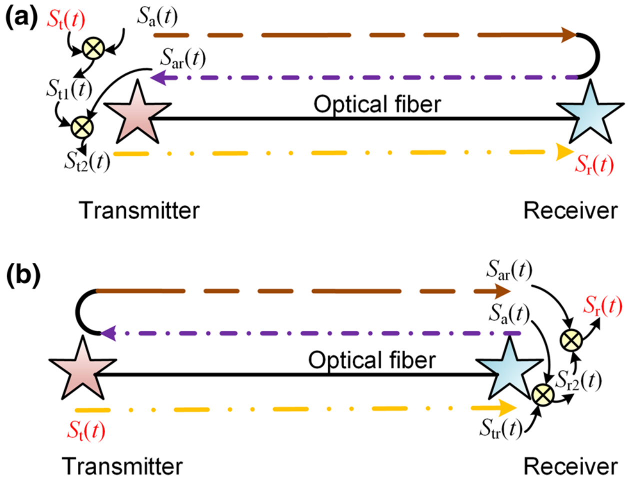

Fig. 1 Schematic diagram of **a** the pre-phase distortion scheme and **b** the post-phase correction scheme

where φ_a and $\Delta\varphi_\mathrm{a}$ represent the initial phase and the random phase noise of the auxiliary signal, respectively. The auxiliary signal modulates on an optical carrier with a wavelength of λ_1 and is injected into the optical fiber. The time delay of the fiber link can be expressed as

$$\tau = \frac{\left(n_\mathrm{c} + \Delta n_\mathrm{en} + \Delta n_\lambda + \Delta n_\mathrm{p}\right)\left(L + \Delta L_\mathrm{en}\right)}{c} \tag{3}$$

where n_c is the effective refractive index of the optical fiber at the wavelength of the optical carrier; Δn_en, Δn_λ, and Δn_p represent the variation in the refractive index induced by environment perturbation, wavelength drift, and polarization rotation of the optical carrier; L stands for the physical length of the optical fiber link; ΔL_en represents the variation in the physical length introduced by environment changes; and c is the speed of light in vacuum.

Assume that the refractive index and the physical length are slowly varying with time, so the forward and backward propagation in the fiber link can be treated to have the same delay. If the time for one-trip transmission of the auxiliary signal is τ_1, the round-trip time delay should be $2\tau_1$. Therefore, we can write the auxiliary signal after a round-trip transmission as

$$S_\mathrm{ar}(t) = \cos\left[0.5\omega_0\left(t - 2\tau_1\right) + \varphi_\mathrm{a} + \Delta\varphi_\mathrm{a}\left(t - 2\tau_1\right)\right] \tag{4}$$

In the pre-phase distortion configuration where the phase correction is done in the transmitter, as shown in Fig. 1a. The auxiliary signal is generated in the transmitter which is mixed with $S_\mathrm{t}(t)$ to get an up-converted signal,

$$\begin{aligned} S_\mathrm{t1}(t) = \cos[&1.5\omega_0 t + \varphi_0 + \Delta\varphi_0(t) \\ &+ \varphi_\mathrm{a} + \Delta\varphi_\mathrm{a}(t)] \end{aligned} \tag{5}$$

$S_\mathrm{t1}(t)$ is sent to a second mixer, to mix with the auxiliary signal after a round-trip transmission, as expressed in (4). The down-converted component can be written as

$$S_{t2}(t) = \cos\left[\omega_0 t + \omega_0\tau_1 + \varphi_0 + \Delta\varphi_0(t) - \Delta\varphi_a(t - 2\tau_1) + \Delta\varphi_a(t)\right] \tag{6}$$

It should be noted that the up-converted and down-converted components in (5) and (6) are selected by electrical band-pass filters.

As shown in (6), a conjugate phase term of $\omega_0\tau_1$ is introduced to the RF signal $S_{t2}(t)$. Then, $S_{t2}(t)$ modulates another optical carrier with a wavelength of λ_2 and is delivered through the same fiber link to the receiver. If the transmission delay of $S_{t2}(t)$ is τ_2, the received signal is

$$S_r(t) = \cos\left[\omega_0 t + \omega_0(\tau_1 - \tau_2) + \varphi_0 + \Delta\varphi_0(t - \tau_2) - \Delta\varphi_a(t - 2\tau_1 - \tau_2) + \Delta\varphi_a(t - \tau_2)\right] \tag{7}$$

As shown in (7), if τ_1–τ_2 equals to a constant, a stabilized signal with its phase independent of environment variation is obtained in the receiver.

In the post-phase correction configuration, as shown in Fig. 1b, the RF signal $S_t(t)$ transmits from the transmitter to the receiver. After transmission, the signal can be rewritten as

$$S_{tr}(t) = \cos\left[\omega_0 t - \omega_0\tau_2 + \varphi_0 + \Delta\varphi_0(t - \tau_2)\right] \tag{8}$$

Then, $S_a(t)$ in (2) is mixed with $S_{tr}(t)$ to generate an up-converted signal

$$S_{r2}(t) = \cos\left[1.5\omega_0 t - \omega_0 + \varphi_0 + \Delta\varphi_0(t - \tau_2) + \varphi_a + \Delta\varphi_a(t)\right] \tag{9}$$

Again, a second mixer is applied to mix $S_{r2}(t)$ in (9) with $S_{ar}(t)$ in (4). A down-converted component is thus obtained

$$S_r(t) = \cos\left[\omega_0 t + \omega_0(\tau_1 - \tau_2) + \varphi_0 + \Delta\varphi_0(t - \tau_2) - \Delta\varphi_a(t - 2\tau_1) + \Delta\varphi_a(t)\right] \tag{10}$$

As shown in (10), as long as the difference between τ_1 and τ_2 is a constant, the signal $S_r(t)$ is free from the phase variation introduced by fiber transmission.

From the above analysis, for both pre-phase distortion and post-phase correction passive phase correction scheme, the key is to ensure a constant difference in τ_1 and τ_2. Since the signals are transmitted in the same fiber, Δn_{en} is almost the same for the RF and auxiliary signals, so we can obtain the residual phase variation induced by fiber transmission,

$$\Delta\phi = \omega_0(\tau_1 - \tau_2) = \frac{\omega_0\left(n_{c1} - n_{c2} + \Delta n_{\lambda 1} - \Delta n_{\lambda 2} + \Delta n_{p1} - \Delta n_{p2}\right)(L + \Delta L_{en})}{c} \tag{11}$$

In (11), the difference in the effective refractive index n_{c1}–n_{c2} is a fixed value if λ_1 and λ_2 are given, which can be minimized if λ_1 is close to λ_2. $\Delta n_{\lambda_1} - \Delta n_{\lambda_1}$ is introduced because of the wavelength drifts of the two laser sources. Since the wavelength-dependent refractive index can be attributed to the fiber chromatic dispersion, a dispersion compensation module or dispersion-flattened fibers can be adopted to solve this problem. The refractive index variation caused by Δn_{p1}–Δn_{p2} usually originates from the random birefringence of the fiber link. Due to polarization mode dispersion (typically 0.1 ps km$^{-1/2}$ for standard single-mode fiber), the irregular rotation of the polarization states of the two optical carriers would lead to residual phase noise. According to the research results in [36], polarization scramblers are effective tools for solving the problem. Schemes for dynamic polarization control developed in fiber communication systems may also be utilized to remedy this.

The physical length variation in the fiber, i.e., ΔL_{en} in (11), is usually caused by temperature changes and mechanical perturbations. It has been proved that the influence of temperature change on the fiber refractive index (∼7 ppm/°C) is more than one order of magnitude higher than that on the physical fiber length (∼0.5 ppm/°C); thus, the RF phase variation caused by the physical length variation due to temperature changes can be neglected. Different from the thermal-induced slow fiber length variation, the mechanical vibration may cause fast change in the physical fiber length. Pressures applied directly on the fiber also cause considerable RF phase variation (∼8 ppm/Mpa). However, these effects could be weakened or even eliminated by means of protecting jacket or deep laying under the ground.

Since the auxiliary signal has to be transmitted in the optical fiber link bidirectionally using the same optical carrier, Rayleigh backscattering of the forward optical signal will interfere with the backward optical signal, and vice versa, resulting in coherent Rayleigh noise which could significantly deteriorate the phase noise of the RF signal. Wavelength conversion is a solution for this problem when the variation in effective refractive index caused by the chromatic dispersion and the polarization mode dispersion is under control.

Additionally, as can be clearly seen from (7) and (10), the phase noise of the auxiliary signal $\Delta\varphi_a$ is added to the RF signal every time when mixed with the RF signal. That means, more stages of frequency mixing bring in more noise. In addition, more signal sources are needed when the auxiliary signals with different frequencies are used. Frequency mixing would also bring in problems such as large conversion loss and distortion. Take into consideration the performance, cost, and complexity of the stable phase transmission system, less stages of frequency mixing and less auxiliary signals are highly desirable.

In the last few years, great efforts were devoted to the necessary improvements of the passive phase correction method. Both the pre-phase distortion in the transmitter and post-phase correction in the receiver were proposed and demonstrated.

3 Post-phase correction

In 2013, a passive phase correction scheme for stable RF transfer via optical fiber was reported using three stages of frequency mixing [37], in which the RF signal is transmitted from a remote site to the local station with post-phase correction. The schematic diagram is shown in Fig. 2. An optical carrier is directly modulated by the RF signal to be transmitted in the remote site, which is then transmitted to the local station through a fiber link. Meanwhile, at the local station, a local oscillator (LO) reference signal (LO1) at half frequency of that of the RF signal modulates another optical carrier and then travels a round-trip through the fiber. Considering that LO1 undergoes a doubled time delay and has a half frequency compared to the RF signal, it has the same phase variation caused by environmental fluctuations as the RF signal. After the two signals are frequency mixed with two other reference sources (LO2 and LO3), respectively, the obtained two down-converted signals are mixed with each other to generate an intermediate frequency (IF) signal. Thanks to the multistage frequency mixing, the phase term induced by fiber transmission delay is eliminated. Thus, passive compensation of the phase error is achieved. In an experiment, a 2.8-GHz RF signal is transmitted through a 10-km fiber link and then down-converted to a stable 10-MHz IF signal with a phase jitter of <0.05 rad.

The main drawback of this scheme is that it requires three stages of frequency mixing which results in a large conversion loss and distortion. In addition, the use of three auxiliary sources not only increases the cost and complexity of the system but also induce intolerable phase noise to the IF signal.

To remedy these, another passive phase correction scheme is developed, with the schematic diagram shown in Fig. 3 [38]. In the local station, a signal generated by a LO, having a half frequency of that of the RF signal to be transmitted, is used as an auxiliary signal in the remote site. This auxiliary signal travels a round-trip through the fiber; thus, it has the same phase vibration caused by environmental fluctuations as the transmitted RF signal. Then, the transmitted RF signal is mixed with the auxiliary signal from the LO. The up-converted signal at the frequency that is three times of that of the LO is selected out and then mixed with the round-trip travelled auxiliary signal. The down-converted signal has the same frequency with the transmitted RF signal, and the phase term due to fiber delay is eliminated, leading to the stabilized RF phase transfer. In an experiment, a 6-GHz RF signal is

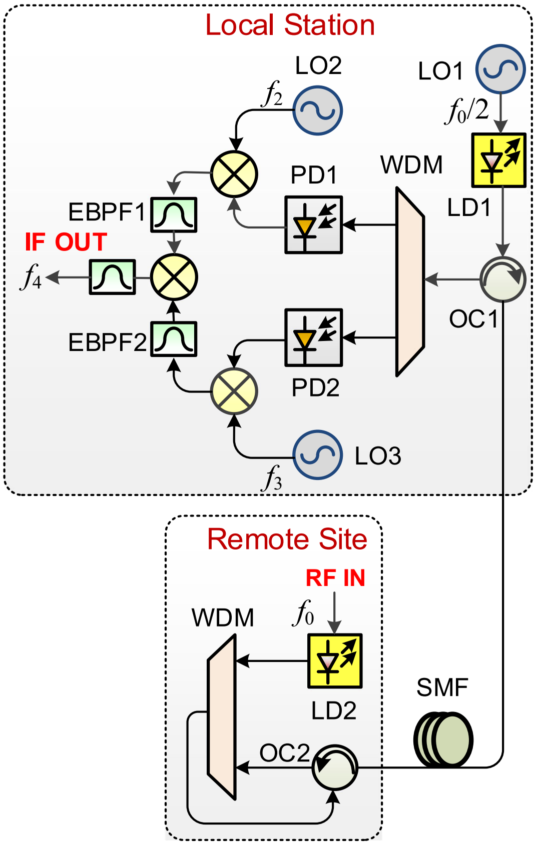

Fig. 2 Diagram of the post-phase correction scheme with three auxiliary RF sources and three stages of frequency mixing [37]. *LD* laser diode, *SMF* single-mode fiber, *WDM* wavelength division multiplexer, *EBPF* electrical band-pass filter, *LO* local oscillator, *OC* optical circulator, *PD* photodetector

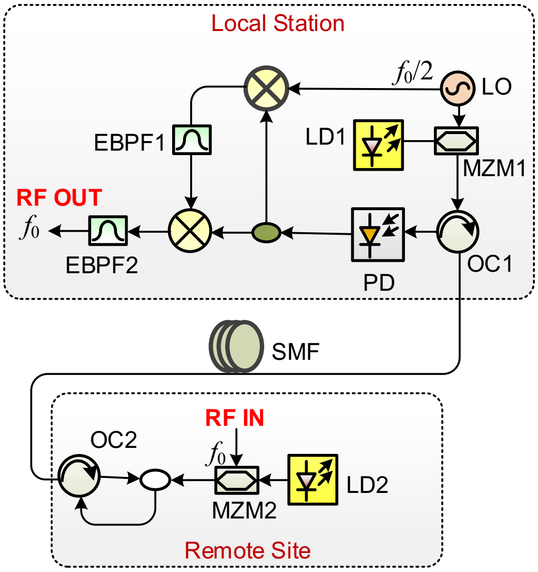

Fig. 3 Schematic diagram of the post-phase correction scheme with one auxiliary RF sources and two stages of frequency mixing [38]. *MZM* Mach–Zehnder modulator

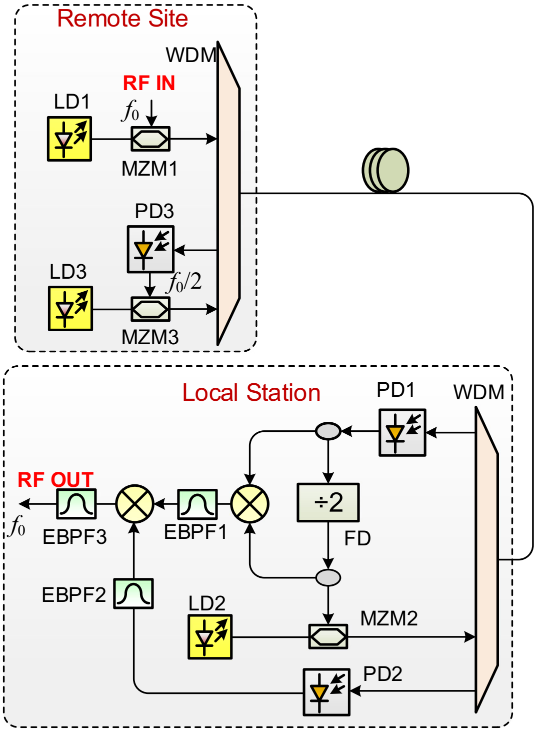

Fig. 4 Schematic diagram of the post-phase correction scheme without any auxiliary signal [39]. *FD* frequency divider

transmitted over 20-km SMF with a root mean square (RMS) timing jitter of 1.33 ps.

This scheme uses only one reference source; thus, the system complexity and cost are significantly reduced as compared to [37]. Besides, the phase noise degradation due to frequency mixing and power amplification is alleviated, since only two stages of frequency mixing are required in the scheme.

Further reduction in the number of the auxiliary RF sources can be realized by applying a frequency divider, to generate the half-frequency auxiliary signal from the RF signal. The idea is demonstrated by Li et al. [39] with the schematic diagram shown in Fig. 4, by which passive phase correction without any reference source is realized. The RF signal generated at the remote site is first transmitted to the local station. At the local station, the signal is divided into two branches. One branch is passed through a frequency divider and the obtained half-frequency signal is mixed with the RF signal in the other branch. A signal at the frequency that is 3/2 times of that of the RF signal is achieved. At the same time, the other portion of the auxiliary signal from the frequency divider is modulated onto a second optical carrier and travels a round-trip through the fiber. The received auxiliary signal is then mixed with the 3/2-time frequency signal, generating a frequency component at the RF signal frequency with its phase stabilized by the passive phase correction. In an experiment, a 9.6-GHz signal is delivered through the optical fiber link with a RMS timing jitter of 0.76 ps.

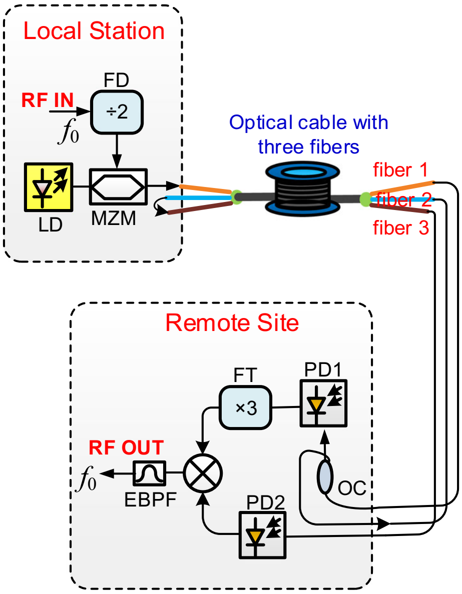

Fig. 5 Schematic diagram of the post-phase correction scheme based on an optical cable with three fibers [41]. *FT* frequency tripler

The advantage of this scheme is that no reference signal is required, which can avoid the extra phase noise due to the use of reference signals. Besides, wavelength conversion is performed in the remote site to avoid coherent Rayleigh noise in the optical fiber by which the bidirectional transmission of a RF signal on the same optical carrier results in significantly increased phase noise [40]. The drawback is that the phase variation caused by chromatic dispersion would be considerable. In addition, more laser sources, electro-optic modulators, and optical/electrical amplifiers are required.

To address the issue of coherent Rayleigh noise without using complex wavelength conversion, the abundant fibers in the optical cable (containing many fibers in bundles) can be taken into account considering that some of the RF signal dissemination is directly implemented in the existing optical communication networks. One study is carried out by Zhang et al. [41], with the scheme shown in Fig. 5. The signal to be transmitted with a frequency of f_0 is firstly frequency divided by two to get a signal with a frequency of $0.5\,f_0$ which modulates on an optical carrier and is transmitted to the remote site through fiber 1 in the optical cable. In the remote site, the microwave photonic signal is divided into two parts by the optical coupler. One part is detected by the photodetector (PD1), and the signal at $0.5\,f_0$ is filtered out and further frequency tripled to generate a signal at $1.5\,f_0$. The other part is injected into fiber 2 and transmitted to the local station. Since fiber 2 is directly connected to fiber 3 in the local station, the microwave photonic signal transmits back to the remote site through fiber 3 and is detected by PD2. Under the assumption that the three fibers (fibers 1–3) are in the same bundle and they experience the same temperature and mechanical stress, the recovered signal at $0.5\,f_0$ has the same phase variation accumulated along the optical fibers as the signal at $1.5\,f_0$. When the two signals are mixed in a mixer, the phase variation is eliminated and a stable signal at f_0 is obtained.

This scheme is compact since only one stage of frequency mixing is used and no reference source is required. The RF signal is free from the coherent Rayleigh noise. But the frequency tripler would add noises to the signal, and the inconsistency of the three fibers might result in residual phase variation.

4 Pre-phase distortion

In addition to the post-phase correction schemes, passive phase correction can also be carried out by pre-phase distortion, in which the RF signal to be transmitted is introduced with a conjugate phase that is expected to counteract exactly the phase variation that would accumulated along the transmission in the optical fiber link. Then, the RF signal is stabilized when received at the receiver.

A pre-phase distortion scheme shown in Fig. 6 for stable RF transfer from the local station to the remote site is reported in [42]. In order to transmit a RF signal with a frequency of f_0, an auxiliary signal (generated by LO1) with a frequency of $0.5\,f_0$ is transmitted a round-trip through the fiber link. After transmission, there is a phase change corresponding to the fiber transmission delay of the auxiliary signal. The transmitted auxiliary signal is then mixed with another LO signal (generated by LO2) with a frequency of $1.5\,f_0$. After mixing, the conjugate phase is brought into the generated frequency component with a frequency of f_0. When this component is transmitted via optical fiber and received at the remote site, the transmission-induced phase variation is eliminated. In an experiment, a 2.42-GHz RF signal is transmitted over a 30-km fiber link, and the RMS timing jitter is 1.7 ps.

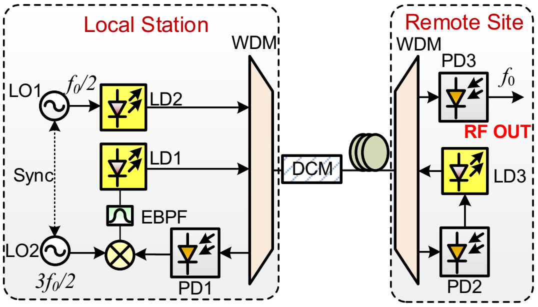

Fig. 6 Schematic diagram of the pre-phase distortion scheme using two synchronized LOs [42]. *DCM* dispersion compensation module

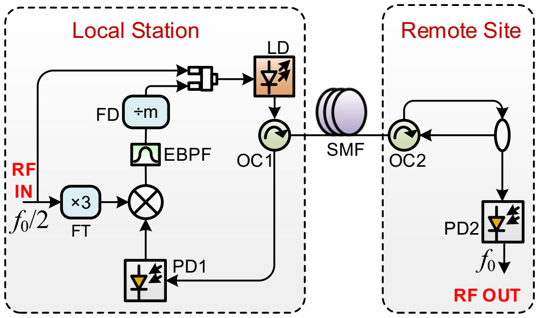

Fig. 7 Schematic diagram of the pre-phase distortion scheme with an external input auxiliary signal [43]

In addition to the pre-phase distortion, wavelength conversion is also performed at the remote site to prevent coherent Rayleigh noise, and a dispersion compensation module is inserted in the fiber link to prevent phase variations caused by chromatic dispersion. However, stable RF transfer based on this approach requires two well-synchronized LO sources, which increases the system cost.

This problem is solved in another study which employs a frequency tripler to generate the $1.5\,f_0$ component from the $0.5\,f_0$ auxiliary signal [43], as shown in Fig. 7. The basic principle of the scheme is almost the same as that in [42]. One part of the auxiliary signal with a frequency of $0.5\,f_0$ is frequency tripled to get a signal with a frequency of $1.5\,f_0$. The $1.5\,f_0$ signal is then mixed with the other part of the auxiliary signal which has been traveled a round-trip in the fiber link. The phase of the down-converted signal with a frequency of f_0 is thus phase pre-distorted. The phase pre-distorted signal is then frequency divided by m to get a signal with a frequency of f_0/m. The m is chosen to make the mth-order harmonics of the f_0/m signal sufficiently small so that it can be combined with the round-trip auxiliary signal and directly modulated on an optical carrier without any interference. The received signal with the frequency of f_0/m is free from the phase variation caused by environmental fluctuation. In an experiment, a 200-MHz signal is delivered through 100-km optical fiber with a long-term fractional instability of 2×10^{-17} at 10^5 s (Allan deviation).

Compared to [42], the scheme in [43] has simpler structure. However, the frequency tripler would add considerable phase noises to the RF signal. According to a study in [44], if the $0.5\,f_0$ signal and the $1.5\,f_0$ signal are generated simultaneously through photodetection of an optical frequency comb (OFC) with a frequency space of $0.5\,f_0$, the RMS timing jitter of the generated f_0 component is about 10 times better than that generated in [43]. One stable RF signal delivery experiment is performed using the OFC-based signal generation, in which a 200-MHz signal is delivered via a 10-km optical fiber with an instability of 1.1×10^{-17} at 10^4 s (Allan deviation).

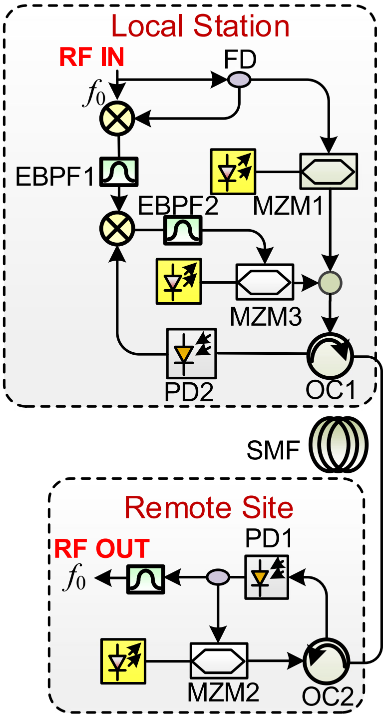

Fig. 8 Schematic diagram of the pre-phase distortion scheme without any auxiliary signal

In [42–44], the RF signal to be transmitted is generated by two LO signals, but in practice the RF signal to be transmitted is generated externally. To perform passive phase correction using the external input RF signal, another scheme is developed which employs a frequency divider to generate the $0.5 f_0$ signal and a mixer to achieve the $1.5 f_0$ component (by mixing the f_0 signal with the generated $0.5 f_0$ signal) [45]. The schematic diagram of the scheme is shown in Fig. 8.

For all the schemes discussed above, only passive phase correction based on frequency mixing is used for stable phase transmission of RF signals. Even though the passive phase correction schemes have a fast compensation speed, the phase variation caused by environmental fluctuations cannot be compensated when the timescale of the environmental variation is smaller than the round-trip transmission time in the fiber link. For instance, if the optical fiber link is 50 km, the round-trip transmission time in the fiber link is about 0.5 ms, the phase noise above 2 kHz cannot be effective reduced.

To achieve both long-term stability and short-term stability, a stable RF transmission scheme using passive phase correction together with a PLL is proposed [45], as shown in Fig. 9. Assume that the frequency of the RF signal in the local station is $f_{0\mathrm{M}}$, and the frequency of a high-quality quartz oscillator is $f_{0\mathrm{S}}$. $f_{0\mathrm{S}}$ is set to be very close to $f_{0\mathrm{M}}$ and serves as the auxiliary signal for passive phase correction. The $f_{0\mathrm{S}}$ signal modulates on an optical carrier and is transmitted to the local station via optical fiber. After received in the local station, it is mixed with a frequency-doubled signal at $2 f_{0\mathrm{M}}$. The down-converted signal with a frequency of $2 f_{0\mathrm{M}} - f_{0\mathrm{S}}$ is phase pre-distorted. If $f_{0\mathrm{S}}$ is exactly the same as $f_{0\mathrm{M}}$, the down-converted signal received at the remote site will be free from phase variation induced by environmental fluctuation. Otherwise, if there is a phase error between $f_{0\mathrm{M}}$ and $f_{0\mathrm{S}}$, the PLL will output an error signal to drive the oscillator until $f_{0\mathrm{S}}$ is exactly the same as $f_{0\mathrm{M}}$. When a 20-MHz RF signal is transmitted in a 100-km fiber, the fractional frequency stability was 6×10^{-17} at an averaging time of 10^4s (Allan deviation).

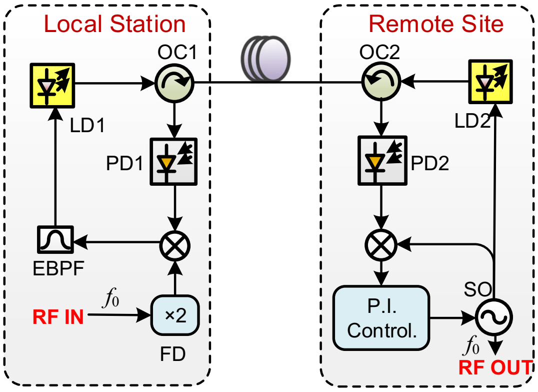

Fig. 9 Schematic diagram of the pre-phase distortion scheme together with a PLL [45]. *SO* slave oscillator, *P.I. control* proportional integral controller

5 Conclusion and discussion

In conclusion, we have established an analytical model for the stable RF transfer system based on passive phase correction, by which the principle of the method and the key performance limitations can be clearly understood. Typical techniques to address the issues of the method are briefly described and discussed.

Despite that great efforts have been devoted to the perfection of the method during the past few years, there is still a considerable room for improvement. One key issue that may come into view is the effect of polarization mode dispersion (PMD). According to the experimental results shown in [36], because of different polarization states of the optical signals launched to the optical fiber, the microwave photonic signals experience different time delays, which leads to considerable residual phase noise. The influence of the PMD can be reduced by using polarization scramblers [36], which may also be applicable for stable fiber RF transfer system based on passive phase correction. The configuration, however, should be carefully designed, since bidirectional transmission in the optical fiber is required.

Another problem associated with the passive phase correction is its incapability of wideband stable RF transfer. If an amplitude term $A(t)$ and a phase term $\phi(t)$ are added to the RF signal to be transmitted in (1), we will achieve $A(t-\tau_2)$ and $\phi(t-\tau_2)$ in (7) and (10), showing that the amplitude profile and phase profile will not be affected by the passive phase correction, i.e., the profiles are still sensitive to the environmental variation. This problem might be solved by using wideband auxiliary signals. But the intrinsic nonlinearity in the mixers would further deteriorate the quality of the signal after transmission.

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