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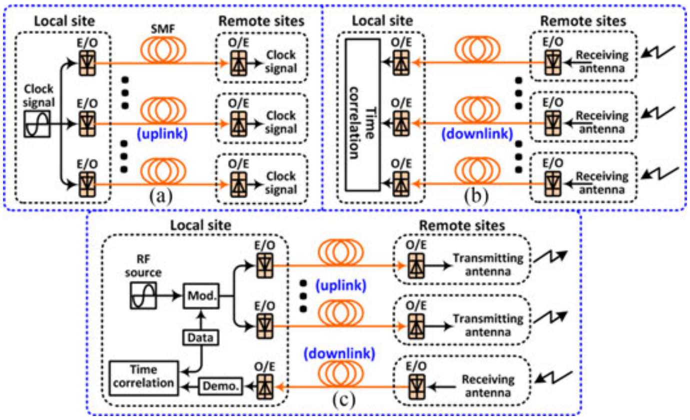

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Phase Fluctuation Cancellation for Uplink Radar Arrays Based on Passive Frequency Mixing

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Abstract: Precise time-difference detections among different radars in uplink radar arrays require ultrastable phase transfer in bidirectional analog optical fiber links. We propose and demonstrate a scheme based on passive frequency mixing to satisfy this requirement in which two continue wave (CW) radio frequency (RF) signals after passing through double-path of the transport fiber are utilized for dynamic phase fluctuation cancellation in uplink and downlink, respectively. Our scheme has the capabilities on stable phase transfers for both CW and pulsed RF signals. Experimental results show that the phase stability improvements in uplink and downlink are greater than a factor of 30 and a factor of 20 for 2.4-GHz RF signals over a 2-h measurement period along 25-km single mode fiber.

Index Terms: Time/frequency dissemination, radio over fiber, uplink radar array, downlink radar array, clock synchronization.

1. Introduction

Optical fiber has been intensively used for transmitting radio frequency (RF) signals over long distance mainly due to its low loss in contrast to electric cable. However, because the optical fiber is sensitive to environmental variations (e.g., temperature and mechanical stress), the refractive index and fiber length change accordingly, resulting in phase fluctuations on the transmitted RF signals. Nevertheless, some specialty applications require extremely stable phase transport over the fiber. One is the clock dissemination as shown in Fig. 1(a), in which fiber-optic signal transport is usually for the remote dissemination of extremely stable frequency and timing metrology references generated in the local site, e.g., clock synchronization in X-ray free-electron lasers and particle accelerators [1]–[3]. Another one is downlink antenna arrays as shown in Fig. 1(b), in which multiple RF signals received by different antennas in the remote sites should be phase-stably transferred to the local site to accurately decode the time difference among them by time correlation, for spacecraft position, navigation, imaging, etc. [3]–[7]. Such as Atacama large millimeter array (ALMA) [4] and multistatic interferometric radar in national aeronautics and space administration (NASA) deep space network (DSN) [7], the former one can reveal the structure of the cold regions of the universe and the latter one can extract topographic information of the target.

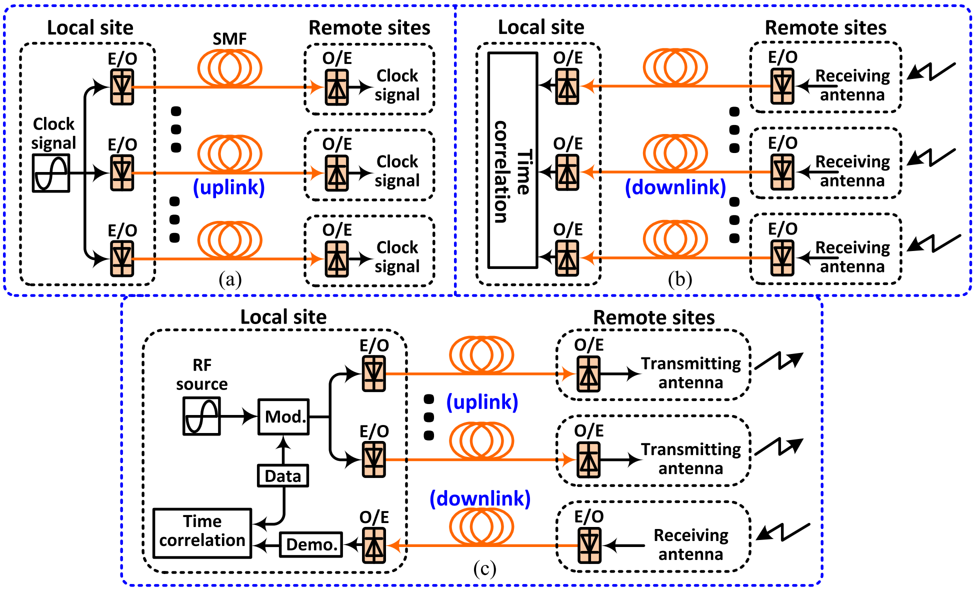


Fig. 1. Three typical applications that requiring stable phase transfers: (a) clock dissemination, (b) downlink radar array, and (c) uplink radar array. E/O: electrical/optical conversion; O/E: optical/electrical conversion; SMF: single mode fiber.

The stable phase transfers for both clock dissemination and downlink radar arrays are normally unidirectional, but there is another application, i.e., uplink radar array as shown in Fig. 1(c), requires stable phase transfers in bidirectional optical fiber links. In detail, the pulsed RF signal generated in the local site should be phase-stably transmitted to multiple remote sites and emitted out by different transmitting antennas. After reflected by the target these pulsed RF signals are received by a receiving antenna in a remote site at different time slots, and should be phase-stably transmitted from this remote site to the local site for precise time-difference extractions to realize the navigations, velocities and locations of the spacecraft, planets and aircrafts [7]–[8]. 34-meter uplink radar array [8] in NASA DSN is a typical one, which can realize imaging of asteroids with high resolution.

Applying feedback loop is the most commonly used approach to realize stable phase transfers in these applications [9], in which the phase error extracted between the reference signal and the optical fiber link round-trip signal is used to control electrical or optical modules (e.g., optical/electrical delay lines [10], fiber stretchers [11], and voltage-controlled oscillators (VCOs) [12]) for phase fluctuation cancellation. Recently, another approach named passive frequency mixing is proposed to realize stable phase transfers for clock disseminations [13]–[15], or downlink radar arrays [5], [9], [16], with the merits of rapid and endless post error cancellation, and obvious electronic complexities reduction. Until now, the schemes based on passive mixing are only used for the stable phase transfers of CW RF signals in uplink or downlink, however, stable phase transfers for pulsed RF signals and in both uplink and downlink are also required in uplink radar arrays.

In this paper, an approach based on passive frequency mixing is proposed to realize stable phase transfer for uplink radar arrays. Briefly speaking, two CW RF signals after passing through double-path of the transport fiber are utilized for dynamic phase fluctuation cancellation by simply using two microwave mixers, for both CW RF signals and pulsed RF signals in both uplink and downlink. On the other hand, frequency multipliers (FMs) and frequency dividers (FDs) are utilized for carrier recoveries. For 25-km SMF transmission over a measurement period of 2 hour in a proof-of-concept experiment, the ranges of the phase jitters are reduced from ∼320 ps to ∼10 ps in uplink and from ∼130 ps to ∼6 ps in downlink, respectively.

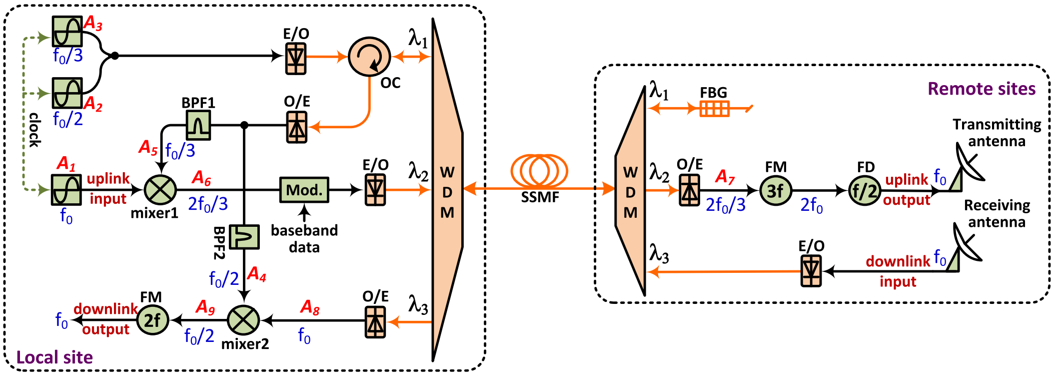


Fig. 2. Schematic diagram of the proposed phase fluctuation cancellation scheme for bidirectional optical fiber link. OC: optical circulator; FBG: fiber Bragg grating; FM: frequency multiplier; FD: frequency divider; BPF: band pass filter; WDM: wavelength division multiplexer; SSMF: standard single mode fiber.

2. Operation Principle

Fig. 2 shows the schematic diagram of the proposed bidirectional phase fluctuation cancellation scheme. RF signal with a frequency of f_0 (signal A_1) is employed as electrical carrier and should be phase stably transmitted in bidirectional optical fiber link. In order to realize this goal, other two CW RF signals with frequencies of $f_0/2$ (signal A_2) and $f_0/3$ (signal A_3) are generated and synchronized with the signal f_0 by sharing the same 10-MHz clock, thus, there is no phase fluctuations among them. Signals A_2 and A_3 are modulated on an optical carrier with a central wavelength of λ_1 and transmitted from the local site to remote site over the optical fiber link (i.e., uplink), and further reflected back to the local site (i.e., downlink) by a fiber Bragg grating (FBG) with a central wavelength of λ_1. After optical/electrical (O/E) conversion, signal with the frequency of $f_0/3$ (signal A_4) is selected by band pass filter1 (BPF1) and signal with the frequency of $f_0/2$ (signal A_5) is selected by BPF2. If the phase fluctuation caused by the optical fiber link corresponding to frequency f_0 over one-path fiber transmission is φ_P, A_1, A_4, and A_5 after amplitude normalization and ignoring fixed phase term can be expressed as

$$\begin{cases} A_1 = \cos(2\pi f_0 t) \\ A_4 = \cos(\pi f_0 t + \varphi_P) \\ A_5 = \cos(2\pi f_0 t/3 + 2\varphi_P/3) \end{cases} \tag{1}$$

In order to eliminate phase fluctuation in the uplink, mixer1 is employed to change both frequency and phase terms of the signal A_1 to ensure that its phase term is negative to the corresponding phase jitter caused by one-path optical fiber link transmission. The output signal of mixer1 can be written as

$$A_6 = \cos(4\pi f_0 t/3 - 2\varphi_P/3) \tag{2}$$

A_6 is modulated by the digital baseband data A_k, and further modulated on the optical carrier with a central wavelength of λ_2, then transmitted from the local site to remote site over the same optical fiber link. After O/E conversion, the recovered RF signal can be expressed as

$$A_7 = A_k \cos(4\pi f_0 t/3) \tag{3}$$

Equation (3) clearly states that phase fluctuation φ_P in the uplink can be eliminated. The frequency of signal A_7 is further converted to f_0 by cascaded FM by 3 and FD by 2, and emitted out through a transmitting antenna. After reflected by targets, it is received by a receiving antenna, modulated on an optical carrier with a central wavelength of λ_3, and transmitted from the remote site to the local site over the same optical fiber link. After O/E conversion, the recovered RF signal can be

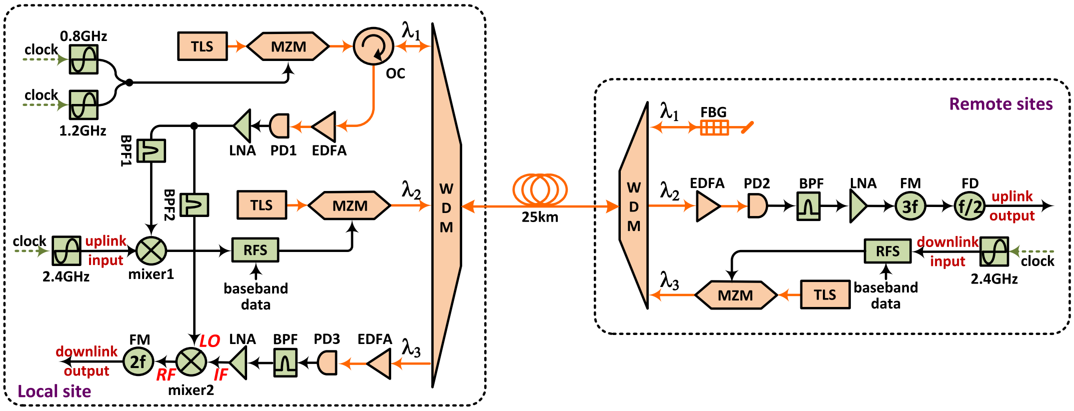


Fig. 3. Experimental setup of the proposed phase fluctuation cancellation scheme for bidirectional optical fiber link. TLS: tunable laser source; MZM: Mach-Zehnder modulator; RFS: radio frequency switch; FBG: fiber Bragg grating; EDFA: erbium-doped fiber amplifier; PD: photo-detector; LNA: low noise amplifier; BPF: band pass filter; WDM: wavelength division multiplexer; FM: frequency multiplier; FD: frequency divider.

written as

$$A_8 = A_k \cos(2\pi f_0 t + \varphi_P) \tag{4}$$

In order to eliminate phase fluctuation in the downlink, mixer2 is used to mix signal A_4 and A_8, then the output signal of mixer2 can be expressed as

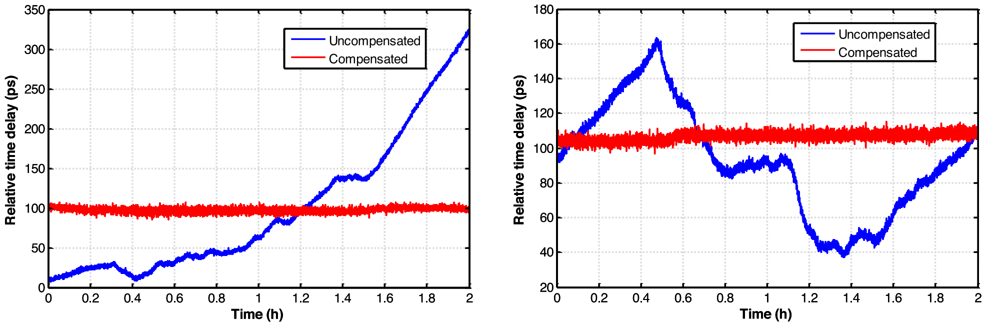
$$A_9 = A_k \cos(\pi f_0 t) \tag{5}$$

Thus, the phase jitter term φ_P in the signal A_8 is removed, i.e., stable phase transfer in the downlink is realized, and then the frequency of signal A_9 is changed to f_0 through a FM by 2. Consequently, phase fluctuation caused by optical fiber link transmission in both downlink and uplink can be cancelled by our proposal, which is independent of A_K, i.e., both CW (A_K is all “1”) and pulsed (A_k comprises both “1” and “0”) RF signals can be phase-stably transmitted. Note that, even the same fiber spool is used to transmit the uplink and downlink data simultaneously, our scheme can still work when two fiber spools are used to transmit uplink and downlink data separately.

3. Experimental Setup

Fig. 3 illustrates the experimental setup of our approach. Three vector signal generators (VSGs) are synchronized through a 10-MHz reference clock, the frequencies of their output signals are 2.4-GHz, 1.2-GHz, and 0.8-GHz, respectively, and the 2.4-GHz signal is the electrical carrier. 1.2-GHz and 0.8-GHz signals are combined by a power combiner and further modulated on an optical carrier through a Mach-Zehnder modulator (MZM) biased at $V_\pi/2$. The optical carrier is generated by a wavelength ultra-stable tunable laser source (TLS) with a central wavelength of $\lambda_1 = 1549$ nm, a peak power of 10-dBm and a 3-dB linewidth of 100-KHz. After passing through an optical circulator (OC) and a wavelength division multiplexer (WDM), the modulated optical beams are sent to the remote site through a standard SMF link. Once the optical beams arrived at the remote site they are reflected back to the local site by a fiber Bragg grating (FBG) with a central wavelength of 1549 nm. After passing through the same OC and amplified by an EDFA, the optical signals are converted into RF signals by PD1, which are amplified by a low noise amplifier (LNA) and further sent to band pass filter1 (BPF1) and band pass filter2 (BPF2) after divided into two branches by a power splitter. The 0.8-GHz and 1.2-GHz signals are selected by BPF1 and BPF2, and further sent to mixer1 and mixer2, respectively.

In the uplink, after mixed with the 0.8-GHz signal through the mixer1, the 2.4-GHz signal is frequency shifted to a 1.6-GHz signal and gated by the digital baseband signal (A_K) through a RF



(a) (b)

Fig. 4. Measured relative time delays between the input signal and the output signal in (a) uplink and (b) downlink when the digital baseband signal is set to all ‘1’ (blue: uncompensated, red: compensated).

switch (RFS), the gated RF signal with a carrier frequency of 1.6 GHz is further modulated on an optical carrier with a central wavelength of $\lambda_2 = 1550\,\mathrm{nm}$ that generated by another TLS. The modulated optical beam is then sent into the same optical fiber link and detected by PD2 after passing through two WDMs and an EDFA sequentially. After passing through a FM by 3 and a FD by 2, the 1.6-GHz signal is recovered to the 2.4-GHz signal as the uplink output signal. In the downlink, a 2.4-GHz signal (generated by the same VSG used in the uplink) is gated by the digital baseband signal (A_K) to emulate the RF signal received by the antenna, which is further modulated on an optical carrier with a central wavelength of $\lambda_3 = 1551\,\mathrm{nm}$ that generated by the third TLS and sent to the local site through the same optical fiber link and detected by PD3. The detected 2.4-GHz signal is mixed with the 1.2-GHz signal through the mixer2, which has a high isolation ratio of 46 dB between the LO port and the RF port, and a conversion loss of 6 dB between the IF port and the RF port. The 1.2-GHz signal with 10-dBm peak power and the 2.4-GHz signal with 0-dBm peak power are sent to the LO port and the IF port of the mixer2, respectively. Thus, the power of the 1.2-GHz leakage signal at the RF port is about -36 dBm, which is about 30 dB less than that of the 1.2-GHz signal through frequency conversion at the same port, so the effect of signal leakage on stable phase transfer can be ignored. The 1.2-GHz output signal of the mixer2 is frequency-recovered to the 2.4-GHz signal through a FM by 2 as the downlink output signal.

4. Results

To evaluate the performance of our proposal, we have measured the relative time delays between the input signals and output signals in the uplink and downlink, respectively. In order to check the capability of our system on CW RF signals, the digital baseband data is set to all ‘1’. Fig. 4 shows the relative time delays between the input CW 2.4-GHz signals and output CW 2.4-GHz signals in (a) uplink and (b) downlink measured by the oscilloscope over a 2-hour period. The time delay measurement resolution of oscilloscope is $\sim$1.35 ps. In the uplink case shown in Fig. 4(a), the phase jitter is varied in a range of $\sim$320 ps without compensation (i.e., RF signal is simply modulated on the optical carrier through the MZM, transmitted through the SMF and detected by the PD), while after compensation, the phase jitter is only varied in a range of $\sim$10 ps. The improvement is greater than a factor of 30. Furthermore, in the downlink case shown in Fig. 4(b), the phase jitter is in a range of $\sim$130 ps without compensation, while after compensation, the range of the phase jitter is reduced to $\sim$6 ps. The improvement is greater than a factor of 20. Consequently, the phase jitters in both uplink and downlink have been effectively compensated for CW RF signals. Note that, due to the effects of the extra optical and electrical components (e.g., TLS, PD, FM, and FD) that used for phase fluctuation cancellation, the short-term phase stability with compensation is slightly worse than without compensation.

To realize time-difference detections in practical uplink radar arrays, the signals transmitted and received by the antennas are normally pulsed RF signals rather than CW RF signals. In order to

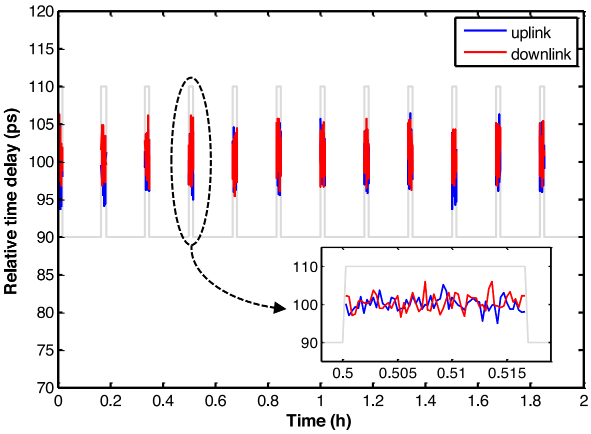


Fig. 5. Measured relative time delay between the input signal and the output signal in uplink (blue line) and downlink (red line) when the digital baseband signal is a pulse signal with a duty cycle of 60 s and a period of 600 s with compensation over a measurement period of 2-hour, the insert shows the detail of the 4th duty cycle.

check the capability of our scheme on pulsed RF signals, the digital baseband data A_k is set to a very simple period pulse signal for the proof-of-concept demonstration, whose duty cycle is 60 s with a period of 600 s. The blue and red lines in Fig. 5(a) show the relative time delay between the input CW 2.4-GHz signal and the output pulsed 2.4-GHz signal over a 2-hour measurement period in the uplink and downlink, respectively. The ranges of the phase jitters are $\sim$10 ps and $\sim$6 ps in uplink and downlink, respectively, during the 720-s time length corresponding to the total duty cycles in 2-hour. The insert shows a more detailed measurement result corresponding to the 4th duty cycle. Thus, pulsed RF signals can also be phase-stably transmitted by our scheme. We also need to note that, when signal A_6 is modulated by the baseband signal A_k, it's changed from a single frequency signal to a multiple frequency signal (the bandwidth equals to the bandwidth of signal A_k). Different frequencies experience different phase jitters during the fiber transmission, and use single frequency signals A_4 and A_5 to eliminate the phase jitters would induce residual phase noise [17]. Thus, the performance of stable phase transfer for pulsed RF signal would be degraded, and it is highly related to the bandwidth of signal A_k and the phase jitter φ_P. In our experiment, the bandwidth of signal A_k is very small (less than 1 Hz), thus, no phase stability degradation is observed compared with the CW RF signal case.

5. Conclusion

In this paper, aiming for satisfying the requirements of stable phase transfers in uplink radar arrays, we propose and experimentally demonstrate a stable phase transfer approach based on passive frequency mixing. The novel approach utilizes two mixers for real-time phase fluctuation cancellation in the assistance of two CW RF signals that over double-path optical fiber link transmission. With this method, obvious phase jitter reduction is achieved for both CW and pulsed RF signals, which may be a potential way to reduce the complexities of current uplink radar arrays.

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