SPECIAL SECTION ON NEW WAVEFORM DESIGN AND AIR-INTERFACE FOR FUTURE HETEROGENEOUS NETWORK TOWARDS 5G

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Enhanced Frequency Stability Over Fiber Link With Improved Phase Discrimination Scheme

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ABSTRACT We demonstrate a phase-stability radio-frequency (RF) dissemination system via fiber link with direct phase discrimination. The phase fluctuation of the RF signal is identically transferred to a 10 MHz intermediate frequency (IF) by using dual-heterodyne phase error transfer. It guarantees that the phase discrimination of the IF signals and the atomic clock frequency signal can be directly performed without the frequency division or multiplication. This scheme can enhance the frequency stability of the dissemination system by mean of higher precision phase detection and high noise suppression capability. Experimentally, the residual phase noise of compensated system with improved phase detection scheme is −50 dBc/Hz and −67 dBc/Hz at 0.01 Hz and 1 Hz frequency offset, respectively, the RMS timing jitter in the frequency range from 0.01 Hz to 1 MHz reaches about 50 fs. Compared with the frequency division and multiplication methods, the frequency stability is improved nearly one orders of magnitude to 5×10^{-17} at 2000 s averaging time.

INDEX TERMS Microwave photonics, fiber optics communications, analog optical signal processing, phase-locked loop.

I. INTRODUCTION

The transfer of ultrastable frequency reference is required by many applications in time and frequency metrology, fundamental physics, particle accelerator, and astrophysics [1]–[3]. Especially, the current developments of the atomic clock, high stability frequency distribution and comparison have become a new challenge in the field of frequency metrology. Traditionally, long-distance clock comparisons are performed via satellites, such as global positioning system (GPS) [4], given a frequency stability of 10^{-14} at one day averaging time, or about 10^{-15} over one day averaging time for two-way satellite time and frequency transfer (TWSTT) [5]. These techniques are consequently insufficient to distribute the modern atomic clock having demonstrated a frequency stability of few 10^{-16} at one day. Due to the low attenuation, high reliability, and immunity to electromagnetic interference, the remote distribution of frequency reference over optical fiber has been investigated for several years [6], [7]. However, the transmission delay would change randomly because of mechanical stress and temperature variations on the fiber links, which severely degrades the phase stability of the remote signal. To realize high stable frequency reference remote distribution via the optical fiber, the phase fluctuation induced by the fiber transmission delay variation need to be corrected in real.

It is usually executed by either passively phase-conjugate to cancel the phase fluctuation [8]–[12] or actively phase precompensating of the reference signal in the optical domain and electrical domain [13]–[19]. The passive compensation based on the phase-conjugate frequency mixing technique is an open-loop scheme that could avoid the use of phase-locking loop (PLL) and tunable compensation devices. However, it will induce serious intermodulation distortion and large conversion loss due to large-number-stage frequency mixing signal processing. In the active phase compensation scheme, a closed-loop feedback control including the fiber stretcher [13], [14] or voltage-controlled oscillator (VCO) [15]–[19] is often adopted for phase compensation. These closed-loop feedback control schemes have the advantages of fast response and high precision compensation. However, in the phase detection part of the feedback control

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loop, since the reference frequency signal of the atomic clock is fixed, the two input signals of the phase detector often need to be divided or multiplied to achieve the same frequency phase discrimination. On the one hand, since the frequency of the phase discrimination is reduced after the frequency division of the input signal, resulting in a smaller bandwidth of the loop and thus weakening the noise suppression capability [20]. On the other hand, the use of frequency divider and multiplier increases the phase noise floor of the compensation system [21]. In previous work, we have achieved 20 GHz [16] and 100 GHz [17] frequency signal remote distribution based on the dual-heterodyning phase error transfer (DHPT) scheme. In order to match the frequency of the atomic clock, the beat signal generally needs to be divided or multiplied, then phase discriminate with the atomic clock. However, it will weaken the ability of phase compensation due to the deterioration of phase discrimination accuracy.

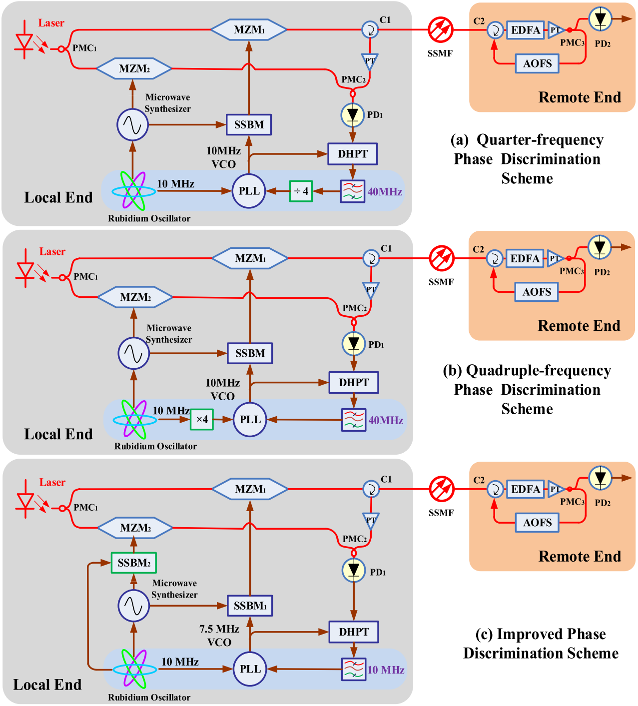
In this paper, we design a radio-frequency (RF) stable transmission system that uses two single sideband modulators (SSBM) for direct phase discrimination without frequency division or multiplication. It guarantees the advantage of transmitting high frequency signals [22], and the high frequency phase discrimination enhances phase noise suppression because it gives the feedback system a larger loop bandwidth. At the same time, the phase noise of the PLL is reduced by avoiding the use of the frequency divider or multiplier. Experimentally, we transfer a 20 GHz RF signal over 80 km standard single-mode fiber (SSMF) by the quarter-frequency, quadruple-frequency and directly phase discrimination scheme, respectively. Compared with the frequency divided and multiplied methods, the residual phase noise of the system based on the direct phase discrimination mechanism is reduced by 10 dB to −50 dBc/Hz at 0.01 Hz frequency offset, and the frequency stability is improved nearly one orders of magnitude to 5×10^{-17} at 2000 s averaging time.

II. PRINCIPLE

The schematic of the RF dissemination system with three configurations are illustrated in Fig. 1. A 10 MHz rubidium oscillator (FS725) is used as the frequency standard, which is synchronized with the microwave synthesizer (E8257D). A low frequency VCO first SSB modulates (SSB90120N) one branch of the microwave source with an electrical SSB modulator, then the modulated microwave signal continues to modulate one portion of a narrow line-width laser (E15) at 1550 nm with a Mach-Zehnder modulator (MZM) (MXAN-LN-10) based on double-side-band with carrier suppression (DSBCS). The modulated optical signal can be written as,

$$\begin{aligned} E_{Local}(t) &= \exp\left\{j\left[(\omega_c+\omega_{RF}+\omega_{VCO})\,t+\varphi_c+\varphi_{RF}+\varphi_v(t)\right]\right\} \\ &\quad + \exp\left\{j\left[(\omega_c-\omega_{RF}-\omega_{VCO})\,t+\varphi_c-\varphi_{RF}-\varphi_v(t)\right]\right\}, \end{aligned} \quad (1)$$

where ω_c, ω_{RF} and ω_{VCO} are the angular frequencies of the optical carrier, microwave synthesizer and the VCO, respectively. φ_c, φ_{RF}, and $\varphi_v(t)$ is the instantaneous phase of the optical carrier, the microwave synthesizer and the VCO, respectively. Due to the fact that signal amplitude has a limited impact on the system, it is omitted for the sake of simplicity, and the nonlinearities of the power amplifiers and MZMs are also omitted [6], [7].



(a) Quarter-frequency Phase Discrimination Scheme

(b) Quadruple-frequency Phase Discrimination Scheme

(c) Improved Phase Discrimination Scheme

FIGURE 1. Experimental setups for the frequency reference dissemination over optical fiber with (a) quarter-frequency phase discrimination scheme; (b) quadruple-frequency phase discrimination scheme; (c) Improved (direct) phase discrimination scheme. MZM, Mach–Zehnder modulator; SSBM, single sideband modulator; PMC, polarization-maintaining coupler; AOFS, acousto-optic frequency shifter; PLL, phase-locked loop; EDFA, erbium-doped optical fiber amplifier; PD, photo-detector; PT, polarization tracker; SSMF, standard single-mode fiber; C, circulator. DHPT, dual-heterodyne phase error transfer; ÷4, fourfold frequency divider; ×4, fourfold frequency multiplier.

After transmitting to the remote end, the modulated optical signal goes through another optical circulator and then boosted by an erbium-doped fiber amplifier (EDFA). The signal with amplified power is then power split into two branches by a polarization-maintaining coupler (PMC). One is used to obtain the RF signal by optical heterodyne beating the two optical sidebands with a high-speed photo-detector (PD) (DSC-R401HG), it can be expressed as,

$$I_{RF}(t) = \cos\left[2\left(\omega_{RF}+\omega_{VCO}\right)t+2\varphi_v(t)-2\varphi_p(t)\right], \quad (2)$$

which $\varphi_p(t) = (\omega_{RF}+\omega_{VCO})\,\tau$ is the phase fluctuation by the fiber link, and τ is the transmission delay. Therefore, in order to receive a phase stable RF signal at the remote end, the phase of VCO $\varphi_v(t)$ has to be tuned to compensate for the optical fiber path induced phase fluctuation $\varphi_p(t)$.

The other is frequency down-shifted 40 MHz by an acousto-optic frequency shifter (AOFS) (SFO2692-T-M040) to avoid the Rayleigh backscattering and transmitted back to the local end through the same fiber link. Due to the high reciprocity of the forward and backward signal path [7], the round-trip signal will exhibit twice delay variations at the local end.

At the local end, the other branch of microwave source modulates the other portion of the laser with the other MZM based on DSBCS. This modulated optical signal is used as the reference signal for detecting the optical fiber induced phase fluctuation, and it can be written as,

$$E_{REF_1}(t) = \exp\{j[(\omega_c + \omega_{RF})t + \varphi_c + \varphi_{RF}]\} + \exp\{j[(\omega_c - \omega_{RF})t + \varphi_c - \varphi_{RF}]\}. \quad (3)$$

To alleviate the polarization fading effect, the round-trip signal first passes through a polarization tracker (PT) (POS-002), then is mixed with the reference signal on low-speed PD (PDB415C). Based on our proposed DHPT scheme [17], a beat note signal can be obtained,

$$I_{IF_1}(t) = \cos 4\omega_{VCO}t + 4\varphi_v(t) - 4\varphi_p(t). \quad (4)$$

It should be noted that the phase of the beat note signal denotes the transmission fiber inducing the phase fluctuation of the remote RF signal.

In the phase feedback control system consisting of a PLL, a phase frequency discriminator (PFD) is used to detect the phase error between the beat signal and the rubidium oscillator at the same frequency. The phase error signal goes through a loop filter and controls the low-frequency VCO phase, which is then transferred to the transmitted RF signal with the SSB modulator, and consequently, the phase noise induced by the fiber link is canceled at the remote end. Therefore, the phase noise of the PLL is critical to the residual phase noise and the frequency stability of the RF distribution system. Total phase noise in a PLL can be expressed as follows [23],

$$PN_{PLL} = PN_{floor} + 20\lg N + 10\lg f_{PFD}, \quad (5)$$

where PN_{floor} is the the noise floor due to the PLL synthesizer circuit itself. $20\lg N$ is the increase of phase noise due to the frequency division associated with the coefficient N. $10\lg f_{PFD}$ is the increase of phase noise associated with the PFD frequency f_{PFD}.

Fig. 1 (a) shows the traditional phase discrimination mechanism for dividing the beat signal $I_{IF_1}(t)$ to match the rubidium oscillator. It introduces a frequency divider that not only increases residual phase noise, but also reduces the PFD frequency that will degrade the phase discrimination accuracy. By multiplying the rubidium oscillator is also adopted for the phase discrimination as shown in Fig. 1 (b), however, the multiplier will introduce additional $20\lg N$ times the phase noise to deteriorate the stability of the signal [21].

In order to directly phase discrimination between the beat signal and the rubidium oscillator without the frequency multiplication or demultiplication, an improved phase detection structure is introduced and is shown in Fig. 1 (c). The first SSBM is applied to identically transfer the IF phase compensation to the RF driven signal of the MZM, the second SSBM is used to frequency offset so that the beat signal can directly discriminate with the atomic clock's phase without using the frequency divider or multiplier.

The one branch of the microwave source is firstly SSB modulated by the rubidium oscillator, and then, it modulates one portion of the laser with MZM based on DSBCS. This modulated optical reference signal can be expressed as,

$$\begin{aligned} E_{REF_2}(t) &= \exp\{j[(\omega_c+\omega_{RF}+\omega_{Rb})t+\varphi_c+\varphi_{RF}+\varphi_{Rb}]\} \\ &\quad + \exp\{j[(\omega_c-\omega_{RF}-\omega_{Rb})t+\varphi_c-\varphi_{RF}-\varphi_{Rb}]\}. \end{aligned} \quad (6)$$

which ω_{Rb} is the angular frequencies of the rubidium oscillator, φ_{Rb} is the initial phase of the rubidium oscillator and it is considered as a constant. By using two SSB modulators to perform the shifted of the optical reference signal and the modulation of the optical transmission signal, respectively. Then, the obtaining beat signal can be able to match the rubidium oscillator to avoid the frequency division or multiplication processing, and it can be written as,

$$E_{IF_2}(t) = \cos\left[(4\omega_{VCO} - 2\omega_{Rb})t - 4\varphi_p(t) + 4\varphi_v(t) - 2\varphi_{Rb}\right]. \quad (7)$$

Thus the error signal can be obtained,

$$E_{err}(t) = \varphi_{Rb} - \left[4\varphi_v(t) - 4\varphi_p(t) - 2\varphi_{Rb}\right]. \quad (8)$$

When the phase-locked loop is locked by adjusting the frequency of the VCO, i.e., $E_{err}(t) = 0$, the phase relationship between $E_{IF_2}(t)$ and the rubidium oscillator will satisfy the relation,

$$4\left(\varphi_v(t) - \varphi_p(t)\right) = 3\varphi_{Rb}. \quad (9)$$

Substituting (9) into (2), the remote RF signal can be expressed as,

$$I_{RF}(t) = \cos\left[2(\omega_{RF} + \omega_{VCO})t + \frac{3\varphi_{Rb}}{2}\right]. \quad (10)$$

From (10), it can be seen that $I_{RF}(t)$ is independent of the delay variation induced by the transmission link. Thus, a phase stabile RF signal at the remote can be obtained.

III. EXPERIMENT AND RESULTS

Based on the direct phase discrimination scheme, the experimental setup of the RF dissemination system is shown in Fig. 2. The local end and the remote end are connected by 80 km of spooled single mode fiber, which is located in an open environment with a larger temperature variation. The microwave synthesizer producing a 10 GHz sinusoidal signal that is power splitting into two branches. Then, both of them are single-sideband modulated by the rubidium signal and a 7.5 MHz VCO signal with two electronic SSB modulators, respectively. The low-frequency VCO's pull range is ±200ppm, which is adequate for this system. The modulated optical signal (Path a) is passed through an optical circulator and then injected into the spooled 80 km SSMF. To compensate for the optical loss caused by the transmission

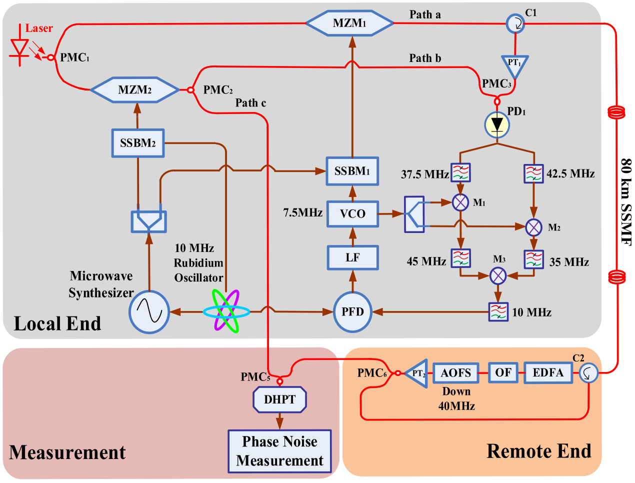


FIGURE 2. Experimental setups for the frequency reference dissemination over 80 km optical fiber with improved phase discrimination structure.

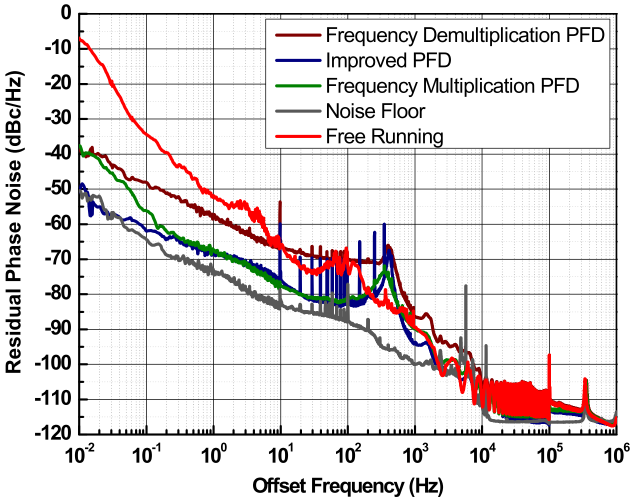


FIGURE 3. The residual phase noise of the RF dissemination system in condition of phase-locked 80 km fiber with three PFD methods, free running 80 km fiber, and phase locked 1 m fiber.

links, an EDFA (EDFA100P) is employed at the remote end. Besides, an optical filter (XTM-50) is adopted to suppress the amplified spontaneous emission (ASE) noise of the EDFA.

A phase noise analysis module is designed to evaluate the performance of the frequency dissemination system which includes the residual phase noise and frequency stability. As shown in Fig. 2, reference path c is optical heterodyned with the remote modulated optical signal, thus obtaining a 5 MHz beating signal after some electrical signal processing. According to the DHPT scheme, the residual phase noise of the remote 20 GHz signal can be evaluated by measuring the phase noise of 5 MHz heterodyne beat signal with a phase noise analyzer (Microsemi's 5125A). For comparative analysis, the performance of the transmission system under the frequency divided and multiplied phase discrimination mechanism are also tested.

Fig. 3 shows the residual phase noise of the frequency dissemination system in condition of phase locked (80 km compensated link with three PFD methods), free running (80 km fiber link without phase compensation) and a short fiber (phase locked 1m fiber). The result for phase locked 1 m fiber gives the noise floor of our experimental system, which is mainly determined by electric signal processing and optical modulation and detection at the two ends. Moreover, in order to guarantee that the residual phase noise measurements are taken under equal conditions, the same loop bandwidth about 400 Hz is used, which is mainly determined by optical fiber length. A large bandwidth may cause loop instability; a small bandwidth may hinder the system's ability to suppress higher-frequency link fluctuations. It can be seen that the phase noise of the free running system is significantly higher than the phase-locked systems at the lower offset frequency since all of these schemes can efficiently suppress the phase noise induced by the fiber link temperature variation. It can be observed that the phase locked system with the improved phase detection scheme reaches −50 dBc/Hz and −67 dBc/Hz at 0.01 Hz and 1 Hz frequency offset, respectively. It reduces phase noise about 15 dB at 1 Hz frequency offset and over 40 dB at 0.01 Hz frequency offset compared with the free running system. However, compared with the improved phase detection scheme, the phase noise of the 80 km compensated link with frequency multiplication or demultiplication schemes deteriorate approximately 10 dB at 0.01 Hz frequency offset. Thanks to the direct phase discrimination structure, it avoids the introduction of additional phase noise due to the division and multiplication. The RMS timing jitter in the frequency range from 0.01 Hz to 1 MHz reaches 50 fs. Some bumps around 400 Hz are observed which is due to the bandwidth of the control loop. Moreover, since the phase noise at higher frequency components is dominated by delay self-heterodyne interferometric noise and the correlated phase noise of the microwave signal, some ripples can be seen in the phase locked system and free running system.

The fractional frequency stability of the RF distribution system is evaluated by the Allan deviation and shown in Fig. 4. Compared with the free running system, it can be seen that the frequency stability of the phase locked system with three phase discrimination methods is significantly improved when the averaging time increases to several hundred seconds. This demonstrates that all of the schemes can efficiently compensate for low-frequency noises of fiber link mainly induced by temperature variation. Since the additional phase noise introduced by the frequency divider and multiplier degrades the performance of the phase compensation, it causes the system's long-term stability that is worse than the directly phase discrimination scheme by an order of magnitude. The 80 km transmission system's stability for the free running case is 2.5×10^{-13} at 2000s average time. On the contrary, the stability of the transmission system with the improved phase detection achieves 5×10^{-17} at 2000s average time. The system's frequency stability is improved by approximately four orders of magnitude. The fitted curves show that the frequency stability

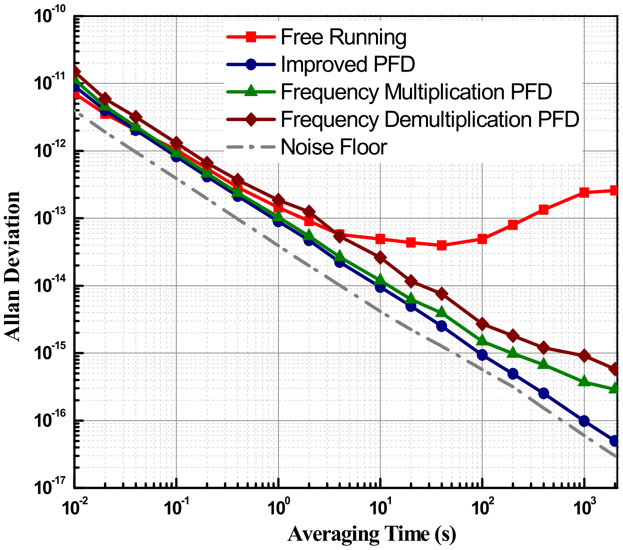


FIGURE 4. Fractional frequency stability of RF dissemination system in condition of phase-locked 80 km fiber with three PFD methods, free running 80 km fiber, and phase locked 1 m fiber.

is proportional to the τ^{-1}, indicating that the residual noise is white phase noise dominated. It is also can be observed that the stability of the improved compensated link slightly degrades that of the system floor, which is caused by the noise of the source signal and the polarization mode dispersion (PMD). Possible further improvements may include inserting the polarization scrambler to reduce the PMD. Also, a more stable atomic clock can be adopted to improve system performance.

IV. CONCLUSION

In summary, we demonstrated a RF dissemination system in which the phase error is directly detected instead of frequency division or multiplication processing. In this scheme, two single sideband modulators are adopted to perform the optical frequency shifted and modulation, respectively, so that the feedback signal can directly discriminate with the atomic clock signal without using the frequency divider or multiplier. Then the error signal between the feedback signal and atomic clock signal goes through a loop filter and controls a low-frequency VCO phase to compensate the phase fluctuation of the remote RF signal. The phase noise within the loop bandwidth is effectively suppressed, thus, a high phase stable RF signal is achieved at the remote end. An experiment has been demonstrated with this structure to transfer a 20 GHz RF signal through 80 km fiber link. The residual phase noise of compensated system with improved phase detection scheme is −50 dBc/Hz and −67 dBc/Hz at 0.01 Hz and 1 Hz frequency offset, respectively, the RMS timing jitter in the frequency range from 0.01 Hz to 1 MHz reaches about 50 fs. The long-term frequency stability also achieves 5×10^{-17} at 2000 s average time, which shows an improved performance.

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