Distribution of high-stability 10 GHz local oscillator over 100 km optical fiber with accurate phase-correction system

Siwei Wang, Dongning Sun, Yi Dong,* Weilin Xie, Hongxiao Shi, Lilin Yi, and Weisheng Hu

State Key Laboratory of Advanced Optical Communication Systems and Networks Shanghai Jiao Tong University, Shanghai 200240, China

**Corresponding author: yidong@sjtu.edu.cn*

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We have developed a radio-frequency local oscillator remote distribution system, which transfers a phase-stabilized 10.03 GHz signal over 100 km optical fiber. The phase noise of the remote signal caused by temperature and mechanical stress variations on the fiber is compensated by a high-precision phase-correction system, which is achieved using a single sideband modulator to transfer the phase correction from intermediate frequency to radio frequency, thus enabling accurate phase control of the 10 GHz signal. The residual phase noise of the remote 10.03 GHz signal is measured to be −70 dBc/Hz at 1 Hz offset, and long-term stability of less than 1×10^{-16} at 10,000 s averaging time is achieved. Phase error is less than $\pm 0.03\pi$. © 2014 Optical Society of America

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Remote distribution of radio-frequency (RF) local oscillator (LO) signals over optical fiber, in which the LO signal is transferred through the fiber using amplitude modulation, has gained growing research interest. Its applications include deep-space networks [1,2], very long baseline interferometer [3,4], particle accelerators [5], and remote clock signal comparison [6,7]. However, mechanical stress and temperature variations on the fiber links may cause transmission delay variations, which degrade phase stability at the remote end. It is usually countered with a round-trip phase-correction mechanism [8].

Round-trip phase-correction systems generally consist of a delay or phase compensator and some signal processing for the feedback loop. Delay compensation using a fiber stretcher has been widely investigated [4,9–14]. Its frequency-independent compensation enables distribution of high-frequency references directly. However, its small compensation range and slow response time limit its application in distribution systems that may suffer large and fast variation of the transmission delay. Phase compensation using voltage-controlled oscillators (VCO) has infinite compensation range and fast frequency response, and there are several reports of VCO-based round-trip phase correction [15–18]. However, it is difficult to distribute high-frequency (approximately 10 GHz) LO reference with VCO-based methods due to the high tuning sensitivity (K_v) of high-frequency VCOs. Generally, commercial high-frequency VCOs exhibit large K_v, usually in the MHz/V range, which is undesirable in the feedback loop of RF remote distribution systems. According to phase-locked loop design theory [19], a large K_v will increase the system's sensitivity to electrical noise in the phase-locked loop. Thus, some researches on VCO-based compensation mainly focused on transmission of lower frequency signals [7,10,15,17] (usually ≤1 GHz). Fujieda *et al.* proposed an effective method of high-frequency transmission by using a frequency comb to multiply a 1 GHz VCO to 10 GHz [20]. The phase of the 10 GHz signal is controlled through that of the 1 GHz signal, achieving dissemination of 10 GHz reference. However, the scheme has little flexibility in adapting to direct transfer of RF signal of different frequencies.

In this Letter, we propose a phase-correction system for direct remote distribution of a 10 GHz LO signal with accurate phase compensation and a composite feedback technique. The accurate phase compensation is achieved with an intermediate frequency (IF) VCO operating in the megahertz range, which with low phase noise is easily achievable due to its small K_v. A single sideband (SSB) modulator is used to transfer the phase correction from IF to RF. The feedback network is designed with frequency independence in mind such that most of the signal processing is performed at IF rather than RF. In fact, the frequency of the RF reference being transferred in our scheme is flexible; no changes in configuration are required for a wide range of frequencies. We demonstrate the concept by transmitting a 10.03 GHz microwave LO signal via 100 km single-mode fiber, achieving residual phase noise of −70 dBc/Hz at 1 Hz offset and long-term stability of less than 1×10^{-16} at 10,000 s averaging time. Phase error is less than $\pm 0.03\pi$.

Schematic of the experimental setup is shown in Fig. 1. The local end and the remote end are connected by 100 km spooled single mode fiber (SMF). Two sources are used in the system: a rubidium (Rb) oscillator operating at 10 MHz and a RF source producing 10 GHz sinusoidal signal that is phase-locked with the Rb oscillator. The 10 GHz RF source output is single-sideband modulated by a 30 MHz VCO signal with an electrical SSB modulator. The VCO that we chose has a low tuning slope of 90 ppm/V (~2.7 kHz/V), which is adequate for this system. The SSB modulator output then modulates a 1550 nm distributed feedback (DFB) laser with a Mach–Zehnder modulator (MZM). The optical signal is transmitted through the 100 km spooled SMF. FC/APC (angled physical contact) connectors are used whenever possible to reduce reflection. An erbium-doped fiber amplifier (EDFA) is used to compensate for the approximately 20 dB power loss caused by the long-haul transmission.

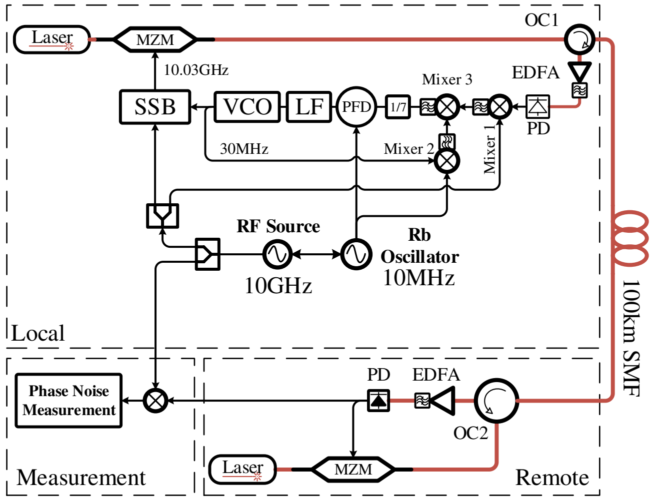

Fig. 1. Experimental setup for the remote distribution of LO signal over 100 km optical fiber. EDFA, erbium-doped fiber amplifier; LF, loop filter; MZM, Mach–Zehnder modulator; OC, optical circulator; PD, photo-detector; PFD, phase frequency detector; Rb, rubidium; RF, radio frequency; SMF, single mode fiber; SSB, single sideband modulator; VCO, voltage-controlled oscillator.

Amplified spontaneous emission (ASE) noise of the EDFA is suppressed by an optical filter. The optical filter also serves the purpose of reducing interference between the forward and backward signal, which is caused by fiber reflection. A photo detector converts the optical signal to the electrical domain, which is then split into two parts; one of them as output to the remote user, the other one amplifies and modulates the returning optical carrier, which is provided by another DFB laser operating at a 0.4 nm offset wavelength from the local one to minimize SNR deterioration caused by Rayleigh backscattering. Another EDFA, optical filter, and photo detector at the local end amplifies the returning signal and converts it to electrical domain for phase-compensation feedback.

The phase-compensation feedback network consists of a phase-locked loop and some signal processing. The signal processing, which is made up of three mixing and filtering operations, is performed on the received signal such that the output represents fiber-link-induced phase-fluctuation information. This signal goes through a loop filter and controls the 30 MHz VCO phase, which is then transferred to the transmitted RF signal with an SSB modulator. Consequently, the fiber-link-induced phase fluctuation is canceled, and the remote signal phase is independent of the optical fiber-link length fluctuations.

The two sources used in this scheme, an Rb oscillator operating at 10 MHz and an RF source producing 10 GHz sinusoidal signal, can be denoted as $\cos(\omega_{\mathrm{Rb}}t + \varphi_{\mathrm{Rb}})$ and $\cos(\omega_{\mathrm{RF}}t + \varphi_{\mathrm{RF}})$, respectively. The output of the SSB modulator can be represented by

$$E_t(t) = \cos[(\omega_{\mathrm{RF}} + \omega_v)t + \varphi_{\mathrm{RF}}(t) + \varphi_v(t)], \qquad (1)$$

in which $\omega_v = N \cdot \omega_{\mathrm{Rb}}$ and $\varphi_v(t)$ are the center frequency and phase of the VCO ($N = 3$ in this experiment). Due to the fact that signal amplitude has limited impact on the system, it is omitted for the sake of simplicity. Omitting the nonlinearities of the power amplifiers and MZM, the optical signal transmitted from the local end can also be represented by Eq. (1).

The phase perturbation caused by fiber link can be denoted as $\varphi_\tau(t) = (\omega_{\mathrm{RF}} + \omega_v) \cdot \tau(t)$, where $\tau(t)$ is the transmission delay. It is a function of time because of the time varying nature of temperature and mechanical stress exerted upon the fiber. The remote signal phase is a combination of VCO output phase and transmission delay-induced phase, which is then amplified and transmitted back along the same fiber. Due to high reciprocity of the forward and backward signal path [7], the returning signal experiences approximately the same transmission delay as the forward signal. A more accurate deduction in which the forward and backward time delay are not considered to be equal may use the technique shown in [21]. The remote signal and the returning signal can be denoted as

$$E_r(t) = \cos[(\omega_{\mathrm{RF}} + \omega_v)t + \varphi_{\mathrm{RF}} + \varphi_v(t) - \varphi_\tau(t)], \qquad (2)$$

$$E_{rt}(t) = \cos[(\omega_{\mathrm{RF}} + \omega_v)t + \varphi_{\mathrm{RF}} + \varphi_v(t) - 2\varphi_\tau(t)]. \qquad (3)$$

The returning signal is converted to the electrical domain using a photo detector and passes through a signal-processing network, the output of which can be denoted as

$$E_{M3}(t) = \cos[(2N + 1)\omega_{\mathrm{Rb}}t + \varphi_{\mathrm{Rb}} + 2(\varphi_v(t) - \varphi_\tau(t))]. \qquad (4)$$

Thus the error signal can be obtained:

$$E_{\mathrm{err}}(t) = \varphi_{\mathrm{Rb}} - [2\varphi_v(t) + \varphi_{\mathrm{Rb}} - 2\varphi_\tau(t)]/(2N + 1). \qquad (5)$$

When the phase-locked loop is in-lock, the steady-state error is canceled through tuning VCO control voltage, i.e., $E_{\mathrm{err}}(t) \to 0$. Consequently, the locked remote signal can be expressed as

$$\begin{aligned} E_{r(\mathrm{lock})}(t) &= \cos[(\omega_{\mathrm{RF}} + \omega_v)t + \varphi_{\mathrm{RF}} + N\varphi_{\mathrm{Rb}}] \\ &= \cos[(\omega_{\mathrm{RF}} + N\omega_{\mathrm{Rb}})t + \varphi_{\mathrm{RF}} + N\varphi_{\mathrm{Rb}}]. \end{aligned} \qquad (6)$$

Note that $E_{r(\mathrm{lock})}(t)$ is independent of $\varphi_\tau(t)$; thus the remote signal phase is independent of the optical-fiber-link length fluctuations.

The bandwidth of the loop filter is mainly determined by optical fiber link length and phase-noise suppression bandwidth. A large bandwidth may cause loop instability; a small bandwidth may hinder the system's ability to suppress higher-frequency link fluctuations. The loop bandwidth is optimized to be approximately 100 Hz in our experiment.

Residual phase noise of the 10.03 GHz remote signal is obtained by measuring the phase noise of the 30 MHz heterodyne beat note between the remote signal and local RF source with a phase-noise test set (Symmetricom 5120A). Figure 2(a) shows the phase-noise measurement of the phase-locked system, a free-running system (no round-trip phase correction, VCO locked to Rb oscillator), and a short fiber system (100 km fiber spool replaced with a 1 m fiber-optic patch cord). The measurement shows the residual SSB phase noise induced by the LO distribution system reaches −70 dBc/Hz at 1 Hz offset frequency from carrier. It can be observed that the phase-locked system reduced phase noise by 10 dB at 1 Hz frequency offset and over 20 dB at 0.01 Hz frequency offset. The noise-suppression ratio is highly related to the ambient environment, which changes very little in our laboratory setting. It may appear to be larger in more realistic scenarios. A bump should appear at approximately the loop bandwidth [19], which can be observed in Fig. 2(a) at about 70 Hz. The ripple at 600 Hz and above can be seen in the free-running and locked configuration. It is caused by the phase noise of the RF source. Long-term stability is shown as an Allan deviation in Fig. 2(b), achieving less than 1×10^{-16} at 10,000 s averaging time. A plateau around the 10–100 s range should be caused by polarization mode dispersion (PMD) [10]. It corresponds to the bump observed at around 10^{-1} Hz in the phase noise plot. The small difference between the short fiber configuration and locked configuration at smaller averaging time (10^{-1} to 10^{1}) corresponds to the ripple on the phase-noise plot above 100 Hz, which is caused by phase noise of the RF source. The time-domain phase error between the local Rb oscillator and remote 30 MHz beat note is shown in Fig. 3. In locked configuration, phase

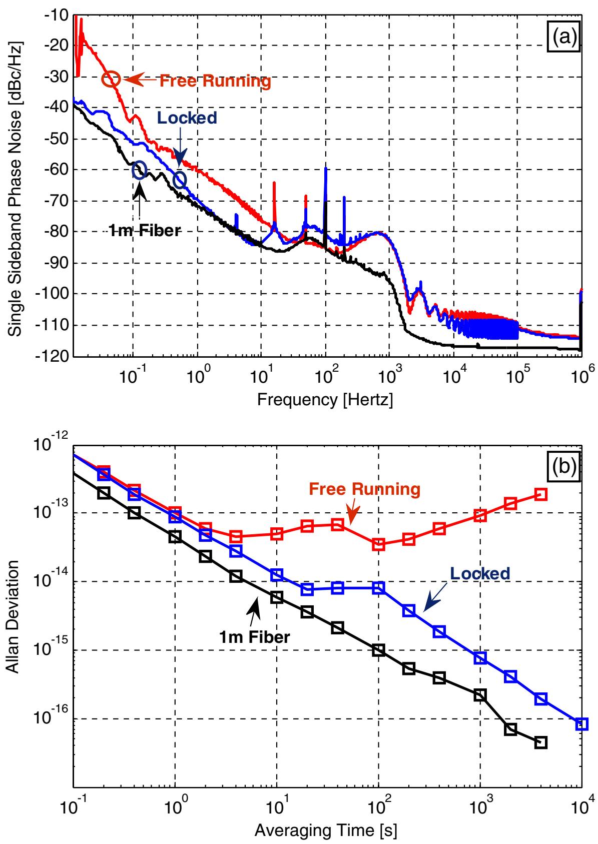

Fig. 2. (a) Residual phase noise (at 10.03 GHz) and (b) Allan deviation of LO distribution system. Noise equivalent bandwidth is 500 Hz ($\tau_0 = 1$ ms). The three curves show the phase noise of a locked 100 km system, a free-running system, and a 1 m fiber system, respectively.

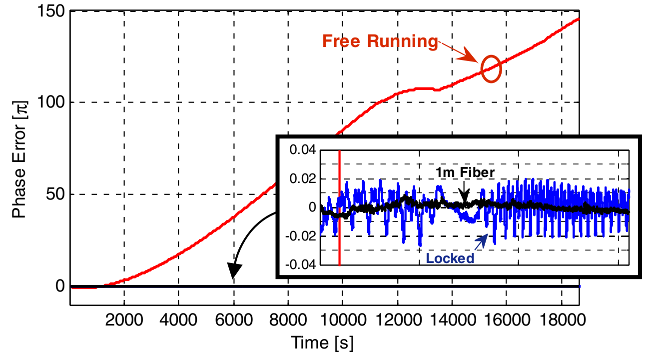

Fig. 3. Phase error of remote signal in three configurations: locked 100 km system, free-running system, and 1 m short fiber system, respectively. Inset shows magnified plot of locked and 1 m short fiber system phase.

error is less than $\pm 0.03\pi$. The system shows good performance in suppressing phase-noise induced by transmission through optical fiber. Possible further improvements may include inserting the polarization scrambler to reduce PMD. Also, a more sophisticated filter can be used to improve system performance [22].

In summary, we have demonstrated a LO distribution system in which phase correction is achieved with an IF VCO instead of a RF VCO for the sake of lower phase noise and simpler control. A SSB generator transfers the phase correction from an intermediate to higher frequency. The feedback network is designed such that most of the signal processing is performed at IF rather than RF. A LO distribution system transferring a 10.03 GHz clock signal over 100 km optical fiber is demonstrated. Residual phase noise of the system is measured to be −70 dBc/Hz at 1 Hz offset; long-term stability is less than 1×10^{-16} at 10,000 s averaging time; phase error is less than $\pm 0.03\pi$.

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