Stabilized Radio Frequency Transfer via 100 km Urban Optical Fiber Link Using Passive Compensation Method

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ABSTRACT A point to point stable radio frequency (RF) signal transfer scheme is proposed and experimentally demonstrated via 100 km noisy urban optical fiber link in Beijing area. We utilize passive frequency mixing method to compensate the variations of the group delay in the optical fiber link. Undistinguished backscattering noise is effectively suppressed by using only two sets of optical transceivers operating on different wavelengths. At the same time, an auxiliary RF signal is employed to accomplish the phase conjugation and effectively eliminate the influence of intrinsic nonlinearity in the mixers. The configuration of dispersion compensation and optical amplification is optimized due to the high loss (31 dB) of this fiber link. In order to carry out the field trial, two prototype modules are fabricated consisting of devices of the transmitting site and receiving site. The measured fractional frequency instability (Allan deviation) of the 2.4 GHz RF transmission system is $6.3 \times 10^{-14}/\sqrt{1 \text{s}}$ and $5.0 \times 10^{-17}/\sqrt{10^4 \text{s}}$, which is superior to that of the reference rubidium clock. The experimental result proves that our frequency transfer system is capable for operating on the underground fiber link and valuable for further applications, such as remote atomic clock comparison.

INDEX TERMS Radio frequency, Optical fiber communication, Optical fiber networks, Radio astronomy.

I. INTRODUCTION State-of-the-art frequency standard generates high precision reference frequency which is essential in the field of frequency metrology. Many applications require highly stable radio frequency (RF) standard distribution, which include Atacama Large Millimeter Array (ALMA), comparison of atomic clocks, and connected-element interferometry in radio astronomy [1]-[2]. Over the past few years, a variety of RF distribution techniques have been developed. One commonly employed approach involves satellites. The stability of conventional frequency transfer based on satellites is limited to $10^{-15}$ at an averaging time of $10^5$ s [3], which is insufficient for most of the aforementioned modern applications. The optical fiber has been recently considered as very attractive transmission medium for stable frequency transfer, which provides much better performance compared with the existing satellite links. Optical fiber has advantages of anti-electromagnetic interference, lower attenuation and better propagation symmetry in both directions of the same fiber link. What’s more, it gives much place to optical fibers for stable frequency transmission with still growing infrastructure of installed fiber links. Many stable RF transfer schemes have been proposed and experimentally demonstrated in the underground optical fiber links[4]-[10].

However, the frequency stability of reference signal transmitted in the fiber link is deteriorated by environment perturbations along the fiber, such as mechanical perturbation and temperature variation, resulting in the phase fluctuations. Thus, phase noise correction is needed to compensate the fluctuation of the propagation delay. In the past few decades, there has been already dozens of research groups working on stable RF transfer over fiber via different phase noise compensation methods, which include both the active compensation technology and passive compensation technology [11]-[18]. The active compensation technology is based on comparing the round trip transmitted signal with the standard
frequency signal to extract the phase error signal, which is used to feedback to some tunable devices, such as optical delay line, electrical delay line or voltage controlled oscillator. The passive compensation technology achieves stable RF transfer by frequency mixing. Some passive devices, like frequency mixer, frequency multiplier or divider are utilized. Compared to the active compensation method, passive compensation scheme has infinite compensation range and its compensation speed isn’t limited by the compensation devices. Thus, it has become an excellent alternative for stable RF transfer over fiber. However, the transmission performance demonstrated in [16]-[18] suffers from the effects of undistinguished backscattering noise and intrinsic nonlinearity in the mixers, which will further deteriorate the stability of the transmitted RF signal. Chen et al. employed different wavelengths to efficiently suppress the effect of backscattering, but the system is not cost effective with three sets of optical transceivers [19].

In this paper, we propose and demonstrate a point to point stable RF transmission scheme based on passive compensation method. On the one hand, our system contains only two sets of optical transceivers with two RF signals co-modulated on the one laser diode. The cost of triple trip transmission wavelength division multiplexers (WDM) system is reduced and there is no effect of backscattering noises. On the other hand, an auxiliary RF signal is utilized to accomplish the phase conjugation and effectively eliminate the influence of nonlinearity in the mixers. The experiment is carried out in metropolitan optical fiber network with a total length of 100 km. In our experiment, the distribution system is designed to transmit a high stable 2.4 GHz RF reference signal, which is phase locked to a rubidium clock frequency standard. The measured standard Allan deviation (ADEV) of the stable RF transmission system is $6.3 \times 10^{-14}/1$ s and $5.0 \times 10^{-17}/10^8$ s.

II. PRINCIPLE

Figure 1 illustrates the diagram of the proposed stable RF transfer via optical fiber system. Our phase noise cancellation scheme can be understood simply as follows. At the transmitting site (TX), a high stable 100 MHz RF signal, referenced to a 10 MHz low phase noise rubidium clock (Quartzlock, A1000), is up frequency converted to 2.3 GHz and 2.4 GHz by two phase-locked dielectric resonant oscillators (PDRO). The PDRO employed in our experiment is a high performance frequency synthesizer, which is phase locked to an external 100 MHz reference. It comprises a phase detector, low pass filter, divider and dielectric resonant oscillator. The PDRO has ultral low phase noises, which are -102 dBc/Hz@100 Hz, -126 dBc/Hz@1 kHz, and -131 dBc/Hz@100 kHz. The 2.4 GHz signal is to be transferred via optical fiber system. Our phase noise cancellation scheme can be understood simply as follows. At the transmitting site (TX), a high stable 100 MHz RF signal, referenced to a 10 MHz low phase noise rubidium clock (Quartzlock, A1000), is up frequency converted to 2.3 GHz and 2.4 GHz by two phase-locked dielectric resonant oscillators (PDRO). The PDRO employed in our experiment is a high performance frequency synthesizer, which is phase locked to an external 100 MHz reference. It comprises a phase detector, low pass filter, divider and dielectric resonant oscillator. The PDRO has ultral low phase noises, which are -102 dBc/Hz@100 Hz, -126 dBc/Hz@1 kHz, and -131 dBc/Hz@100 kHz. The 2.4 GHz signal is to be transferred to the receiving site (RX) with stabilized phase, which can be expressed as a cosine function without considering its amplitude for brevity,

$$E_1 = \cos(\omega_1 t + \varphi_1).$$

\(\omega_1\) and \(\varphi_1\) are its angular frequency and initial phase, respectively. This RF signal is transmitted over 100 km optical fiber link after amplitude modulated to the optical carrier. The optical wavelength channel is channel #33 (1550.92nm). We use a modulation bias controller (MBC) that keeps the modulator operating at orthogonal point where the second component (harmonic tone) of the 2.4 GHz signal is effectively suppressed. The second harmonic suppression ratio is about 50dB. At RX, the 2.4 GHz signal is recovered by an optic/electro converter (O/E), which can be written as

$$E_2 = \cos(\omega_1 t + \varphi_1 + \varphi_p),$$

where \(\varphi_p\) is the phase fluctuation caused by optical fiber environment perturbations corresponding to the angular fre-
In order to generate a phase precompensation signal and eliminate the influence of nonlinearity in the frequency mixer, which has finite harmonic isolation between two ports, a 2.3 GHz auxiliary signal is utilized,

\[
E_4 = \cos(\omega_2 t + \varphi_2).
\]  

One branch of \(E_4\) is mixed with the round trip transmitted 2.4 GHz signal, and a down conversion signal \(E_5\) is generated after a 100 MHz band pass filter (BPF),

\[
E_5 = \cos(\omega_1 t - \omega_2 t + \varphi_1 - \varphi_2 + 2\varphi_p).
\]  

The standard 2.4 GHz signal \(E_1\) is frequency tripled,

\[
E_6 = \cos(3\omega_1 t + 3\varphi_1),
\]  

and mixed with another branch of \(E_4\). After a 4.9 GHz BPF we can get the beat frequency signal,

\[
E_7 = \cos(3\omega_1 t - \omega_2 t + 3\varphi_1 - \varphi_2).
\]  

\(E_5\) is up converted to 4.8 GHz by being mixed with \(E_7\). After a 4.8 GHz BPF, we can get

\[
E_8 = \cos(2\omega_1 t + 2\varphi_1 - 2\varphi_p).
\]  

This phase precompensation signal is co-modulated to the same laser device with \(E_1\) and it will suffer from the phase fluctuation \(2\varphi_p\) after it is distributed over the same optical fiber link. This is under the assumption that the signal experiences the same time delay fluctuation in the forward and backward optical links [20]. At RX, a cleared RF signal can be filtered out by a BPF with center frequency of 4.8 GHz,

\[
E_9 = \cos(2\omega_1 t + 2\varphi_1).
\]  

A devide-by-2 device is employed to obtain a desired 2.4 GHz RF signal \(E_{10}\),

\[
E_{10} = \cos(\omega_1 t + \varphi_1).
\]  

which has the same frequency and phase with the reference standard signal \(E_1\) at TX. The multiplier and divider employed in our system operate on both the frequency and phase of the input RF signal. We can clearly observe that the phase fluctuation of the transmitted RF signal is eliminated by utilizing passive frequency mixing method. There is no active adjustment process in our scheme, which enhances the robustness of the experiment system and makes it more adaptable to be tested in the field-deployed optical fiber link.

III. EXPERIMENT SETUP AND RESULTS

In our experiment, proper low noise electrical amplifiers (EA) are used to remedy the conversion loss of O/E and mixers. We allocate different wavelengths at TX and RX with two dense wavelength division multiplexers (DWDM) equipped. Thus, the effect of backscattering is efficiently suppressed, which is the distance limitation in single wavelength scheme [21]. In order to carry out the field trial expediently, experiment devices of TX and RX are integrated into two standard prototype modules except for the rubidium clock. Power supply and heat dissipation of the two modules are well designed. Each module includes only one set of optical transceiver, which reduces the cost of triple trip transmission WDM system. Figure 2 shows route of the field-deployed telecommunication optical fiber link from Daniufang to Fangzhuang in Beijing area. The fiber metropolitan link used in our experiment is dark fiber. The 100 km fiber link contains two parallel cores of the 50 km fiber link. It’s a part of metropolitan optical fiber network with attenuation of 31 dB. As shown in Fig. 1, three homemade low noise bi-directional erbium-doped fiber amplifiers (bi-EDFA) and one dispersion compensation fiber module (DCF) are employed in our experiment system. This optical fiber link configuration guarantees gain of each bi-EDFA is no more than 25 dB to reduce the deterioration of signal to noise ratio (SNR) during the process of optical amplification. In our experiment, the fiber type is ITU G.652 single-mode fiber. At the wavelength of 1550 nm, the typical value of the dispersion coefficient \(D\) is 17 ps/nm/km. According to the datasheet of the DCF, the residual dispersion is about -0.02 ps/nm/km at the wavelength of 1550 nm. This DCF module is used to reduce the time delay asymmetry of the two transmission directions which is caused by group velocity dispersion.
All the experiment devices are co-located at Daniufang to implement our stable RF transmission experiment and the phase noise measurement. The compensated 2.4 GHz RF signal and the standard reference RF signal are mixed to generate DC error signal after a low pass filter (LPF). The analog mixer employed is a double-balanced mixer, Marki M1-0008. The output of this analog phase detector can be expressed as $V(t)=\left(\frac{V_{pp}}{2}\right)\cos(\Delta \varphi)+V_o$, where $\Delta \varphi$ is residual phase fluctuation of the transmission system, $V_o$ is the inherent DC offset voltage of the analog mixer and $V_{pp}$ is the peak-to-peak voltage of the DC signal $V(t)$. $V_{pp}$ and $V_o$ are measured when the relative phase change between the two mixed signals is greater than $2\pi$. Here, a tunable electric phase shifter is inserted after the standard reference RF signal and employed to accomplish the measurement of $V_{pp}$ and $V_o$. The real-time voltage fluctuation of this DC signal $V(t)$ is collected by a high precision digit multimeter (Keysight 34465A). The relative phase time fluctuation is calculated by using the function $y(t)=(1/2 \pi f_o)\text{arccos}[2(V(t)-V_o)/V_{pp}]$, where $f_o$ is 2.4 GHz. The measured phase time fluctuation is used to calculate the ADEV of our transmission system. The digits of resolution of the multimeter is $6^{1/2}$, and the basic DCV accuracy of the multimeter is 30ppm.

In our experiment, this corresponds to a frequency stability (ADEV) resolution of $\sim 1\times 10^{-15}/1$ s. The measurement time of our experiment is $4\times 10^4$ s. The efficiency of our passive stabilization system can be observed in Fig. 3. The measured fractional frequency instability of our stabilized system reaches $6.3\times 10^{-14}/1$ s and $5.0\times 10^{-17}/10^4$ s, which is superior to that of the reference rubidium clock. While it is $2.1\times 10^{-12}/1$ s for the free running system. Noise floor of our transmission system is $1.6\times 10^{-15}/1$ s and $1.5\times 10^{-17}/10^5$ s, which is measured by replacing the 100 km optical fiber link with 1 m long single mode fiber.

IV. CONCLUSION

In summary, for the first time, a stable RF transmission experiment with passive compensation method is demonstrated via such a long distance metropolitan optical fiber link. The excellent results of our experiment are given that ADEV of the RF transmission system reaches $6.3\times 10^{-14}/1$ s and $5.0\times 10^{-17}/10^4$ s. It proves that our experimental system is robust for running steadily for several days, and there is no active adjustment during the field trial. Standard integrated prototype modules are well designed with optimized transmission system, which is quite meaningful for the realistic applications where a local oscillator needs to be distributed to another station with least phase variation, such as atomic clock comparison and square kilometer array. For further work, we will improve the transmission distance if longer distance underground optical fiber link is available. What’s more, we will also carry out measurement for longer time.

REFERENCES


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