New Method for Cascaded Fiber-Optic Radio Frequency Transfer

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***Abstract*—We report on a new method for cascaded long-haul fiber-optic radio frequency (RF) transfer. The phase noise compensation device is placed at the relay site to simultaneously compensate for phase noise coming from the front and the second segment fibers. At the same time, the technique can have the capability to share the modulated optical signal for the both links, simplifying the configuration at the relay site. This scheme not only greatly simplifies the cascaded RF transfer system but also effectively improves the system noise floor. Experimentally, we demonstrated a 1 GHz signal transfer over a 210 km (100+110 km) fiber-optic link, achieving the fractional frequency stability less than 2.3×10^{-14} at 1 s and 5.4×10^{-17} at 10,000 s.**

***Index Terms*—radio frequency transfer, novel cascaded scheme, long-haul fiber-optic link**

I. Introduction

Transfer of ultra-stable radio frequency (RF) via long-haul fiber-optic link is indispensable in numerous applications, such as Square Kilometre Array (SKA) [1] and very long baseline interferometry (VLBI) [2]. There are two fundamental limitations in long-haul fiber-optic RF transfer. One is the deterioration of the receiver signal-to-noise ratio (SNR) induced by the phase noise accumulation along the long-haul fiber link. The other one is the compensation bandwidth limited by the propagation delay of the fiber link. Although the single-stage span transfer scheme by adopting the bidirectional optical amplifiers can achieve long-haul RF transfer by optimizing the configuration of the fiber link, the limited compensation bandwidth and the accumulated excessive phase link noise pose greatly challenges [3]. Compared with the single-stage span transfer, the cascaded transfer scheme with independent link phase noise compensation for each segment is more favorable for long-haul ultra-stable RF transfer. Unfortunately, the relative frequency stability degrades $\sqrt{N}$ times in the cascaded system configuration with N stages [4]. How to improve the noise floor in a cost-effective way through the cascaded scheme, so as to distribute an ultra-stable RF signal via the long-haul fiber link, is a valuable research direction.

In this article, we report on a novel cascaded scheme for long-haul fiber-optic RF transfer. The active compensation device based on the phase-locked loop (PLL) is placed at the relay site (RLS) to simultaneously compensate for phase noise caused by the front and the second span fibers. Our scheme greatly simplifies the cascaded transfer system, thereby improving the system noise floor. Experimentally, we transfer a 1 GHz RF signal via a 210-km (100+110 km) single-mode fiber (SMF) link. The 210-km cascaded system reached the relative frequency stabilities less than 2.3×10^{-14} at 1 s and 5.4×10^{-17} at 10,000 s.

II. Experimental Setup And Results

The schematic diagram of fiber-optic RF transfer based on the novel cascaded scheme is shown in Fig. 1. The principle of the phase noise compensation technique principle of our proposed scheme can be understood simply as follows. At the RLS, the probe signal with $\omega_{vco}t + \varphi_c$ produced by the voltage-controlled oscillator (VCO) is modulated onto the optical carrier by the electrical-optical converter (E/O), which is transmitted to the local site (LS) and the remote site (RS) via the first and second segment fiber links, respectively. At the LS, the probe signal detected by the optical-electrical converter (O/E) and the detected signal can be denoted as $\omega_{vco}t + \varphi_c + \varphi_{pa}$, where φ_{pa} stands for the phase fluctuation induced by the first segment fiber link. The frequency standard (FS) signal with the expression of $\omega_{RF}t + \varphi_{RF}$ is mixed with the probe signal through the dual frequency mixers (DFM) [5]. The obtained lower-side signal subsequently transmits to the RLS and can be denoted as $(\omega_{RF} - \omega_{vco})t + \varphi_{RF} - \varphi_c$. Another probe signal at the RS recovered by the O/E, which can be expressed as $\omega_{vco}t + \varphi_c + \varphi_{pb}$, where φ_{pb} is the phase fluctuation caused by the second segment fiber link. The part of The recovered signal is provided to can be used for the user or the next cascaded stage. At the same time, the other part is returned to the RLS via the second fiber link, the detected RF signal can be given by $\omega_{vco}t + \varphi_c + 2\varphi_{pb}$. Moreover, it should be noted that ω_{vco} and ω_{RF} have the relationship of $\omega_{RF} \approx 2\omega_{vco}$. The two probe signals returning to the RLS fed into the PLL unit (consisting of mixer, PID controller and VCO). When the PLL unit is active, the phase error is canceled through tuning the VCO control voltage. Then we obtain the relationship of $\omega_{RF} = 2\omega_{vco}$ and $\varphi_c = \varphi_{RF}/2 - \varphi_{pb}$. In this way, it can be obviously found that the stable RF signal can be recovered at the RS.

The experiment setup is shown in Fig.1. The first and second segment fiber links are composed of 100 km and 110 km SMF, respectively, placed in the lab room with temperature fluctuations about 3°C [6]. The FS (Rigol Inc., DSG 821) is set to 2 GHz. The signal generated by the VCO is set to approximately 1 GHz. To compensate for the attenuation of the optical fiber link, we placed two home-made bidirectional

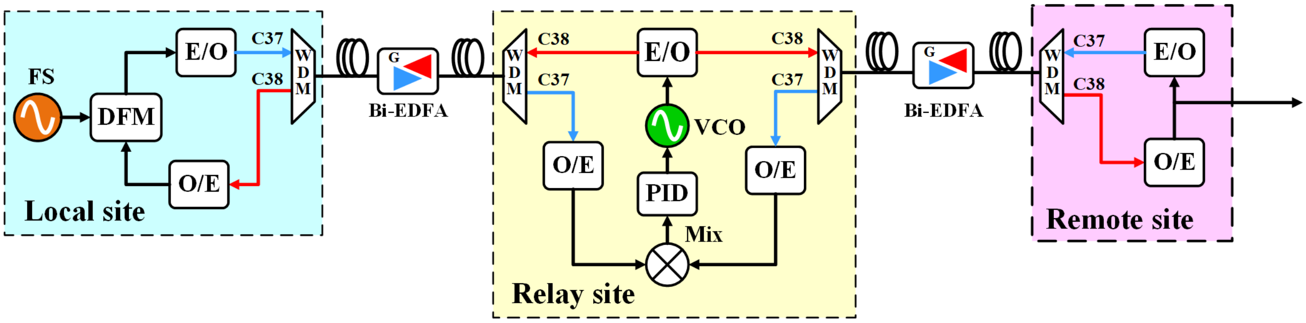

Fig. 1. Schematic diagram of the proposed fiber-optic radio frequency transfer based on the novel cascaded scheme. FS: frequency standard, E/O: electrical-optical converter, O/E: optical-electrical converter, WDM: wavelength division multiplexer, Bi-EDFA: bidirectional erbium-doped fiber amplifier. VCO: voltage-controlled oscillator, MIX: frequency mixer, DFM: dual frequency mixers.

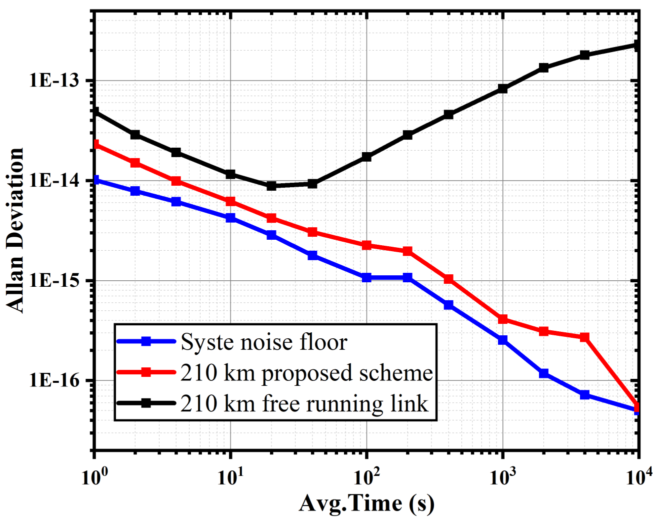

Fig. 2. Measured Allan deviation (ADEV) in the different transfer configurations: the back-to-back system noise floor (blue curve), the 210 km proposed scheme (red curve) and the 210 km free running link (black curve).

erbium-doped fiber amplifiers (Bi-EDFAs) to boost the fading optical signals. The structure of the Bi-EDFA is similar with Ref [7]. Moreover, in order to suppress the impact of chromatic fiber dispersion, the proper dispersion compensation fiber is placed in the fiber link. The measured Allan deviation (ADEV) in different transfer configurations are illustrated in Fig.2. The 210 km proposed scheme reaches the relative frequency stabilities less than 2.3×10^{-14} at 1 s and 5.4×10^{-17} at 10,000 s. Compared with the 210 km free running link, the long-term stability of the 210 km proposed scheme is improved from 2.3×10^{-13} to 5.4×10^{-17} at the averaging time of 10,000 s. The system configuration of the noise floor is replaced the long-haul fiber link of the proposed scheme with 1 m SMF, achieving the relative frequency stabilities less than 1×10^{-14} at the integration time of 1 s and 5×10^{-17} at 10,000 s.

III. Conclusion

In conclusion, we report on a novel cascaded scheme for long-haul fiber-optic RF transfer. This scheme not only greatly simplifies the cascaded RF transfer system but also effectively improves the system noise floor. Experimentally, we demonstrated a 1 GHz signal transfer over a 210 km (100+110km) fiber-optic link, achieving the relative frequency stabilities less than 2.3×10^{-14} at 1 s and 5.4×10^{-17} at 10,000 s.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China (61627817, 61535006).

References

[1] S. W. Schediwy, D. R. Gozzard, C. Gravestock, S. Stobie, R. Whitaker, J. A. Malan, P. Boven, and K. Grainge, "The mid-frequency square kilometre array phase synchronisation system," *Astron. Soc. Australia*, vol. 36, p. e007, 2019.

[2] C. Clivati, R. Aiello, G. Bianco, C. Bortolotti, P. D. Natale, V. D. Sarno, P. Maddaloni, G. Maccaferri, A. Mura, M. Negusini, F. Levi, F. Perini, R. Ricci, M. Roma, L. S. Amato, M. S. de Cumis, M. Stagni, A. Tuozzi, and D. Calonico, "Common-clock very long baseline interferometry using a coherent optical fiber link," *Optica*, vol. 7, no. 8, pp. 1031–1037, Aug 2020.

[3] D. Wang, T. Jiang, C. Liu, S. Zhou, and S. Yu, "Stable radio frequency dissemination via a 1007 km fiber link based on a high-performance phase lock loop," *Opt. Express*, vol. 26, no. 19, pp. 24 479–24 486, Sep 2018.

[4] C. Gao, B. Wang, X. Zhu, Y. B. Yuan, and L. J. Wang, "Dissemination stability and phase noise characteristics in a cascaded, fiber-based long-haul radio frequency dissemination network," *Rev. Sci. Instrum.*, vol. 86, no. 9, p. 09311, 2015.

[5] H. Li, G. Wu, J. Zhang, J. Shen, and J. Chen, "Multi-access fiber-optic radio frequency transfer with passive phase noise compensation," *Opt. Lett.*, vol. 41, no. 24, pp. 5672–5675, Dec 2016.

[6] Q. Li, L. Hu, J. Zhang, J. Chen, and G. Wu, "Fiber radio frequency transfer using bidirectional frequency division multiplexing dissemination," *IEEE Photon. Technol. Lett.*, vol. 33, no. 13, pp. 660–663, 2021.

[7] H. Zhang, G. Wu, X. Li, and J. Chen, "Optical amplification for BTDM-SFSW-based time transfer," *J. Light. Technol.*, vol. 35, no. 19, pp. 4337–4343, 2017.