Elimination of the PMD Related Delay Jitter in an Ultra-Stable Microwave Signal Distribution System

Xi Wang, Wei Wei*, Xiyi Weng, Danyang Wang, Jiawang Wei, Weilin Xie, and Yi Dong
Key Laboratory of Photonic Information Technology, Ministry of Industry and Information Technology, School of Optics and Photonics, Beijing Institute of Technology, Beijing 100081, China
**weiwei@bit.edu.cn*

Abstract: We realize an ultra-stable frequency signal distribution system. The relative delay jitter of the 24 GHz signal is only 13.0 fs after eliminating the PMD-related jitter originated from the stretching of the piezoelectric fiber stretcher.
OCIS codes: (060.2360) Fiber optics links and subsystems; (060.5625) Radio frequency photonics.

1. Introduction

The distribution of an ultra-stable signal to different locations is a key technology in a variety of applications [1]. Taking advantage of the low loss, high reliability, and immunity to electromagnetic interference, the fiber optic link has become a promising candidate for signal distribution [2-4]. However, the fiber link usually suffers from environment perturbations, which will change the effective length of the link, thus deteriorating the phase stability of the signals at the remote end [5]. To compensate for this phase variation, an optical phase-locked loop (OPLL) with the round-trip coherent detection and the piezoelectric fiber stretcher (PFS) based compensation is often employed. However, the delay variation originating from the PFS stretching known as polarization mode dispersion (PMD) still leads to the drift of the real propagation time of the transmitted signal even under the locking state [6].To alleviate the PFS-induced polarization variation specifically, a feedback control system is proposed with a well-designed iterative searching algorithm to ensure that the optimal injected polarization state of the PFS can be achieved and fixed by tuning a polarization controller [7]. However, this method still does not completely fix the output polarization state of the PFS, and the delay jitter originated from the PFS stretching remains even in the tracking state. Until now, it is still a great challenge to eliminate the PMD related delay jitter caused by the PFS stretching.

In this paper, we present an ultra-stable 24 GHz signal distribution system. To eliminate the delay jitter caused by the PFS stretching, an orthogonal-polarized round-trip PFS structure is proposed to maintain the output polarization state of the PFS. The relative root-mean-square (RMS) delay jitter of the signals in two different remote ends via 200 m single-mode (SM) and polarization-maintaining (PM) fiber are 13.0 fs and 17.7 fs within one hour, respectively.

2. Principle

To obtain an ultra-high stable microwave signal distribution system, any tiny transmission delay jitter of the signal at the remote end should be first detected and then compensated precisely. The phase variation of the optical carrier after the transmission can be measured with a precision as high as sub-femtosecond by using a round-trip Michelson interference structure. In such a precise system, a PFS is often adopted for adjusting the fiber length with high control precision and considerable compensation range, ensuring a constant round-trip delay. Figure 1(a) shows the traditional PFS compensation structure, denoted as the single compensation (SC) structure. Due to the PFS stretching, the polarization state of the optical signal changes randomly in the PFS, and it enters the transmission fiber afterward with a random polarization state. The PMD of the PFS and the following fiber link transfer the random polarization variation to random and different transmission delay variation along the forward and backward trip. Thus, locking the round-trip delay still does not produce a phase-stable signal at the remote end with the SC structure.

To eliminate this delay jitter produced by the PFS stretching, we propose an orthogonal-polarized round-trip PFS structure composed of a polarization beam splitter (PBS), a PFS, and a Faraday rotator mirror (FRM) as shown in Fig. 1(b). We denote it as the round-trip compensation (RC) structure. In this structure, the optical signal is first injected into a PBS along one polarization fixed port and then entirely passes through the following PFS. Due to the 90° polarization rotation, the backward signal passing through the PFS always experiences an orthogonal polarization evolution and finally reaches the PBS along with the other polarization fixed axis. Therefore, it enters the following transmission fiber in a fixed polarization state. Consequently, the delay jitter in the transmission fiber is equal for the forward and backward link, regardless of the PFS stretching. Meanwhile, provided that the reflected signal from the remote end reversely entering the RC structure has the same polarization state with the forward signal getting out of the RC structure, the polarization-related delay jitter in the PFS for the forward transmission link is exactly the same as for the backward link. Therefore, the delay jitter produced by the PFS stretching has been eliminated with this simple but effective structure. Compared with the algorithm-based polarization control methods, the proposed RC structure can not only fix the polarization state of the PFS output but also eliminate the difference of the polarization-related delay jitter between the forward and backward transmission direction. Furthermore, without any polarization control mechanism or complicated control algorithms, the proposed method is simple, cost-efficient yet with higher systematic stability. The RC structure also doubles the delay compensation range, having the capability to cope with larger environmental variations.

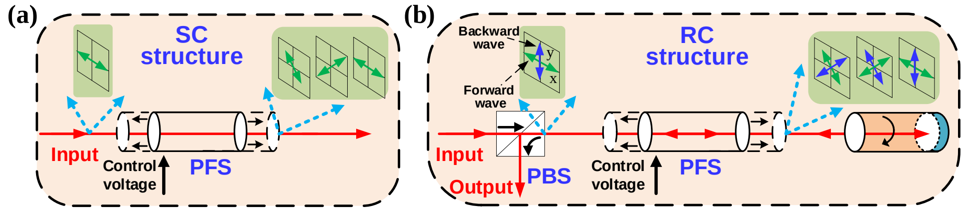

Fig. 1. (a) The single compensation (SC) and (b) the proposed roundtrip compensation (RC) structure.

3. Experiment and results

The experimental setup of the proposed stable microwave signal distribution system with 2 remote ends is shown in Fig. 2. It consists of a local end and two remote ends connected to the local end with 2 separate fiber links. In the local end, a stable fiber laser is firstly split into two parts. The 1% portion is further split into two parts, and each part becomes the reference arm of a Michelson interferometer. The 99% portion is first modulated by a 24 GHz signal generated from a vector network analyzer (VNA) in a Mach-Zehnder modulator (MZM) and then divided into two parts, injecting into two transmission links with a PFS-based delay control module by a 50:50 PM coupler. To verify the advantages of the proposed RC scheme over the traditional SC scheme, we set up two compensation structures for the delay control module. When the switch is on A, the 24 GHz signal first passes through a PM circulator and then enters the RC structure. After the RC structure, the signal passes through a PM circulator and a PM PBS successively. When the switch is on B, the 24 GHz signal merely passes through a PM PBS and then the SC structure. The following motorized optical delay line (MODL) is used for studying the PFS stretching related delay jitter. At the remote end, the optical signal is first frequency shifted by 40 MHz and then divided into two parts. In the one part, the 24 GHz signal is detected by a photodetector. After being amplified by a power amplifier (PA), it is sent to the VNA for the phase detection. The other part is reflected back to the local end by an FRM. After beating with the local optical reference, the 80 MHz IF signal is detected by a balanced photo-detector (BPD). This IF signal then passes through a bandpass filter and enters the OPLL for phase discrimination with a 10 MHz cesium clock reference. The generated error signal is used to feedback control the PFS that adjusts the length of the fiber to compensate for the link delay variation, finally ensuring the stable microwave signal distribution over fiber.

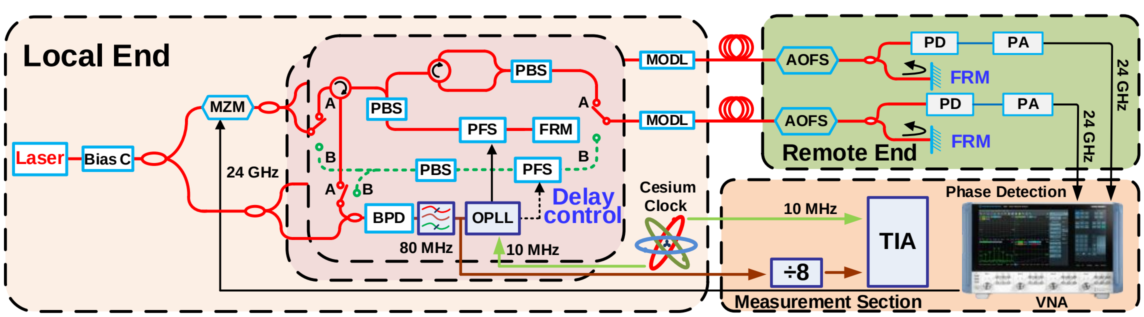

Fig. 2. The experimental setup.

The PMD related delay jitter caused by the PFS stretching is carefully studied after stabilizing the transmission link. We adopt an MODL to change the link length back and force repeatedly, triggering regular and constant PFS stretching. To ensure that the delay jitter is only related to the PMD effect, the PFS is driven at a rate of 0.1 mm/s, which is considerably faster than in the actual working state. The delay jitter of the round-trip link represented by the IF signal is measured both for the proposed RC scheme and the traditional SC scheme as shown in Fig. 3(a). Here, we use 200 m PM fiber to simulate the fiber link with a large PMD value. The small delay fluctuation stems from the static loop locking error, which is limited by the precision of the phase discrimination. Note that this fluctuation is smaller in the RC structure, implying a smaller link delay variation and a more stable locking state. Meanwhile, large spikes in the SC structure have also been well suppressed. The delay jitters of the RC and SC structure remain 0.12 fs and 0.23 fs within 4000 s, respectively. It validates that the well-designed OPLL provides a high precision phase compensation with almost no error even for the large and fast PFS stretching with a large PMD value, ensuring the stability of the transmission link. Figure 3(b) and 3(c) show the relative delay jitter of the RF signal at 2 remote ends through 200 m SM fiber and 200 m PM fiber transmission with the SC and RC structure, respectively. Here, the delay jitter caused by the group velocity change has been removed. Due to the absence of the chromatic dispersion in the MODL and the phase locking of the optical carrier, the RF signal at the remote end experiences a determinate phase variation that is proportional to the delay variation induced by the MODL. In the 200 m SM fiber with a small PMD value, the constant delay change induced by the MODL is set to 18 ps for both RC and SC structures. In the other case with larger PMD fiber, it is 24 ps and 9 ps for the RC and SC structure which is the same as in Fig. 3(a), because the further increase of the delay change leads to a losing lock state for the SC structure. It is clearly observed that for the RC structure, the relative delay jitter keeps the same fixed value which is only determined by the fixed dispersion. As to the SC structure, however, the values of the relative delay jitter have obvious random fluctuations. These fluctuations are owing to the random polarization changes caused by the PFS stretching that produces the difference between the delay variation of forward and backward links. The increase of fluctuations is attributed to the increase of the PMD value for different fibers. Therefore, the RC structure can effectively eliminate the PMD related delay jitter which dramatically hinders the link stability in the SC structure.

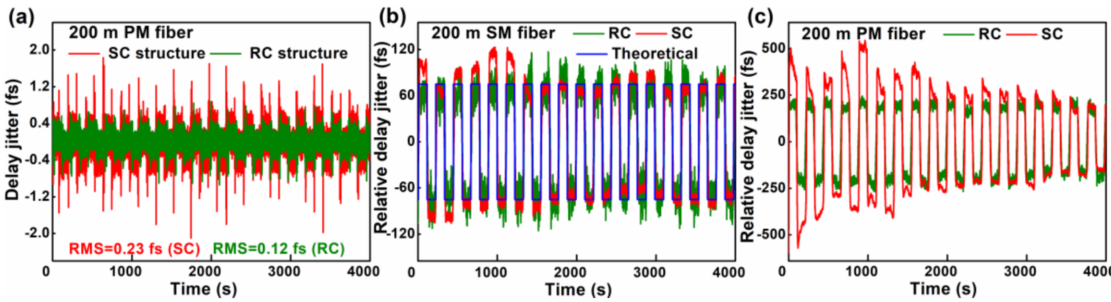

Fig. 3. (a)The round-trip delay jitter of the transmission link with large regular PFS stretching. (b) The relative delay jitter of the signal via 200 m SM fiber (c) The relative delay jitter of the signal via 200 m PM fiber.

Finally, the relative stability of the two links within 1 hour is carefully measured under the RC structure. Figure 4(a) and 4(b) show the relative delay jitter of a 24 GHz signal transmitted to two remote ends via 200 m SM fiber and 200 m PM fiber, respectively. After the elimination of the PMD related jitter caused by the PFS stretching, the RMS value of the relative delay jitter is as small as 13.0 fs and 17.7 fs for the 2 cases. It evidently proves the feasibility of the proposed RC PFS structure and shows the high long-term stability of the demonstrated transmission link.

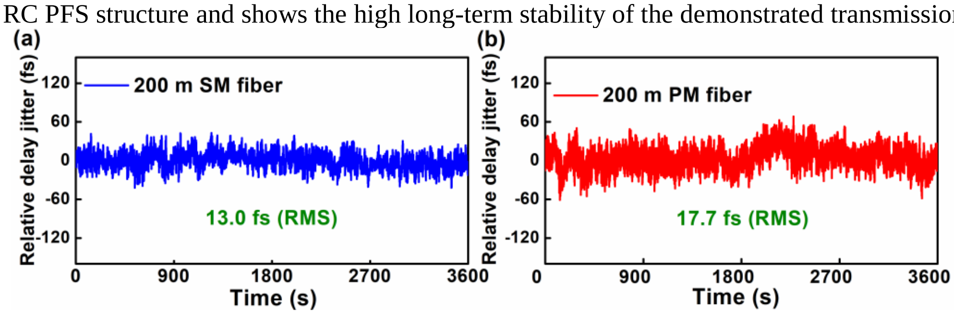

Fig. 4. The relative stability of the two links with RC structure through (a) 200 m SM fiber, (b) 200 m PM fiber.

4. Conclusion

We present an ultra-high stable microwave signal distribution system based on a round-trip Michelson interference structure and a PFS that is controlled by a well-designed OPLL. An orthogonal-polarized round-trip compensation structure is proposed. It can effectively fix the polarization state of the PFS output, thereby suppressing the delay jitter originate from the PFS stretching and leading to a stable signal transmission to the remote end. After eliminating the PMD related instability, the RMS relative delay jitters of the 24 GHz signal transmitted to the remote end are 13.0 fs and 17.7 fs for the 200 m SM fiber and 200 m PM fiber with different PMD values within 1 h, respectively.

5. Reference

[1] S. M. Foreman, et al., Rev. Sci. Instrum. **78**, 021101 (2007).
[2] X. Ming, et al., Optica **5**, 1564–1578 (2018).
[3] D. Sun, et al., Opt. Lett. **39**, 2849–2852 (2014).
[4] F. Yin, et al., Opt. Express **22**, 878–884 (2014).
[5] S. Huang, et al., in Proc. 38th Annu. PTTI Syst. Appl. Meet. 293–304 (2006).
[6] P. Shen, et al., J. Lightwave Technol. **26**, 2754-2763 (2008).
[7] J. A. Castillo, et al., IEEE Photon. J. **4**, 2390–2397 (2012).