Study on long-term stability of asymmetric optical fiber radio frequency transmission system

Jiahui Cheng
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
Cheng_jh@bupt.edu.cn

Hao Gao
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
hao@bupt.edu.cn

Yaojun Qiao
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
*qiao@bupt.edu.cn

Sen Zhang
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
z-s@bupt.edu.cn

Bin Luo
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
*luobin@bupt.edu.cn

Song Yu
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing, China
yusong@bupt.edu.cn

***Abstract*—The long-term stability of the radio frequency (RF) transmission system is limited by the optical path asymmetry, violating the assumption of equality between the forward and backward paths. In this paper, we experimentally investigate the effects of wavelength asymmetry and fiber length asymmetry on the long-term stability of the RF transmission system. The phase fluctuations introduced by these asymmetries are measured using a 600 km dual-wavelength RF transmission system and a dual-branch RF transmission system, respectively. The experimental results demonstrate that wavelength asymmetry has a minimal effect on the long-term stability, deteriorating by about 0.05 orders of magnitude for every 0.8 nm increase in the wavelength difference. Conversely, fiber length asymmetry exerts a more significant impact, with the long-term stability deteriorating rapidly by half an order of magnitude when the fiber length difference reaches 2 m.**

Keywords—radio frequency transmission, long-term stability, optical path asymmetry

I. Introduction

Many advanced scientific and industrial fields rely on high-precision optical fiber frequency synchronization technology, such as atomic clock comparison [1], navigation and positioning [2] and fundamental physics research [3]. However, mechanical vibrations and temperature variations can cause fluctuations in the length of the optical fiber, resulting in random phase changes in the frequency signals transmitted in the fiber. Currently, these environmentally induced phase noises are mainly suppressed by employing active or passive compensation techniques [4-8], in which signals need to propagate bidirectionally in the same fiber to offset the phase noise caused by the optical fiber link. The perfect elimination of phase noise by these techniques is based on the assumption that the forward and backward optical paths are identical when signals are transmitted over the same optical fiber. However, in practical experiments, the phase noise of the optical fiber link cannot be completely offset due to the wavelength asymmetry and fiber length asymmetry between the forward and backward optical paths.

In this paper, we investigate the effect of wavelength asymmetry and fiber length asymmetry between the forward and backward on the stability of the radio frequency (RF) transmission system. We set up a 600 km dual-wavelength RF transmission system, and the forward and backward wavelength difference is increased from 0.8 nm to 5.6 nm. The experimental results show that the wavelength asymmetry has a small effect on the long-term stability of the system, and the long-term stability of the system deteriorates by about 0.05 orders of magnitude for every 0.8 nm increase in wavelength difference. In addition, we also set up a dual-branch RF transmission system, by adding different lengths of fiber in one of the branches to simulate the effect of fiber length asymmetry on the stability of the system. The experimental results show that the fiber length asymmetry has a larger effect on the long-term stability of the system, when the fiber length difference increases to 2 m, the long-term stability of the system deteriorates rapidly by half an order of magnitude.

II. THEORETICAL ANALYSIS

A. Wavelength asymmetry

In the RF transmission system, in order to avoid backscattering, optical signals with different wavelengths are usually used between the forward and backward directions. The delay fluctuations introduced by the asymmetry of the wavelength are temperature dependent and cannot be compensated, thus limiting the long-term stability of the system. Under the influence of temperature, the delay fluctuations caused by wavelength asymmetry can be expressed as

$$\Delta\tau_w = L\cdot\Delta\lambda\cdot\frac{dD(\lambda)}{dT} + D(\lambda)\cdot\Delta\lambda\cdot\frac{dL}{dT}. \quad (1)$$

Where L is the fiber length, $\Delta\lambda$ is wavelength difference between the forward and backward, $D(\lambda)$ is the dispersion coefficient of optical fiber and $dD(\lambda)/dT$ is the dispersion thermal coefficient of optical fiber.

B. Fiber length asymmetry

In order to realize the stable transmission of RF signal in long-haul optical fiber link, bidirectional Erbium-doped fiber

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amplifiers (Bi-EDFA) are usually installed in the link to offset the link attenuation and improve the signal to noise ratio. A Bi-EDFA is actually composed of two unidirectional erbium-doped fiber amplifiers (Uni-EDFA). The structure of Bi-EDFA is shown in Fig. 1, in which, the forward and backward light will be amplified by two independent Uni-EDFAs. Because the pigtails of different optical devices are different, the lengths of erbium-doped fibers (EDF) are also different, so the fiber lengths of the two Uni-EDFAs cannot be the same. When multiple Bi-EDFAs are used in a long-haul frequency transmission system, the asymmetry introduced by the fiber length difference between the forward and backward becomes larger and larger. Under the influence of temperature, the delay fluctuations caused by fiber length asymmetry can be expressed as

$$\Delta\tau_L = \Delta L a \frac{n_g}{c} \Delta T + \Delta L \beta \Delta T. \tag{2}$$

Where ΔL is the fiber length difference between forward and backward, a is the thermal expansion coefficient of optical fiber, n_g is the refractive index of optical fiber, c is the speed of light in a vacuum, ΔT is the temperature variation, and β is the thermal coefficient of refractive index of optical fiber.

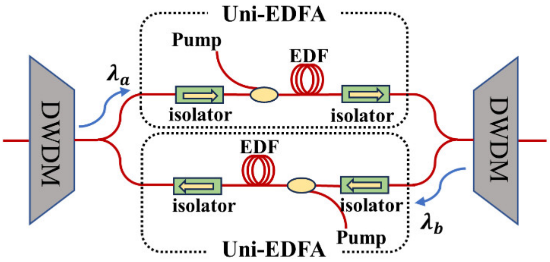

Fig. 1. The structure of the bidirectional Erbium-doped fiber amplifier (Bi-EDFA). DWDM: dense wavelength division multiplexing. Uni-EDFA: unidirectional erbium-doped fiber amplifiers. EDF: erbium-doped fiber. λ_a: forward light wavelength. λ_b: backward light wavelength.

III. EXPERIMENTAL SETUP AND RESULTS

A. *Effect of wavelength asymmetry*

1) *Experimental setup*

In order to analyze the effect of the wavelength difference between forward and backward on the system stability, we set up a 600 km dual-wavelength RF transmission system, as shown in Fig. 2. The RF signal at the local site (LS) modulates two optical signals with different wavelengths at the same time (λ_a, λ_b), the two signals are transmitted through forward and backward optical fiber links respectively. After the signals reach the remote site (RS), they are detected by PD_1 and PD_2, The phase difference between two RF signals at RS is the phase fluctuations introduced by the wavelength asymmetry between the forward and backward.

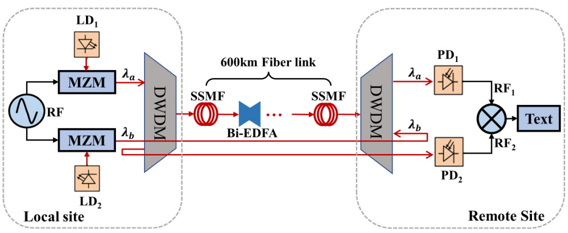

Fig. 2. The 600 km dual-wavelength RF transmission system. LD: laser diode. MZM: Mach-Zehnder modulator. SSMF: standard single-mode fiber. Bi-EDFA: bidirectional erbium-doped fiber amplifier. PD: photo-detector. λ_a: forward light wavelength. λ_b: backward light wavelength.

2) *Experimental results*

We increase the wavelength difference between the forward and backward directions from 0.8 nm to 5.6 nm (the wavelength difference between neighboring channels is 0.8 nm). The Allan deviation (ADEV) curves of the system at different wavelength differences are shown in Fig. 3. The specific ADEV values of the system at 1s and 10000s are given in Table I. The experimental results show that the wavelength difference between the forward and backward doesn't affect the short-term stability of the system and only have a slight effect on the long-term stability. The results in Table I show that the long-term stability of the system deteriorates by about 0.05 orders of magnitude for every 0.8 nm increase in the wavelength difference.

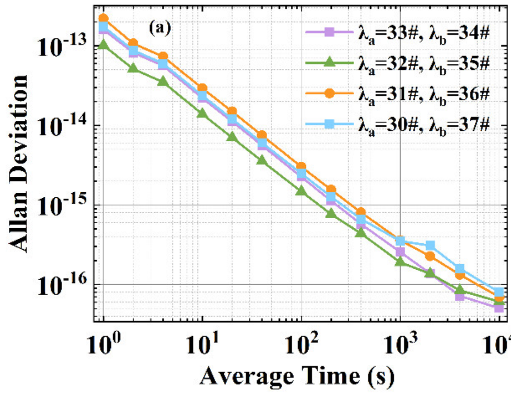

Fig. 3. The ADEV of the system at different wavelength differences.

TABLE I. THE SPECIFIC AEDV OF THE SYSTEM AT 1 S AND 10000 S

(λ_a, λ_b)	wavelength difference	ADEV@1 s	ADEV@10000 s
(33#, 34#)	0.8 nm	1.6E-13	5.04E-17
(32#, 35#)	2.4 nm	1.01E-13	6.09E-17
(31#, 36#)	4 nm	2.2E-13	6.97E-17
(30#, 37#)	5.6 nm	1.75E-13	8.03E-17

B. *Effect of fiber length asymmetry*

1) *Experimental setup*

In order to analyze the effect of fiber length asymmetry between the forward and backward on the stability of the RF transmission system, we set up a dual-branch RF transmission system. The RF signal is loaded on the optical signal and divided into two paths through the coupler (the splitting ratio is 1:1). One of the signals does not pass through the optical fiber, and is directly detected by PD_1 to get RF_1. The other signal needs to pass through a section of optical fiber, and then it is detected by PD_2 to get RF_2. The phase difference between RF_1 and RF_2 is the phase fluctuations caused by the asymmetry of fiber length.

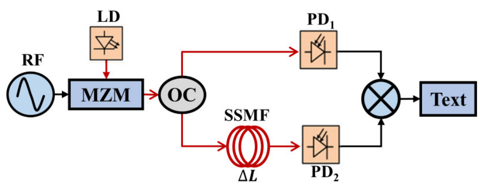

Fig. 4. The dual-branch RF transmission system. LD: laser diode. MZM: Mach-Zehnder modulator. OC: optical coupler. SSMF: standard single-mode fiber. PD: photo-detector.

2) Experimental results

We gradually increase the fiber length of the second branch from 0 m to 100 m, and the stability of the system under different fiber length differences are shown in Fig. 5. It can be found that the short-term stability of the system is basically unchanged with the increase of the length difference between the forward and backward. However, the long-term stability of the system continues to deteriorate.

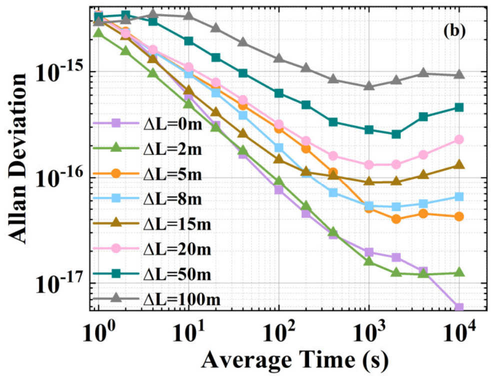

Fig. 5. The ADEV of the system at different fiber length differences.

The relationship between the ADEV values of the system at 10000 s and the fiber length difference (ΔL) is shown in Fig. 6. When ΔL increases from 0 m to 2 m, the long-term stability of the system deteriorates rapidly by half an order of magnitude. When ΔL increases from 2 m, the long-term stability of the system continues to deteriorate, and when ΔL increases to 15 m, the long-term stability of the system deteriorates by an order of magnitude. After that, when ΔL increases from 15 m to 100 m, the long-term stability of the system is still deteriorating, but the deterioration rate slowed down obviously.

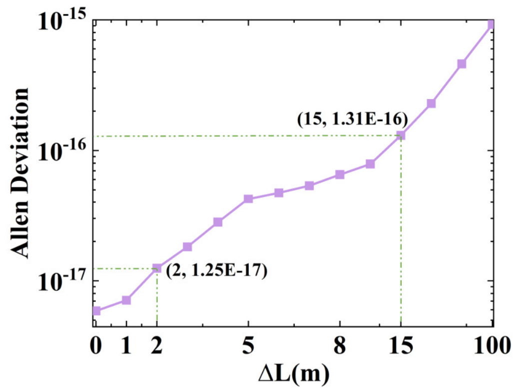

Fig. 6. The ADEV at 10000s of the system at different fiber length differences. ΔL: the fiber length difference between two branches.

Fig. 7 shows the relationship between system phase fluctuations (the orange curve) and temperature variations (the gray curve) when ΔL is 100 m. It can be found that the changing trends of the two curves are basically the same. Therefore, when the fiber length difference between forward and backward of the RF transmission system is large, the phase fluctuations caused by temperature change cannot be compensated, which further deteriorates the long-term stability of the system.

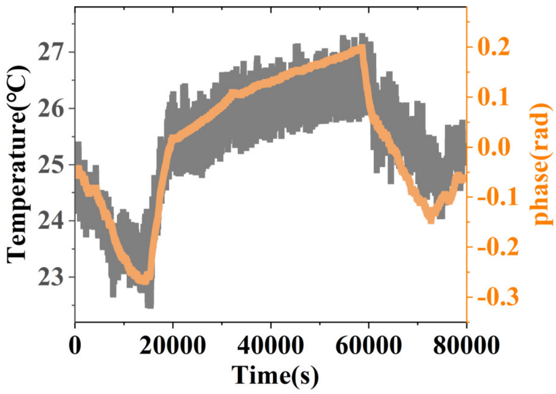

Fig. 7. The relationship between system's phase fluctuations and temperature variations when ΔL is 100 m .

IV. CONCLUSION

In this paper, we experimentally investigate the effect of wavelength asymmetry and fiber length asymmetry between the forward and backward optical paths on the stability of the RF transmission system. The experimental results show that the wavelength asymmetry has a small effect on the long-term stability of the system, and the long-term stability of the system deteriorates by about 0.05 orders of magnitude for every 0.8 nm increase in the wavelength difference. While the fiber length asymmetry between the forward and backward has a larger effect on the long-term stability of the system, when the fiber length difference increases to 2 m, the long-term stability of the system deteriorates rapidly by half an order of magnitude.

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