High-precision Radio Frequency Transmission using 4-core Fibers

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Abstract: *We presents a radio frequency (RF) transmission system based on multi-core fiber (MCF), proving that RF transmission based on 4-core fiber with no frequency conversion methods in the round-trip transmission can reach the stability of 7.15E-18@10000 s, outperforming the RF transmission in standard single-mode fiber (SSMF) with similar conditions. In addition, the results of simultaneous transmission of data signal and frequency signal show that data signal transmission has only small influence on frequency synchronization.*

Keywords: *multi-core fiber, radio frequency transmission.*

I. INTRODUCTION

High precision frequency transmission is widely used in clock reference comparison, deep space exploration and satellite navigation[1-3]. In traditional frequency transmission, it is usually necessary to use round-trip method to first accurately measure the link noise and then compensate it. Ref. [4] proposed a stable phase return scheme of wideband signal, with which the 2.5 GHz frequency signal can be relatively stable at 3.3E−13@1 s and 7.5E−17@10000 s under a 45 km fiber link. However, there were two problems: on one hand, due to the optical scattering distribution along the link, signals return to local end not only contains the return signals from remote end, but also includes backscatter caused by the influence of forward transmission, on the other hand, because of the differences on devices deployed in local and remote end, the noise from devices is asymmetry[5].

The application of multi-core fiber (MCF) provides research ideas for solving these two problems. MCF consists of a number of independent parallel optical core channels, each of which can be used to independently transmit optical signals. Using the high degree of correlation between multiple cores, signals transmitted back and forth experience the same noise/environmental effects, so the noise added by the fiber to the signal can be detected and compensated without the need for bidirectional operation on either core. However, the research of high-precision time-frequency transmission using MCF has just started. In 2024, multi-core fiber is first introduced into the optical frequency transmission, realizing optical frequency stability of 3E-19@10000 s through 25.2 km of fiber[6]. In order to achieve high-precision radio frequency (RF) transmission, this paper proposes a frequency transmission based on 4-core fiber. The experimental results show that our method can realize RF fractional frequency stability of 7.15E-18@10000 s, better than traditional frequency transmission in the same conditions, effectively reducing and compensating noise. In addition, the experiment verifies that data signal transmission in MCF has little impact on radio frequency signal, which provides the possibility for simultaneous time synchronization and data transmission in communication networks such as wide area networks, regional data center interconnect (DCI), further improving the synchronization accuracy of each node in the network and the efficiency of data transmission.

II. EXPERIMENT AND RESULTS

The experimental setup of a high-precision radio frequency transmission system based on 4-core fiber is shown in Fig. 1 and the cross section of 4-core fiber is shown in Fig. 2(a). In the local end, a 1 GHz single-frequency radio signal is generated by the RIGOL DSG821A signal generator locked the Rubidium clock FS 725. The signal is divided into two parts by the splitter, one part is tested as a local reference signal, and the other is modulated to the internally modulated laser. The output optical power and wavelength of the laser are respectively 1.601 mW and 1548.45 nm. After passing through the piezoelectric ceramics fiber delay line (PZTFDL) for small range fast variable delay control and temperature control fiber delay line (TCFDL) for large range slow variable delay control, the output laser is sent through a core of the fiber (Core 1) via the fan-in-fan-out (FIFO) device. At the remote end, the light from Core 1 is distributed by a 1:99 coupler, of which 99% of the light is restored to 3 mW by an Erbium-doped fiber amplifier (EDFA), and then sent back to the local via Core 3. The rest of the light can be demodulated to a remote synchronization signal. At the local end, the optical power returned from Core 3 is 1.014 mW and is input to a photodetector (PD) for photoelectric conversion to restore to frequency signal. The phase of return signal and local reference signal is compared in a phase discriminator. The identification signal is input to the proportion integration differentiation control (PID), controlling PZTFDL and TCFDL to compensate and suppress the link noise, so that the microwave signal recovered at the remote end can maintain the same stability as that at the local end. In order to evaluate the transmission performance, the identification signal is collected and the transmission stability is measured. The phase noise of the system is measured by the phase noise analyzer, shown in Fig. 2(b). The phase noise before transmission noise compensation is -74 dBc/Hz @10 Hz frequency offset.

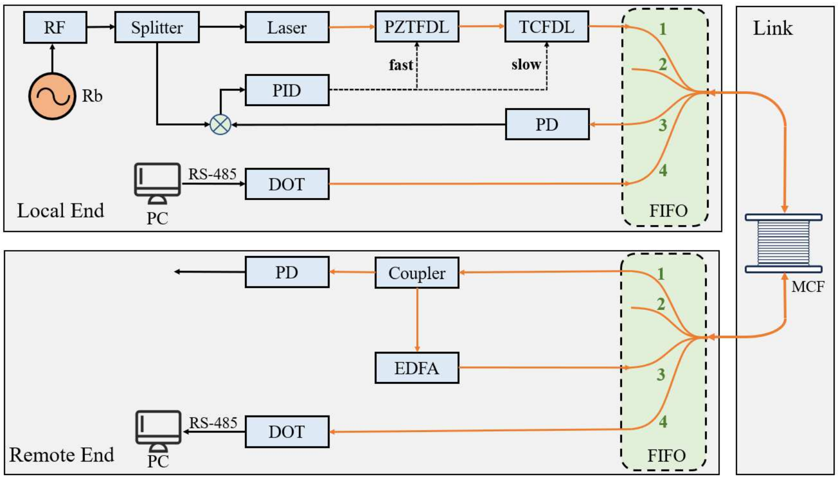

Fig. 1. Schematic of the radio frequency transmission system based on 4-core fiber. Rb: Rubidium clock, RF: radio frequency, PZTFDL: piezoelectric ceramics fiber delay line, TCFDL: temperature control fiber delay line, FIFO: fan-in-fan-out, MCF: multi-core fiber, PD: photodetector, EDFA: Erbium-doped fiber amplifier, PID: proportion integration differentiation control, PC: Personal Computer, DOT: Digital optical transmission module.

(a) (b)

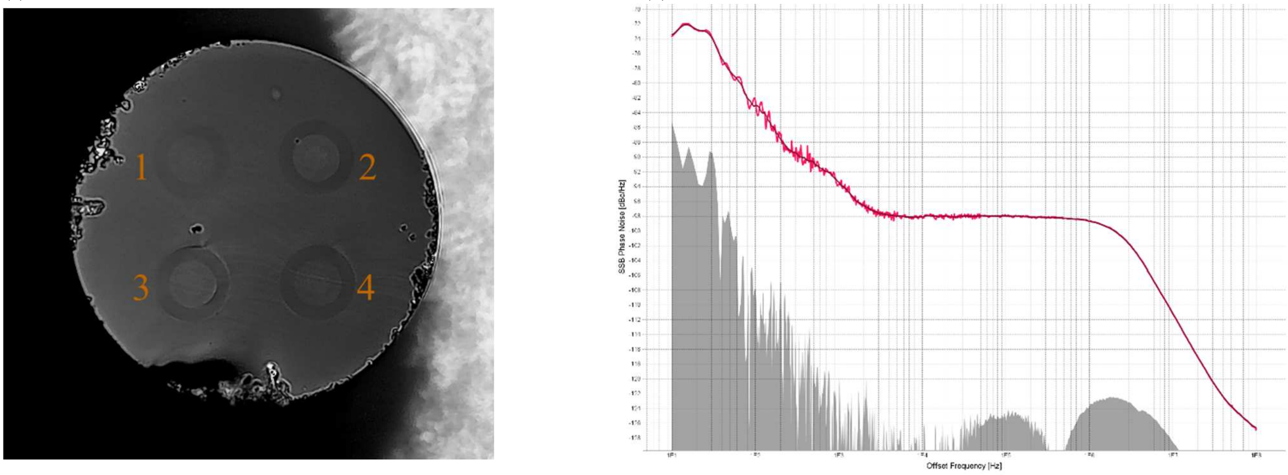

Fig. 2. a) The cross section of 4-core fiber. Cladding diameter: 125 μm. b) Phase noise of tansmission stability of 1 GHz radio frequency signal in 3 km MCF link.

In the experiment, the transmission performance of 1 GHz frequency signals at 3 km link were first tested, including the performance of free running (FR), closed-loop control (CC), and compared with the frequency transmission system based on SSMF. The Allan deviation of transmission stability is shown in Fig. 3(a). For the system based on MCF, ADEV before phase noise compensation are 9.13E-15@1 s and 1.93E-15@10000 s, respectively. After phase compensation, stable MCF links can realize 4.29E-15@1 s and 7.15E-18@10000 s, which proves the effectiveness of our method. Moreover, the stability of the frequency transmission system based on SSMF after phase compensation is 1.28E-17@10000 s, proving that the system based on MCF is superior to the system based on SSMF.

Then, further experiments in 1 GHz frequency signal transmission at 6 km link were tested. The stability of Allan deviation is shown in Fig. 3(b). For the system based on MCF, ADEV show similar trends as those in Fig. 3(a). ADEV before phase noise compensation are 1.64E-14@1 s and 7.22E-15@10000 s, respectively. After phase compensation, it demonstrates frequency stability of 4.23E-14@1 s and 2.05E-17@10000 s, which obtains a good compensation effect. However, compared with Fig. 3(a), the stability is reduced slightly, which may be due to the introduction of more link noise. Specific factors will be further explored in subsequent studies.

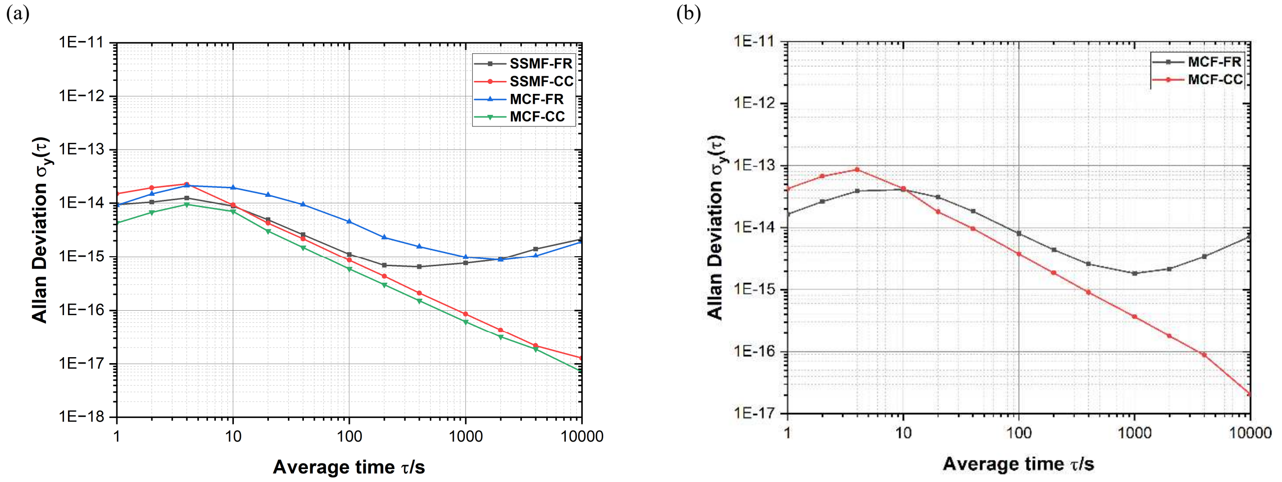

Fig. 3. Allan deviation of tansmission stability of 1 GHz frequency signal in 3 km link (a) and 6 km link (b). FR: free running, PID function is not turned on, CC: closed-loop control, PID function is turned on.

In addition, in order to transfer the data signal and frequency signal simultaneously, we send RS-485 data signal at adjacent core of radio frequency signal (*i.e.*, Core 4), controlling by the process program, of which baudrate is 9600 baud, sending data from 64 bits per second, shown in Fig. 1. The results are shown in Fig. 4. It can be seen that data signal transmission has no obvious effect on frequency signal transmission.

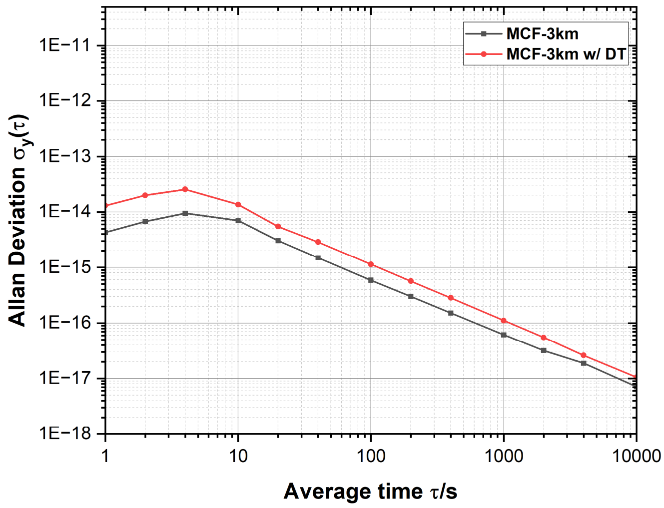

Fig. 4. Allan deviation of tansmission stability of 1 GHz frequency signal with or without data signal transmission in 3 km link. DT: data signal transmission.

III. Conclusions

In conclusion, the RF transmission system based on MCF is proposed, and experimental results show that the stability can reach 7.15E-18@10000 s, which is little better than the system based on SSMF. The method proves that the frequency transmission based on MCF can effectively improve the stability of RF transmission. In addition, the test of simultaneous transmission of data signal and frequency signal reflects the advantages of multi-channel transmission of MCF, which provides application prospects for simultaneous time synchronization and data transmission in communication networks such as wide area networks, regional data center interconnect (DCI).

Acknowledgment

This work was supported by the National Natural Science Foundation of China (12293033), and the National Key R&D Program of China (2022YFB3902503). The work of Fei Yang was supported by the Youth Innovation Promotion Association of Chinese Academy of Sciences (Y2023075).

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