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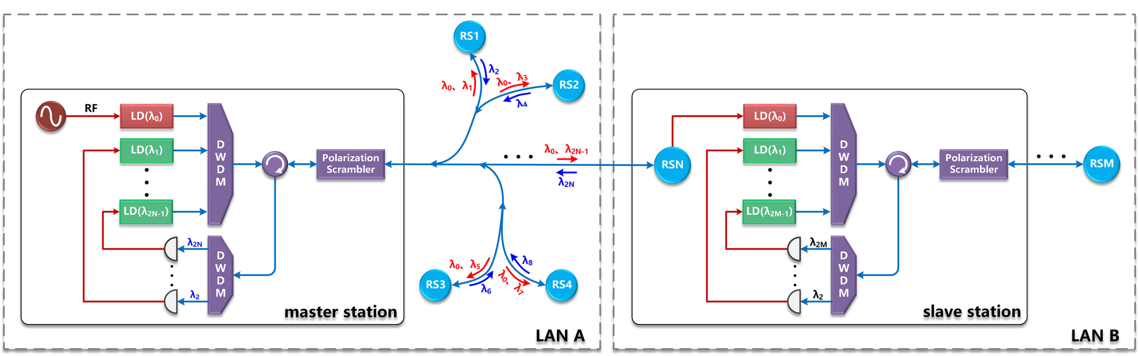

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Multi-Access RF Frequency Dissemination Based on Round-Trip Three-Wavelength Optical Compensation Technique Over Fiber-Optic Link

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Abstract: In this paper, we propose a tree-like topology networking scheme based on round-trip three-wavelength optical compensation technique over fiber-optic link. This scheme simplifies the system complexity of the local site, improves the scalability of the frequency dissemination network, and reduces the influence of Rayleigh backscattering on the local and remote sites. The feasibility of the scheme is verified by a set of fiber-optic frequency dissemination network, with a transmission frequency of 1 GHz. The network consists of two remote sites with distances of 20 and 55 km far from the local site, and the frequency compensation system is optimized. The experimental results show that the fractional frequency stability of the 20 and 55 km fiber links can reach 8.6×10^{-15}@1s, 7.6×10^{-18}@10^4s, and 1.3×10^{-14}@1s, and 8.1×10^{-18}@10^4s. The limitations of electrical amplifiers, WDM, and group velocity dispersion on long-term stability and network capacity are discussed. Our system demonstrates that the stable sharing of frequency signals from ultra-stable frequency sources at any site within a large metropolitan area is achievable.

Index Terms: Fiber optics system, RF frequency transfer, fiber optic network, fractional frequency stability

1. Introduction

High-precision frequency transmission has important applications in basic physics research, time-frequency measurement, navigation and positioning, and gravity potential measurement [1], [2].

Traditional satellite-based transmission methods, such as two-way satellite time-frequency transfer (TWSTFT), Global Positioning System (GPS), can only achieve better frequency stability through long-term averaging due to complex and variable atmospheric turbulence [3]. In recent years, frequency transmission based on optical fiber has been rapidly developed. It shows that this method can provide higher frequency stability than the traditional satellite-based frequency transmission [1], [4], [5]. In general, the noise of the fiber link is compensated by the servo loop that is placed at the local site, which is more suitable for peer-to-peer transmission. For point to multipoint frequency dissemination network applications, such as modern large linear accelerators, Square-Kilometer Array telescopes (SKA), Very Long Baseline Interference (VLBI) and Deep Space Network (DSN) [6]–[9], it is often necessary to build an individual noise compensation system for each remote site at the local site, which greatly increases the structure complexity of the local site. Meanwhile, users cannot monitor at remote sites since the effect of fiber link noise suppression can only be controlled by the local site, which also causes cumbersome operation. Therefore, it is reasonable to consider assigning servo loop to the respective remote site and simplifying the complexity of the local site.

Many teams have proposed a variety of networking RF frequency dissemination scheme [10]–[15]. L. Q. Yu *et al.*, for example, proposed and demonstrated a networking scheme for a tree topology of 1 GHz RF frequency signal, and discussed the network capacity based on wavelength division multiplexing technology [12]. For another example, H. W. Li *et al.* proposed a networking scheme for linear topology of 1 GHz RF frequency signal based on passive phase cancelation, they used multiple mixing to obtain a stable frequency signal and suppress the effects of backscattering by using different wavelengths back and forth [14]. However, these solutions are limited either by the networking method or the impact of link noise such as Rayleigh backscattering and Stimulated Brillouin scattering (SBS). It is difficult to further improve the short-term stability. In this letter, a novel round-trip three-wavelength frequency dissemination (RTTW-FD) scheme based on wavelength division multiplexing (WDM) technology is proposed and applied to frequency transmission networking. A new structure for improving the symmetry of optical components in RF frequency transmission is designed and applied to phase compensation. By using three wavelengths in forth and back directions, the noise compensation system can be placed at the respective remote site, which greatly simplifies the complexity of the local site. Because of different wavelengths of two directions, this scheme can effectively reduce the effect of backscattering. The short-term stability of the scheme is mainly dependent on signal-to-noise ratio (SNR), while the asymmetry of the transfer structure is the main limitation on the long-term stability, which will be discussed later based on the experimental results.

The multi-access frequency dissemination network is designed and demonstrated in the laboratory, where two remote sites are 20 km and 55 km far from the local site. The fractional frequency stability of the 20 km and 55 km fiber links in the frequency dissemination network can reach 8.6×10^{-15}@1s, 7.6×10^{-18}@10^4s and 1.3×10^{-14}@1 s, 8.1×10^{-18}@10^4s, respectively.

2. Principle

Figure 1 shows the principle of the RTTW-OCT scheme. The optical signals emitted by LD1, LD2, and LD3 have a certain wavelength spacing to suppress Rayleigh backscattering and SBS generated in the fiber and Bi-EDFA [16]–[18]. The standard RF frequency signal generated by the local site microwave signal source (atomic clock or high-precision oven-controlled crystal oscillator) is modulated by the modulator MZM1 onto the optical carrier from the LD1 (wavelength of λ_1), and then transmitted to the remote site. For the sake of brevity, the initial frequency signal can be expressed as a simple cosine signal, regardless of the exact amplitude

$$V_0 \propto \cos(\Omega t + \varphi_0), \tag{1}$$

where Ω and φ_0 represent angular frequency and initial phase, respectively. After the optical signal reaches the remote site through the optical fiber link, it first passes through the noise compensation system (NCS) located at the remote site, and then is detected by the photodetector PD1. The

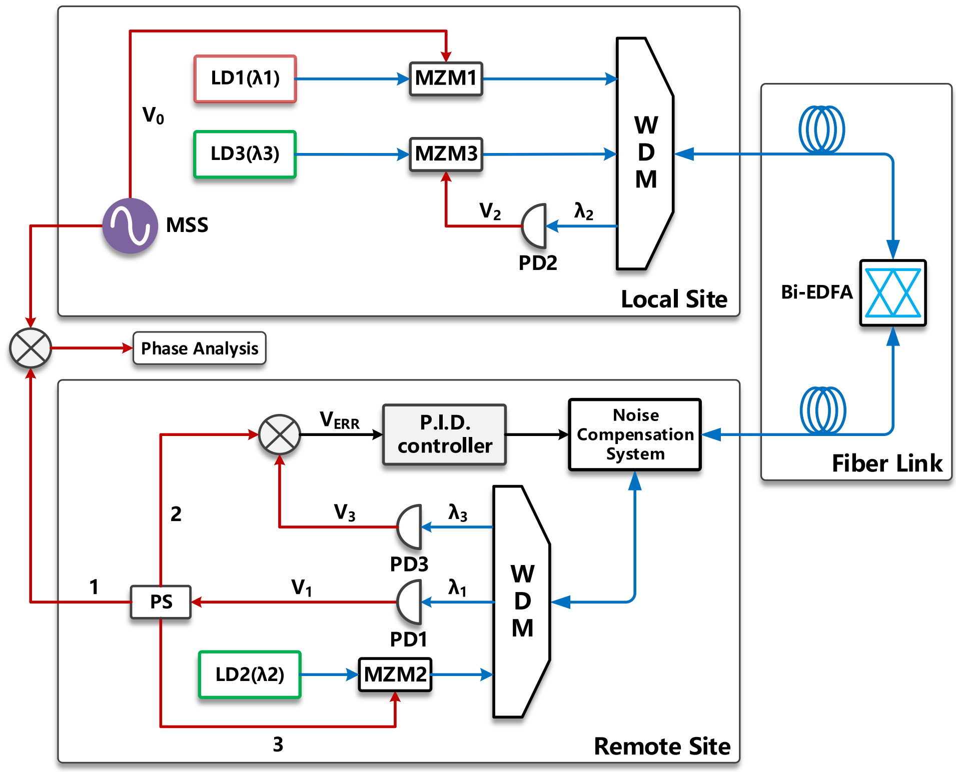

Fig. 1. Schematic diagram of round-trip three-wavelength optical compensation technique. MSS, microwave signal source. LD1, LD2, LD3, Laser diode. MZM1, MZM2, MZM3, Mach-Zehnder modulator. WDM, wavelength division multiplexer. Bi-EDFA, bi-directional erbium-doped fiber amplifier. PD1, PD2, PD3, photodetector. PS, power splitter. P.I.D controller, proportional-integral-derivative controller.

amplified and filtered signal can be written as

$$V_1 \propto \cos\left(\Omega t + \varphi_0 + \varphi_L + \varphi_{NCS} + \Omega \Delta t\right), \tag{2}$$

where φ_L and φ_{NCS} are fixed delays introduced by the fiber link and the NCS, respectively, $\Delta\varphi = \Omega\Delta t$ is the total phase fluctuation caused by one-way propagation, and Δt is the fluctuation of the corresponding propagation delay. V_1 is divided into three parts by the power splitter (PS). The 1st one is used for the output of the remote site, where the performance of the one-way frequency transmission is analyzed by mixing it with the reference signal of the local site in the following experiment. The 3rd one is modulated by the modulator MZM2 onto the optical carrier from the LD2 (wavelength of λ_2), and is transmitted back to the local site through the same fiber link. When the signal arrives the local site, it is demodulated by PD2. Similarly, the output signal of PD2 is modulated onto the optical carrier from LD3 (wavelength of λ_3) and transmitted to the remote site again. Assuming that fiber noise forth and back are the same, we can express the signal that reaches the remote site for the second time and is demodulated by PD3 as

$$V_3 \propto \cos\left(\Omega t + \varphi_0 + 3\varphi_L + 3\varphi_{NCS} + 3\Omega \Delta t\right). \tag{3}$$

The differential signal obtained by mixing V_3 with the 2nd one of the V_1 from PS is proportional to the link fluctuation, and can be expressed as

$$V_{ERR} \propto \cos\left(2\varphi_L + 2\varphi_{NCS} + 2\Omega \Delta t\right), \tag{4}$$

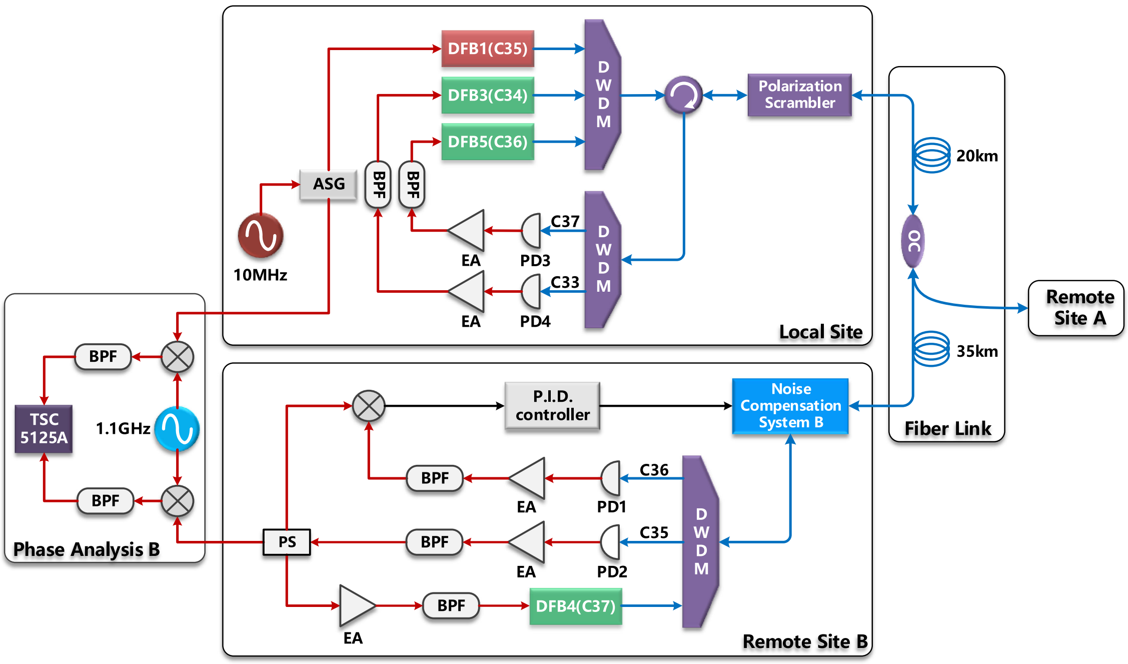

Fig. 2. Experimental setup of branching network based on round-trip three-wavelength frequency dissemination. The structure of the remote site A is the same as that of the remote site B, except that the wavelengths of the optical signals arriving at the remote site A are C35 and C34, and the wavelength of the optical signal transmitted from the remote site A to the local site is C33. ASG, analog signal generator; DWDM, dense wavelength division multiplexer; BPF, bandpass filter; EA, electrical amplifier; DFB1∼5, direct modulated distributed feedback laser diode, and the DFB2 is located at remote site A.

V_{ERR} is input into the P.I.D controller, and the corresponding error signal $-\Omega\Delta t$ is generated as feedback to the NCS to generate a corresponding phase shift:$\varphi'_{NCS} = \varphi_{NCS} - \Omega\Delta t$. Thereby noise from fiber link between the local and remote site is suppressed. The frequency signal output from the remote site becomes a stable one, and can be expressed as

$$V_1{}' \propto \cos\left(\Omega t + \varphi_0 + \varphi_L + \varphi'_{NCS} + \Omega\Delta t\right) = \cos\left(\Omega t + \varphi_0 + \varphi_L + \varphi_{NCS}\right). \tag{5}$$

In this way, the standard RF frequency signal is transmitted forth and back three times through the same fiber link to reduce the structure complexity of the local site in large-scale networking application, and the other merit of this scheme is that each remote site can achieve self-monitoring.

3. Experimental setup

The schematic diagram of the experiment of frequency transfer networking is shown in Figure 2. The experiment was carried out in an air-conditioned laboratory with a temperature range of 22 °C ± 1 °C and a period of about 1 day (86400 s). The spools of 20 km + 35 km of G.652 was used. The distance from the local site to the remote site A is 20 km, and the distance to the remote site B is 55 km, where the two sites share a 20 km fiber link. 1 GHz signal generated by the analog signal generator (Agilent N5181A) is used as the transmission signal V_0, that is phase-locked to a 10 MHz clock source (FS725 Rubidium frequency standard). The lasers of the local and remote sites all use direct modulated distributed feedback semiconductor laser diodes (DFB LD) to eliminate the influence of the temperature drift of the external modulator on the long-term stability. Considering the threshold of stimulated Brillouin, the optical power is limited to 6–7 dBm [18]. The wavelengths of the lasers at the local site are 1549.32 nm, 1550.12 nm, and 1548.51 nm, representing International Telecommunication Standardization (ITU) channels C35, C34, and C36, respectively. Wavelength

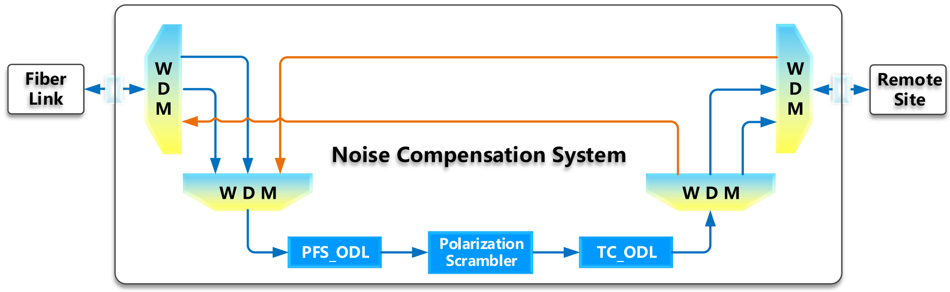

Fig. 3. Structure diagram of noise compensation system. PFS_ODL, piezoelectric fiber stretcher optical delay line; TC_ODL, temperature controlled optical delay line.

of the remote sites A and B are 1550.92 nm and 1547.72 nm, respectively, the corresponding ITU channels are C33 and C37 [19]. Customized wavelength division multiplexers have adjacent channels with a frequency separation of 100 GHz and an isolation of $>$30 dB. Before entering the fiber link, optical signal passes through the polarization scrambler (General Photonics PCD-003) in order to reduce the influence of polarization mode dispersion (PMD) [20], [21], for the reason that PMD may causes the asymmetry of the propagation delay fluctuation of the forward and backward links. Low-noise electrical amplifiers (EAs) (Mini-Circuits ZX60-33LN+) are used after the photodetectors. BPF is 40 MHz narrowband bandpass filter.

The structure of the NCS for fiber frequency transmission is shown in Figure 3, which is placed at each remote site and consists of optical delay line (ODL), polarization scrambler and WDMs. The ODL consists of a 5 km temperature-controlled optical delay line (temperature variation range of approximately 50 °C, delay fluctuation range of approximately 8.992 ns, bandwidth of 10 Hz) and a piezoelectric fiber stretcher optical delay line (bandwidth is 2.2 kHz with a compensation range of approximately 17 ps), which are used to compensate for the slow-changing and fast-changing phase fluctuations of the link, respectively. The polarization scrambler is placed in the ODL to reduce the effect of PMD, which is mainly caused by vibration or temperature variations of the ODL itself [20]. By connecting the four WDMs according to the method shown in Fig. 3, both forth and back signals are transmitted through optical delay lines exactly in the same direction and the same path, which effectively reduces the asymmetry of transmission path when signals pass through ODL.

To evaluate the performance of the frequency transfer, both the reference signal and the signal reproduced at the remote site are converted to 100 MHz by means of dual-mixer method [22]. Subsequently, the two down-converted signals are input into a phase noise analyzer (Symmetricom TSC5125A), whose measurement bandwidth is set to 5 Hz. The bandwidth of the bandpass filter before the TSC5125A is 30 MHz.

4. Result and discussion

The propagation delay fluctuations of the remote site A and B are as shown in Fig. 5, and the corresponding fractional frequency stability is represented by the overlapping Allan deviation to improve the confidence of stability evaluation [23], as shown in Fig. 4. In the closed-loop operation, the fractional frequency stability of remote sites A and B is 8.6×10^{-15} and 1.3×10^{-14} at 1 s, respectively, and 7.6×10^{-18} and 8.1×10^{-18} at 10^4s. The noise floor of the system is obtained by closed-loop measurement using 1 m fiber instead of fiber spool, and the short-term stability is 7.0 $\times 10^{-15}$@1 s and long-term stability is 7.0×10^{-18}@10^4s. From the results in Figure 4, the short-term and long-term stability are significantly improved compared with the results without phase compensation, and both are close to the noise floor of our system, shows that the compensation system of each site effectively suppresses the phase noise caused by the link between local site and remote site.

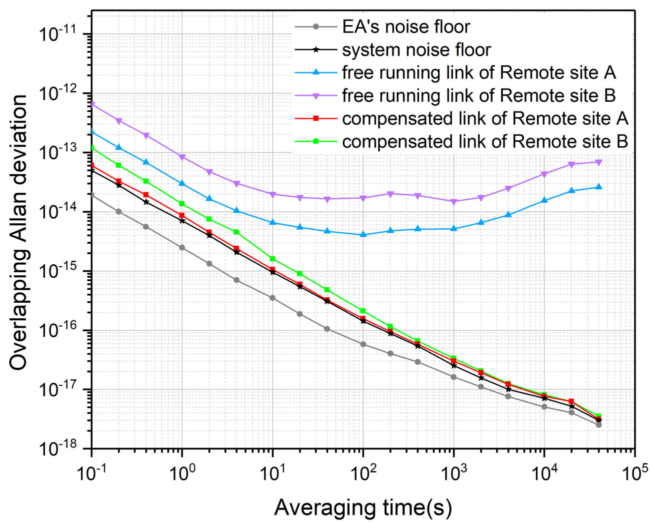

Fig. 4. Results of fractional frequency stability of frequency signal at remote site A and B.

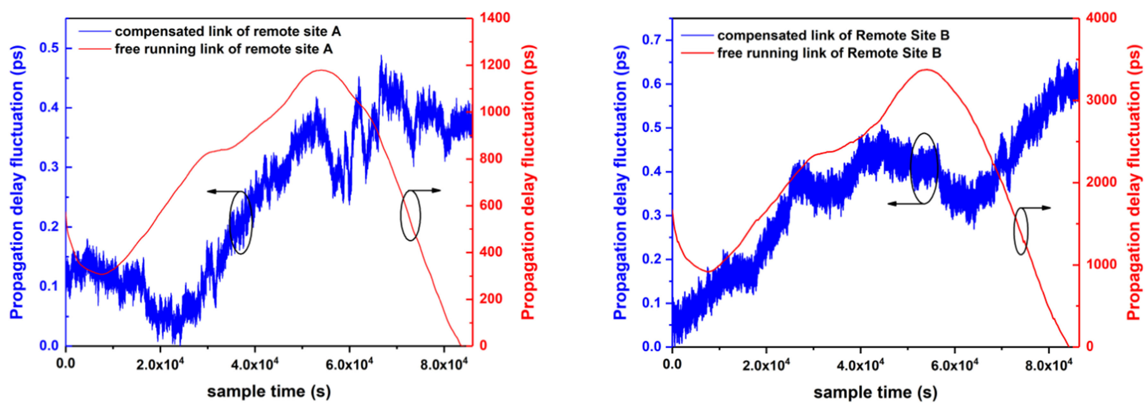

Fig. 5. Propagation delay fluctuation with and without compensation at remote site A and B.

Figure 5 shows the fluctuation of the propagation delay from the local site to the remote site A and B during one day when phase noise is compensated or not. The drift of the propagation delay for free running system is mainly caused by the temperature change. The maximum drift (peak to peak) of remote site A and B is 1179 ps and 3377 ps, respectively, and the root mean square (RMS) value is 325 ps and 892 ps. The maximum drift of the propagation delay of the compensated link is 0.49 ps and 0.66 ps, and the RMS value is 0.12 ps and 0.14 ps, where the asymmetry of the fiber link and the thermal drift of the EA are the main source. By adopting temperature control, it is feasible to reduce the influence of thermal drift of the EA on long-term stability.

The asymmetry of the fiber link is mainly derived from different channels of WDM and the group velocity dispersion (GVD). In WDM, fiber length difference ΔL and group refractive index n_g between channels change with temperature, which results in different propagation delay fluctuations in the forward and backward directions. It is assumed that the temperature fluctuation is approximately a sinusoidal function varying with time:

$$\Delta T(t) = \frac{T}{2}\sin\left(\frac{2\pi t}{P_{\Delta T}}\right), \tag{6}$$

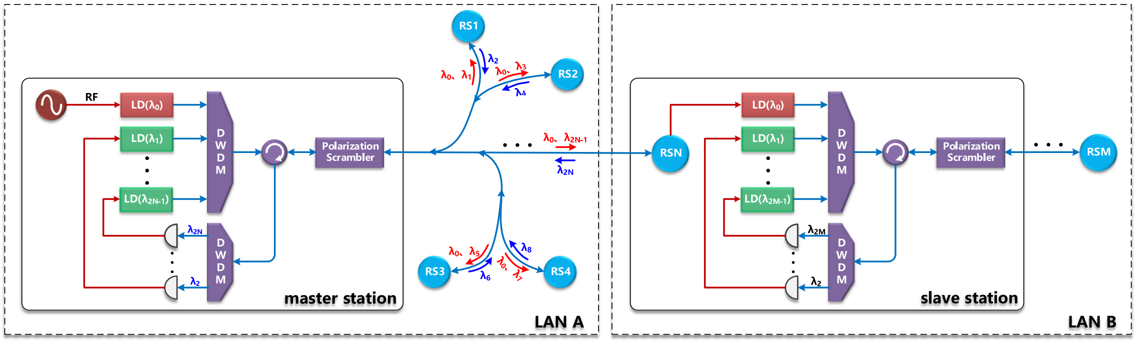

Fig. 6. Schematic diagram of a method for expanding network capacity based on RTTW-FD network. RS1, RS2, RS3, RS4, RSN, RSM, remote site; LAN A, LAN B, local area network.

where $P_{\Delta T}$ and T is the period and the peak-to-peak value of temperature variation [24]. The asymmetry influence on the fractional frequency stability, which is introduced by length difference of different branches of WDM can be deduced as

$$\sigma_y(\tau) = \frac{7.35 \times 10^{-14} \Delta L \cdot T}{P_{\Delta T}} \sin^2\left(\frac{\pi\tau}{P_{\Delta T}}\right). \tag{7}$$

It can be seen from equation (7) that the stability reaches a maximum at the averaging time of $\tau = P_{\Delta T}/2$, and the maximum value is

$$\sigma_{y\,\max} = \frac{7.35 \Delta L \cdot T}{P_{\Delta T}} \times 10^{-14}. \tag{8}$$

In this experiment, the peak-to-peak temperature change in the laboratory is not more than 2 K during period of 1 day. Length difference of the fiber branches of independent channel is controlled within 1 m, we can calculate the maximum value of stability is 1.7×10^{-18} for averaging time $\tau = 43200$ s. As long as length difference is controlled within 1 m, the influence of the asymmetry introduced by WDM on long-term stability is almost negligible for the current system.

For communication network based on WDM technology, the link asymmetry of round-trip caused by the variation of the GVD with temperature is a problem that must be considered. For fiber-frequency dissemination network, this residual asymmetry degrades long-term stability and becomes more pronounced as the wavelength spacing increases [12]. Here, we adopt the networking scheme based on RTTW-FD, where two wavelength channels are needed for each remote site. Additionally, losses are added when network nodes increase. These two reasons will limit the capacity of network. As shown in Fig. 6, the problem of long-term stability and network capacity being limited by the variation of the GVD may be solved by setting up several slave stations at different remote sites, where the received and transmitted optical signal wavelength λ_{2N-1} and λ_{2N} (N = 1, 2, 3...) are set close to λ_0. For the sake of simplicity, only one slave is shown in the figure. The master station and every slave station have their own local area network (LAN), and each LAN can utilize the same wavelengths considering of channel utilization. In addition, in order to expand the network capacity as much as possible with little impact on the long-term stability, it is conceivable to shorten the channel spacing to 50 GHz(0.4 nm) or even 25 GHz(0.2 nm) when for a large LAN [19]. For the additional loss due to increasement of network nodes in the same LAN, it can be solved by inserting a low-noise, high-symmetry bidirectional optical amplifier in front of each remote site.

5. Conclusion

In summary, we propose and demonstrate a round-trip three-wavelength frequency dissemination over stabilized fiber link network. Compared with the existing networking solution, this scheme not only provides a simple, flexible and robust signal access method for multiple users, but also simplifies the complexity of the local site. More importantly, high signal-to-noise ratio is achieveable because backward noise can be suppressed, such as single Rayleigh backscattering, SBS, etc. Experimental results show that the fractional frequency stability of 20 km and 55 km is 8.6×10^{-15} and 1.3×10^{-14} at 1 s, and can reach 7.6×10^{-18} and 8.1×10^{-18} at 10^4s. Furthermore, several major factors that affect long-term stability and network capacity are discussed and related possible solutions are given. This solution provides a new method for the construction of ultra-stable frequency transmission networks in large areas in the future.

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