Precise time transfer over a novel wavelength-division multiplexing bidirectional optical amplification scheme

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Optical amplification, which is necessary for extending the distance of fiber-optic time transfer, has important impacts on the system performance. In this letter, we propose a wavelength-division multiplexing (WDM) based single-fiber bidirectional-transmission unidirectional optical amplification (WSFBT-UOA) scheme with low noise and high symmetry. Compared with single-fiber bidirectional amplifier (SFBA), the effect of backscattering can efficiently be suppressed by WSFBT-UOA scheme. Both SPBA and WSFBT-UOA are validated by the experiment over 200km with one amplifier and 300 km with two amplifiers. Moreover, the time transfer performance, especially short stability is investigated over 300-1500km length fiber links. Results show that SFBA is more suitable over shorter fiber links for its lower complexity and cost, while WSFBT-UOA should be employed for longer fiber links to achieve the accepted time transfer performance.

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Fiber-optic time transfer has been widely adopted in radio astronomy, navigation and metrology due to the advantages of wide bandwidth, low attenuation and high stability[1-6]. When the transmission distance exceeds several dozens of kilometers, considering fiber transmission loss problem, signal regeneration is necessary. Owing to high gain and low noise figure, erbium-doped fiber amplifiers (EDFAs) are widely used in optical systems. In time and frequency (T/F) transfer system, signals from different directions will transfer along the same fiber link for keeping high symmetry, thus bidirectional EDFAs (Bi-EDFAs) are necessary in time and frequency transfer system. Several Bi-EDFA schemes have been proposed and demonstrated [7-9]. To obtain the highest symmetry in both directions, a design that only contains a piece of erbium-doped fiber, a pump laser, and a wavelength multiplexer for the pump and signal light without any isolators and circulators or WDMs is adopted [9]. However, such single fiber bidirectional amplifiers (SFBAs) will allow free propagation of backscattered signals and amplified spontaneous emission (ASE), which will deteriorate signal- to-noise-ratio (SNR), further worsen the stability. Another kind of schemes is based on spectral detuning of the transmitters for blocking unwanted signals using optical isolators, circulators, or WDM filters[3, 7, 8]. However, these methods will unavoidably bring asymmetry, requires calibration with high precision. And bidirectional optical amplifier designed until now need to be custom-built, which cannot be compatible with the unidirectional optical amplifiers (UOAs) in conventional telecom networks. Recently, we proposed two optical amplification schemes applied in bidirectional time division multiplexing transmission over a single fiber with the same wavelength (BTDM-SFSW) system[10, 11]. One is the single fiber bidirectional amplifier with magneto-optical switch (SFBA-MOS), and the other is the single-fiber bidirectional-transmission unidirectional optical amplifier (SFBT-UOA). Though bidirectional delay symmetry can be greatly guaranteed and backscattered noises can be suppressed, a special link access control mechanism to set the states of the MOSs in SFBA-MOS or the 2 × 2 OS in SFBT-UOA is needed, which will add system complexity.

In this letter, we propose a novel bidirectional optical amplification scheme applied in a two-way WDM time transfer system, which can block backscattered signals and ASE noise in transmission path. The configuration of the proposed Bi-EDFA is shown in Fig.1. Two channels of dense WDMs (DWDMs) are equipped to isolate the time signals in two directions. Channel is used for the forward transfer, while channel is used for the backward transfer. The channel spacing is 100 GHz (0.8 nm) with insertion loss less than 1dB. The forward and backward signals are amplified through same unidirectional EDFA incorporating two optical isolators.



Fig. 1. Configuration of the proposed bidirectional optical amplifier. EDFA: erbium-doped fiber amplifier, DWDM: dense wavelength-division multiplexing.

Compared with previously mentioned amplification scheme using optical isolators, circulator and WDM filters, this design need fewer optical devices and lower costs. Moreover, in principle, this bidirectional optical amplification scheme is compatible with UOAs in conventional telecom networks, and thus has the potential to support both time transfer and communication service at the same time. Furthermore, in contrast to SFBA-MOS and SFBT-UOA, WSFBT-UOA doesn’t need link access control mechanism which will add system complexity and maintenance. Though asymmetry will be brought into system since forward and backward signals transfer in different channels of DWDM, this scheme shows good performance in hundreds of kilometers without calibration. We successfully demonstrate a WDM two-way based time transfer adopting 15 equivalent WSFBT-UOAs over 1500 km in our long-haul testbed. The time deviations of less than 158 ps/s and 61 ps/105 s, respectively, are obtained. We also give an evaluation of asymmetry properties of WSFBT-UOA. The propagation delay difference of the WSFBT-UOA is 1.742 ns, standard deviation (RMS) equals 0.2 ps.

The principle of the proposed fiber-optic two-way delayed WDM based time transfer scheme is shown in Fig.2. Unlike normal WDM time transfer scheme[12, 13], the transmission of the 1 PPS at site B is delayed . We have:



where is the time difference between local input 1PPS and received 1PPS at site A (site B); is the propagation delay of fiber link from site A (site B) to site B (site A); and and are the sending delay and receiving delays at site A (site B), respectively.

From equation (1) we can get the difference between two sites



In real network, the transmission delay difference () in both directions will always change due to chromatic dispersion and ambient temperature drift. To realize high precision in WDM time transfer system, link calibration[13] is needed to eliminate delay difference. Moreover, when a Bi-EDFA is added to compensate transmission loss, additional asymmetry will inevitably be introduced into the system, so the symmetry of the Bi-EDFA should be considered. In this letter, asymmetry introduced by WSFBT-UOA is considered and measured by vector network analyzer (Agilent N5247A).

The asymmetry of Bi-EDFA includes two parts, the absolute propagation delays difference in two directions, and its variations. The former can be calibrated at the beginning, whereas the latter cannot be compensated when the variations are unequal. The test scheme for the noise and asymmetry properties of the WSFBT-UOA in the transfer of time signals is shown in Fig. 3.

The experimental setup is shown in Fig. 4. It includes a local modem, a remote modem and one electro-optic switch(EOS). The whole system is in a normal air-conditioned room with an hourly temperature fluctuation of more than 3 ℃. In order to eliminate the effect of clock drifts on the test, the 1 PPS (pulse per second) signal from a common Rb clock (Symmetricom, 8040C) is provided to the time transfer modems at local site and remote site simultaneously. At siteA, the 1PPS signal is encoded into a time code through an encoder [8].



Fig. 2. Principle of two-way delayed WDM based time transfer.

Then the time code is sent to the fiber link through a DWDM small form-factor pluggable (SFP) transceiver with wavelength (1550.12nm in our system). At remote site, the input 1 PPS from the clock is delayed by a time delay adjuster (TDA) implemented in FPGAs till receiving the time code from local site. The delay of the TDA is measured by time interval counter (TIC) 3. The delayed 1PPS is then input to the encoder and transmitted to the fiber link on the light with wavelength (1549.32nm in our system). At each site, the decoder recovers the 1 PPS from the received time code. The time difference between the received 1 PPS and local input one is measured by a TIC (TIC 1 and TIC 2 in the figure). All the adopted TICs in our test are SR620 (Stanford Research System).



Fig. 4. Experimental setup of two-way fiber-optic time transfer exploiting Bi-EDFAs. EOS: electro-optic switch, SFP: small form-factor pluggable transceiver.

The wavelengths of the launched light from two sites are 1550.12 and 1550.92nm, respectively. Fig. 2. (a) shows the measured phase noise spectra of the proposed fiber-optic RF transfer at 10 MHz using three different nonsynchronized RF sources. The results over 1m fiber illustrate the phase noise floors which are mainly determined by RF signal processing, optical transmitting and receiving at each site. As can be seen, the system floors with different RF sources are almost the same due to the negligible propagation delay. As the fiber link extends to 40km, the phase noise is significantly deteriorated, relative to the floor, as without phase noise compensation (free running link). After the proposed compensation using Rigol’s or R&S’s RF source, the phase noise of 40km compensated link is almost approached to the floor at the offset frequency of less than 0.1Hz. It indicates that the fluctuation mainly induced by the ambient variations is efficiently suppressed, and the performance is mainly restricted by the system floor, which can be improved by using high performance RF devices. However, when using the source of Hittite, the phase noise of 40km compensated link is much higher than its floor and even worse than the 40km free running link at the offset frequency less than 100Hz. It mainly attributes to the worse instability of Hittite’s source, whose impact on the phase noise has exceeded that of propagation delay variation induced by ambient variation. The phase noises of 40km compensated link at higher offset frequency using three different sources are almost same since this part is dominated by the amplified spontaneous emission noise of erbium-doped fiber amplifier [15]. We also find that the phase noise of the proposed scheme using Rigol’s or R&S’s RF source is very close to that using the scheme in [3] over 40 km link. It is mainly because the Rigol’s or R&S’s RF source is stable enough during a RTT, and hence the residual phase noise determined by the instability of the RF source in a RTT (the fourth term in Eq.(6)) can be ignored. The corresponding stability (Allan deviation) with a 5 Hz measurement bandwidth is shown in Fig. 2. (b). One can see that the Allan deviation of about and can be achieved over a 40 km compensated link with Rigol’s or R&S’s RF source, respectively.

In [11], the overlapping Allan deviation at 104 s for 50 km frequency transfer with 0.8 nm wavelength difference is below than 3E-18 and near 2E-17 for the temperature variation of below 5°C/day and 30°C/day, respectively. Therefore, the influence of wavelength difference of 0.8 nm over 40 km fiber link can be ignored in our experiment relative to the system floor noise of around 2E-16 at 104 s. Moreover, since the Allan deviation will degrade one order of magnitude for a 10-times distance extension [11], the influence of 0.8 nm wavelength difference will be close to the system floor when the fiber length extends to 500 km and having a temperature variation of 30°C/day in our experiment. In order to achieve higher precision and longer distance, smaller wavelength differences or frequency transfer schemes utilizing the same wavelength [4] should be employed. It is worth noting that the transfer distance is also limited by transmission loss, dispersion, phase compensation range and compensation bandwidth, and the coherence of RF source in a RTT. The transmission loss and the effect of dispersion can be compensated by bidirectional optical amplifier and dispersion compensation [16]. The proposed scheme has an unlimited phase compensation range as a passive compensation schemes, and a higher compensation bandwidth than triple transmission schemes. Therefore, the long-term drift caused by a longer fiber in the loop bandwidth can also be compensated sufficiently as long as employing a nonsynchronized source stable in the corresponding RTT.



Fig. 5. TDEV (1s) over 2m-1600 km fiber link equipped both SPBA and WSFBT-UOA.



Fig. 5. TDEV (1s) of SFBA and WSFBT-UOA over 200km fiber link

The measured phase noise spectra of 500MHz probe signals from the three RF sources are shown in Fig. 3. One can see that Rigol’s and R&S’s ( ~ -65 dBc/Hz @1Hz and ~ -49 dBc/Hz @1Hz) source are more stable than Hittite’s one (~ 0 dBc/Hz @1Hz), which is consistent with the frequency transfer stability of the proposed scheme in Fig. 2. Two crossing points between the spectra of Rigol’s and R&S’s sources at about 0.06 Hz and 20 Hz are also observed in Fig. 2. (a) in 1 m and 40 km compensated link for the influence of the stability of nonsynchronized RF source on the phase noise of the RF transfer.

The frequency transfer stability with the worse Hittite’s source is measured over different length fiber links, shown in Fig. 4. It can be seen that the frequency transfer stability decreases with the increase of the fiber link length. This is mainly because the RF signal from Hittite’s source is incoherent after a RTT delay, and the correlated phase noise between the probe signal and its round-trip signal increases with the growth of the propagation delay (fiber length). On the other hand, for Rigol’s or R&S’s source, the phase noise of 40km compensated link is almost equal to that of 1m fiber link at the offset frequency of less than 0.1Hz. It indicates that the impact of the source on the proposed scheme can be neglected as long as the nonsynchronized source is stable enough in a RTT.

In summary, we propose a passive phase noise compensation scheme for fiber-optic RF transfer with a nonsynchronized RF source to avoid high precision phase locking. Passive phase noise compensation without the effect of backscattering is realized by only employing two wavelengths without the requirement of electrical frequency dividing. The RF transfer performances of proposed scheme are experimentally evaluated using nonsynchronized sources with different stabilities. The impact of the nonsynchronized source under different fiber lengths are also investigated. The results show that the ambient variations induced phase noise over a 40 km fiber link can be efficiently suppressed by the proposed scheme with common oscillators often equipped at the user site in practical applications.



Fig. 6. Absolute time delay in different channel of WSFBT-UOA.

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