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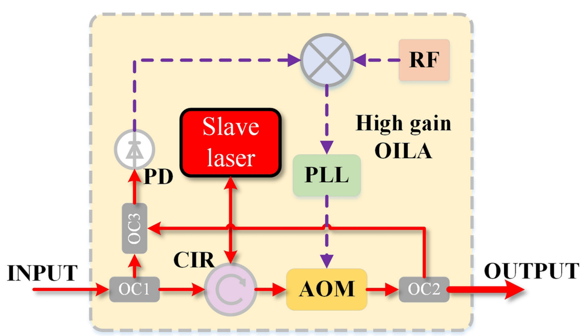

High gain optical injection locking amplifier (OILA)

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High-Gain Optical Injection Locking Amplifier in Phase-Coherent Optical Frequency Transmission

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Abstract: Optical amplification, which is necessary for extending the distance of optical frequency transfer, has a significant impact on the transmission performance. In this paper, we propose a high-gain optical injection locking amplifier (OILA) with low phase noise based on an optical injection phase-locked loop for the phase-coherent optical frequency transmission. The high-gain OILA can provide more than 75-dB gain and ensure that the input carrier frequency fractional stability can reach 8.2×10^{-20} at an averaging time of over 100 s. We then transfer a commercial narrow-linewidth laser over a 220-km fiber link with only one amplification step placed at the remote end. After eliminating the noise induced in the fiber link, the fractional frequency instability of the transferred frequency can reach 9.0×10^{-16} at 1 s and 7.1×10^{-20} at 20 000 s.

Index Terms: Diode lasers, laser injection-locked, metrology, optical standards and testing.

1. Introduction

State-of-the-art optical clocks are superior to the current cesium-based atomic clocks for which the fractional instabilities are below 10^{-17} [1], [2]. Fiber-based high precision phase-coherent optical frequency transfer [3]–[15] for optical clock networks can enable substantial research on fundamental physics, navigation, time keeping, or geodetic applications [16]–[19]. There are two challenges in optical frequency transfer when the distance is up to thousands of kilometers. One challenge in long distance optical frequency transfer is the phase noise added onto the light by acoustic mechanical and thermal perturbations in the fibers. The noise can be canceled in real-time using interferometric stabilization methods. The other is the power consumption of the signal when it is transmitted over the fiber. Standard silica fiber exhibits an attenuation of around 0.2 dB/km for

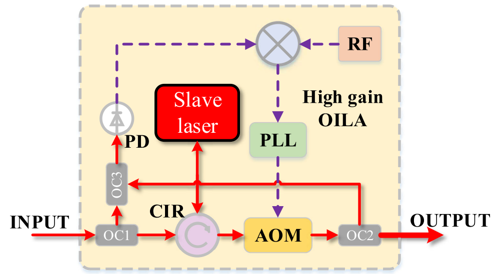

Fig. 1. High gain optical injection locking amplifier (OILA). PD: photodiode; OC: optical coupler; CIR: circulator; AOM: acousto-optic modulator; PLL: phase locking loop; RF: reference frequency.

light of wavelength around 1550 nm. Moreover, if we consider the loss in splices and connectors, the effective attenuation can be greater than 0.25 dB/km. As a consequence, the power loss can accumulate to 500 dB for a 1000 km fiber link round-trip transmission.

Erbium-doped fiber amplifier (EDFA) is the most commonly used fiber amplifier for ultrastable optical frequency transfer. However, the bidirectional nature of the frequency transfer system restricts the optimum gain to about 20 dB to avoid stimulated lasing due to the random point reflections and Rayleigh scattering existing in the fiber link [20]. In consequences, excess losses will accumulate along with the long links unless the distance between two adjacent EDFAs is sufficiently small. For example, to overcome the attenuation in a 920 km fiber link, nine pairs of EDFA systems and two pairs of fiber Brillouin amplifiers (FBAs) [21] are distributed over the entire link length at distances varying from 74 to 119 km [7]. However, there are still several signal failures or cycle slips related to cascading bidirectional EDFA.

In order to extend the amplification distance of a single amplifier, reduce the complexity of the system, and achieve cycle slip-free optical frequency transfer, we have investigated and optimized the use of optical injection locking amplifier (OILA) based on optical injection phase-locked loop (OIPLL) [14], [22], [23] as an alternative technique. In this work, we find the performance of OILA could be enhanced effectively by optimizing the operating frequency and position of the acousto-optic modulator (AOM), and working current and temperature of the slave laser. This optimization enables the amplification of less than 1 nW input optical signal by more than 75 dB in a single gain step. Moreover, by using a high-performance OIPLL, the stability of this high gain OILA can reach 8.2×10^{-20} at 100 s which is suitable for amplification of the present most stable optical signal.

In Section 2 we present the optimization of the attenuation of the amplifier and research on the power and wavelength properties of the slave laser in OILA. A test setup is built to measure the frequency instability of amplifier with different operating current and temperature, which tracks the maximum amplification gain of OILA without deteriorating the frequency stability. In Section 3 we discuss an optical frequency transfer over 220 km fiber link with only one OILA. The frequency stability and phase noise of the transmission signal are tested and compared with the theoretical calculation.

2. Tracking the Limits of OILA

The optimized OILA configuration is shown in Fig. 1. In order to reduce the attenuation of the optical frequency signal transmitting from the input of optical coupler 1 (OC1) to the slave laser in the OILA, the AOM, used for executing OIPLL feedback is moved to the back of the optical circulator and 70% of the optical power is adjusted to be injected into the slave laser. Through the above two steps, the attenuation of the optical frequency signal before injection into the slave laser can be reduced to 2 dBm, which leads to a significant improvement in the signal compared to that in the former scheme with a 7 dBm attenuation [14]. As a further benefit, we have also found that moving the AOM behind the slave laser can increase the stability of the injection locking process. An electro-optic modulator (EOM) [22], [23] or AOM prior to the slave laser adds additional intensity

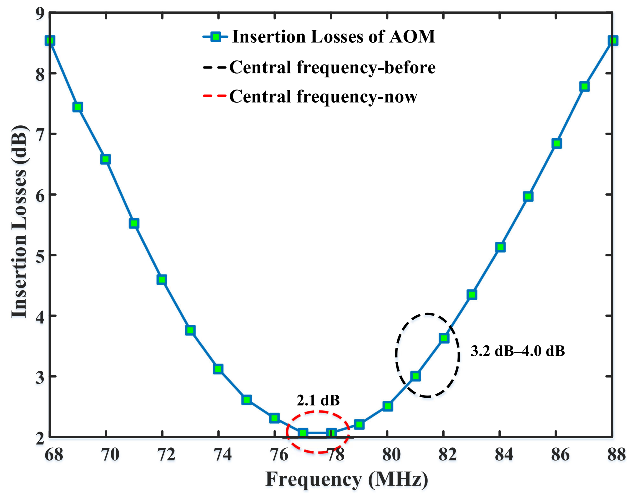

Fig. 2. The relationship between the central frequency of the AOM and its insertion loss.

fluctuations to the injected optical signal, which increases the phase noise to the injection locking process ($\Delta\phi_L \sim \Delta P_{inj}/P_{out}$).

Moving the AOM to a position behind the optical circulator will have additional attenuation on the output power of the OILA. In order to minimize the influence of the insertion loss of the AOM on the output optical power of the amplifier, we study the relationship between the central frequency of the AOM and its insertion loss. Results of the experiment are shown in Fig. 2. It can be seen that within the frequency range of 68 MHz–88 MHz, the insertion loss of the AOM satisfies the rule of decreasing first and then increasing, and although the standard central frequency of the AOM is 80 MHz in the instruction manual, the actual minimum insertion loss position is between 77 MHz and 78 MHz, where the insertion loss is close to 2 dB. In the previous scheme, we used the AOM central frequency of around 82 MHz, where the maximum insertion loss is close to 4 dB. Therefore, in order to reduce the output loss of the amplifier, we use 77.5 MHz as the frequency shift center frequency of the AOM.

To further improve the gain of the OILA, it is necessary to increase the output power of the slave laser without degrading the frequency stability of the amplifier. Since changing the position of the AOM causes an additional attenuation of 2 dB to the output of the OILA, it is desirable that the output of the slave laser can be greater than 17 dBm which ensures the output power of the amplifier reaches 15 dBm of the previous scheme [14]. Fig. 3(a) and (b) shows the wavelength and output power characteristics of the slave laser. When the working temperature of the laser is adjusted to 24.8 °C and the driving current is adjusted to 318 mA (close to the maximum operating current of 320 mA), the wavelength of the slave laser is 1550.12 nm which meets the bandwidth of the injection locking. In this way, we selected four combinations of working current and temperature of the slave laser and got the optical powers of 16.8 dBm, 17.1 dBm, 17.3 dBm, and 17.5 dBm respectively.

We constructed an optical Mach–Zehnder interferometer with a variable attenuator and an amplifier under test in the measurement arm while the other arm was treated as the reference to measure the frequency stability of OILA, as shown in Fig. 4. The AOM inside OILA has a frequency shift of about 77.5 MHz. The variable attenuator in front of the amplifier was used for controlling the optical power injected into the amplifier. In the experiment, we sequentially adjusted the operating temperature and driving current of the slave laser so that the output power of OILA was 14.8 dBm, 15.1 dBm, 15.3 dBm, and 15.5 dBm. For each output power, the input power of OILA was adjusted to −55 dBm, −60 dBm, and −65 dBm. Thus, the amplification gain range of OILA from 69.8 dB to 80.5 dB was achieved. We performed the frequency stability test on the OILA under the different desired amplification gains and calculated the corresponding Modified Allan deviation (MDEV).

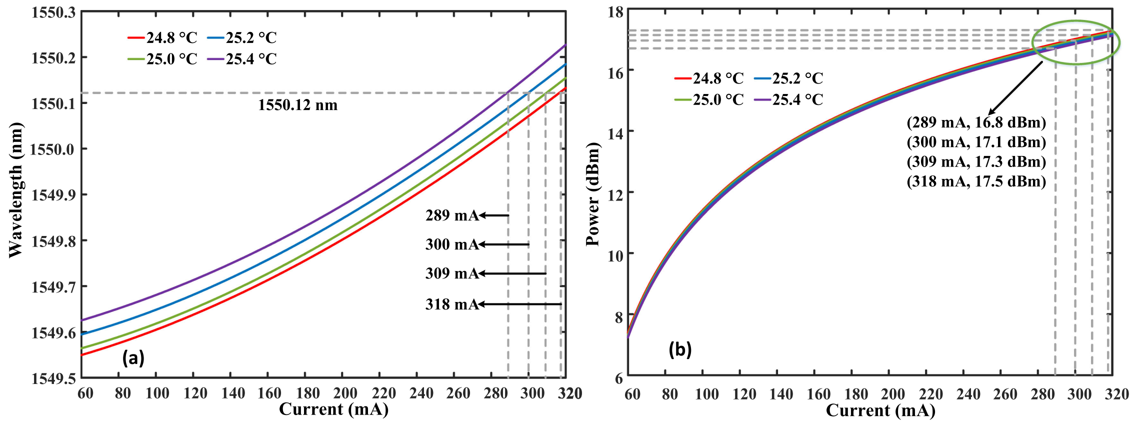

Fig. 3. (a) The wavelength of the slave laser as a function of driving current at different operating temperatures. (b) The output power of the slave laser as a function of driving current at different operating temperatures.

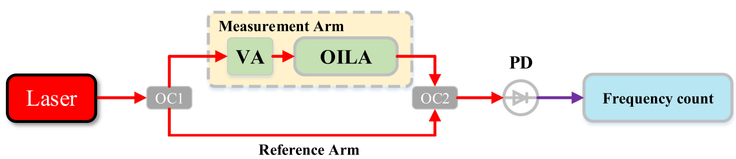

Fig. 4. Set-up to measure the frequency stability of OILA. OILA: optical injection locking amplifier; VA: variable attenuator; PD: photodetector; laser: NKT-X15 narrow-linewidth fiber laser; OC: optical coupler.

Frequency stability of the heterodyne beat signal was recorded by a π–type frequency counter, with the results shown in Fig. 5(a)–(d). The blue curve is the frequency fluctuation of the OILA with the amplification gains of 69.8 dB, 70.1 dB, 70.3 dB, and 70.5 dB, respectively. The corresponding standard deviation at a 1 s time scale is 0.0035 Hz, 0.0043 Hz, 0.0036 Hz, and 0.0044 Hz, respectively. When the gain of the amplifier is increased to 74.8 dB, 75.1 dB, 75.3 dB, and 75.5 dB, the corresponding standard deviation on the 1 s time scale is slightly degraded to 0.0045 Hz, 0.0049 Hz, 0.0048 Hz, and 0.0052 Hz, respectively, as shown by the pink curve. Finally, as shown by the gray curve, when the input power of the OILA is reduced to −65 dBm, some disturbance in the environment causes the OILA to produce a frequency jitter. The frequency jitter of OILA will clear away after the environmental disturbance disappears for the gain of the amplifier is 79.8 dB, 80.1 dB, and 80.3 dB. However, when the gain of the amplifier reaches 80.5 dB, the original lock state of OILA will not recover even after the environmental disturbance disappears. We can conclude that to obtain a low-noise amplifier, the output power of the amplifier cannot be increased blindly. A balance between the two factors needs to be maintained.

MDEVs calculated from these three-time records are depicted in Fig. 6(a)–(d). The OILA exhibits instability of less than 4×10^{-17} at 1 s and decreases below 10^{-19} at 100 s integration time when the input optical power is −55 dBm and −60 dBm for the above four output powers. The calculated MDEV closed in the noise limitation of the interferometer at an averaging time of over 200 s. Also, the MDEV follows the rule of $\tau^{-3/2}$ for the time less than 20 s, indicating white phase noise at this time scale. However, the MDEV deteriorated to 2.2×10^{-16} at 1 s integration time and exhibited a reduced slope when the input power of OILA was reduced to −65 dBm. This is mainly because the input optical power is too weak to tightly injection lock the “slave” laser, thus the environmentally induced instability can easily cause the frequency jitter to deteriorate the stability of OILA.

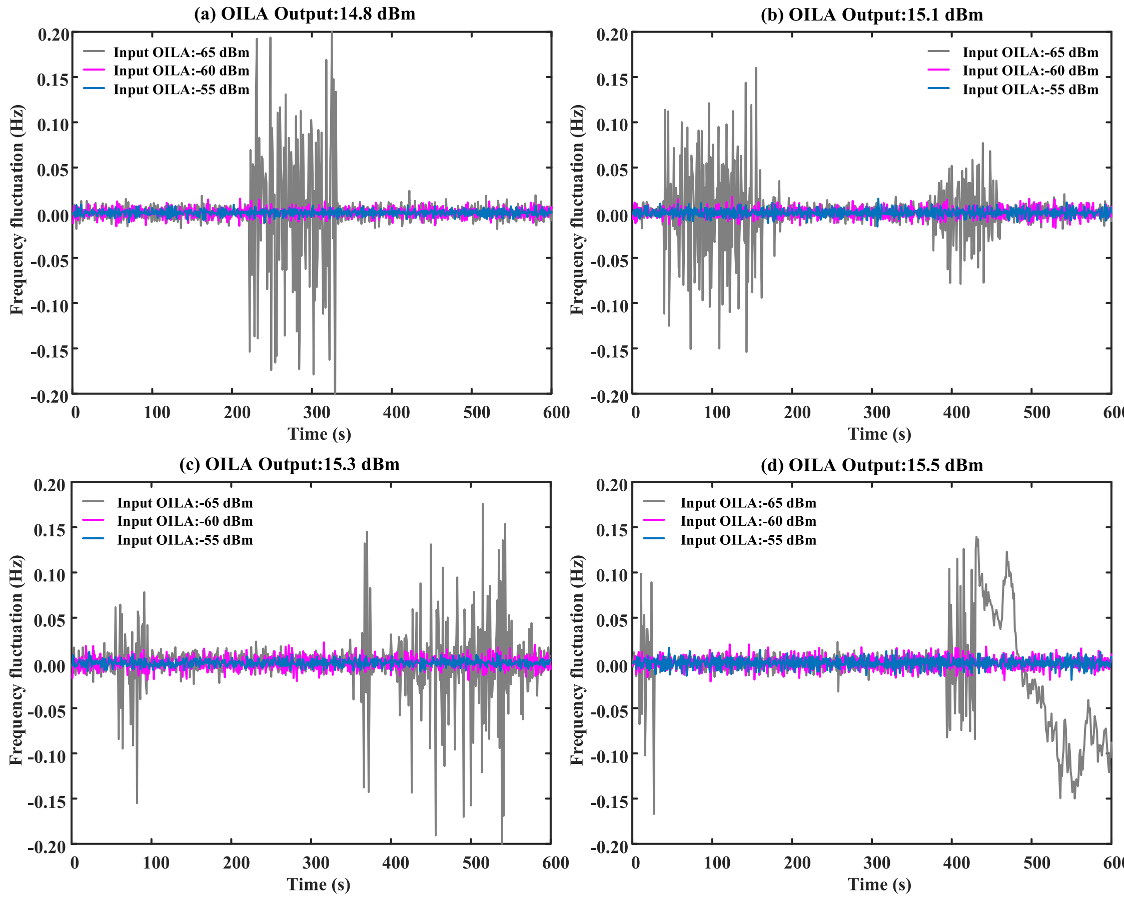

Fig. 5. Frequency fluctuation of OILA with input power of −55 dBm, −60 dBm, and −65 dBm for different output powers. (a) OILA output power of 14.8 dBm. (b) OILA output power of 15.1 dBm. (c) OILA output power of 15.3 dBm. (d) OILA output power of 15.5 dBm.

3. Optical Frequency Transfer Over a 220 km Fiber Link

To transfer a narrow-linewidth optical frequency over a long optical fiber link, the phase noise accumulated along the fiber and the attenuation need to be compensated. In this section we present construction of an optical frequency transfer system based on interferometric stabilization technology to transfer an optical carrier over 220 km fiber spools, as depicted in Fig. 7. The amplification scheme that utilizes OILA placed at the end of a 220 km fiber link is tested in a single amplification step. The power attenuation caused by fiber is around 0.24 km/dB. Thus, the total attenuation of 220 km round-trip is almost 106 dB.

The transfer laser is a commercial NKT-X15 narrow-linewidth fiber laser with an optical wavelength close to 1550.12 nm and an output power of 10 dBm. After passing a 30/70 splitter, a circulator, and an AOM, the signal power injected into the fiber link is 5 dBm. Attenuation of the 220 km fiber link causes the optical power to drop to −48 dBm (equivalent to 16 nano Watt) before reaching the OILA. After amplification and frequency-shifting by the OILA, part of the signal in the optical carrier (almost 5 dBm) will return back to the local end through a circulator for compensation system. A beat signal at the remote end between the transfer light and the light from a reference arm indicates the 220 km fiber link stability.

The phase noise of the beating signal is measured before and after suppressing the noise induced by the fiber link, as shown in Fig. 8(a). The phase noise reduction is −47.26 dB at 1 Hz, which is close to the theoretical limit of −47.98 dB at 1 Hz predicted by the formula [24], [21]:

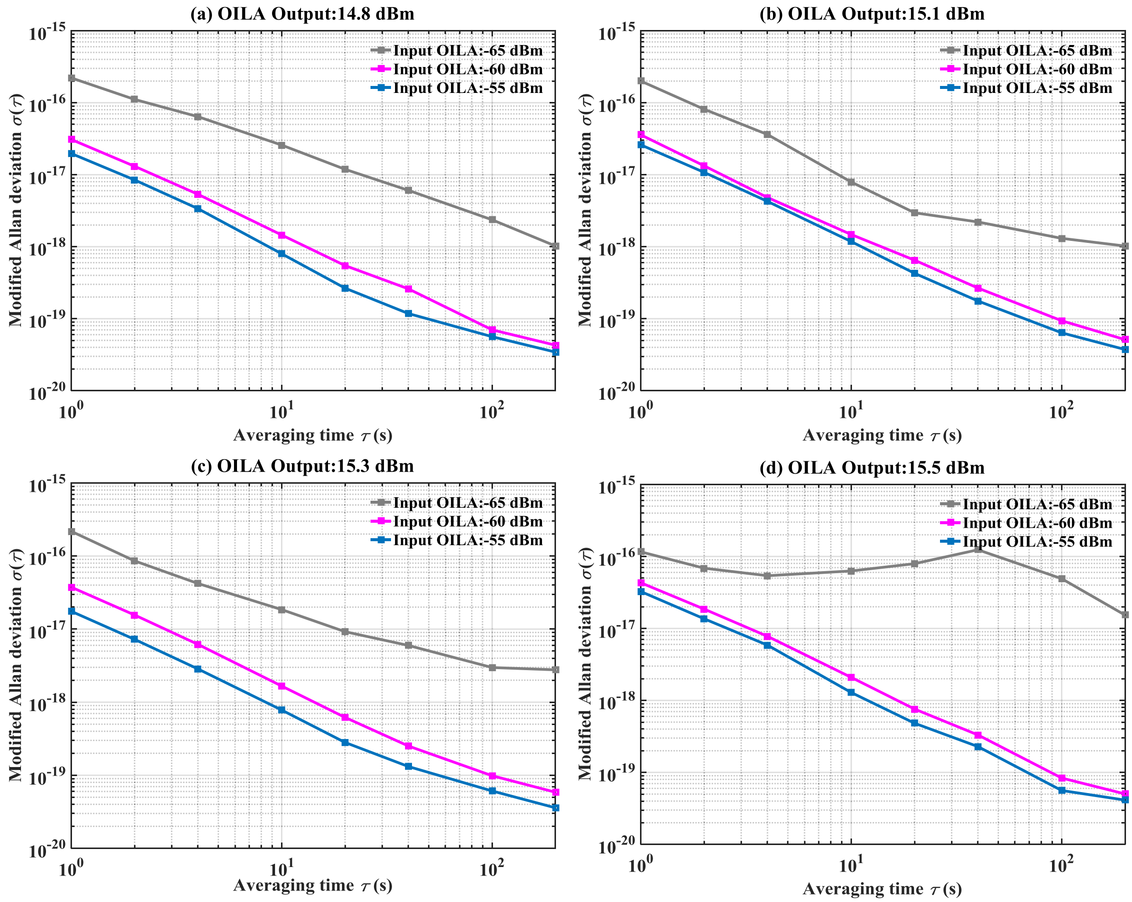

Fig. 6. Modified Allan deviation of OILA with input power of −55 dBm, −60 dBm, and −65 dBm and different output powers. (a) OILA output power of 14.8 dBm. (b) OILA output power of 15.1 dBm. (c) OILA output power of 15.3 dBm. (d) OILA output power of 15.5 dBm.

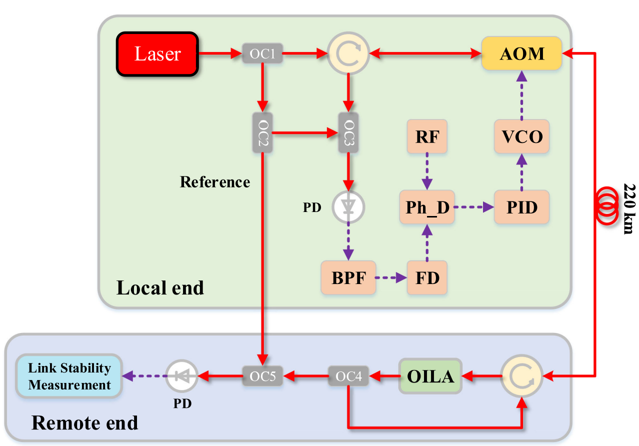

Fig. 7. Schematic diagram of optical frequency transfer for the 220 km fiber links with an optical injection locking amplifier (OILA). laser: NKT-X15 narrow-linewidth fiber laser; PD: photodiode; VCO: voltage-controlled oscillator; AOM: acousto-optic modulator; OC: optical coupler; BPF: band pass filter; FD: frequency divider; RF: reference frequency; Ph_D: phase detector.

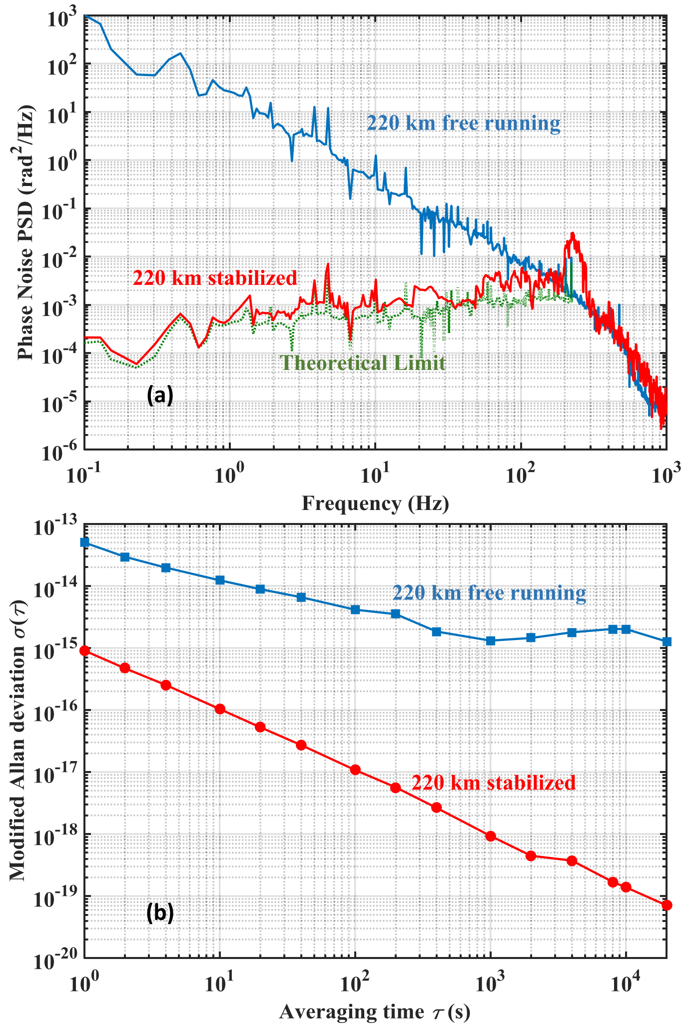

Fig. 8. (a) Phase noise of the transmission light before (blue line), and after (red line) compensation. The green dashed line gives the theoretical compensation limit. (b) Modified Allan deviation with compensated (red circles) and uncompensated (blue squares) phase noise.

$S_{\phi}^{stab}(f) = (4\pi^2/3)(f\tau_d)^2 S_{\phi}^{free}(f) = 1.6 \times 10^{-5} f^2 S_{\phi}^{free}(f)$, where $S_{\phi}^{free}(f)$ is the phase noise of the free-running fiber, τ_d is the time taken for a one-way trip in the fiber and f is the Fourier frequency. It is close to the optimal calculation result (green dashed line in Fig. 8(a)) within the theoretical compensation bandwidth. The bump of about 227 Hz is the bandwidth of compensation system for the 220 km fiber link, which fits the estimated value calculated by $1/4\tau$.

We used the π–type dead time free frequency counter to measure the long-term frequency stability of optical transmissions at the user end. The MDEV results of the measurements before (blue squares) and after (red circles) the noise suppression is shown in Fig. 8(b). After applying the compensation, the stability of the optical transmission reach 9×10^{-16} at 1 s which is in good agreement with the value calculated from the integrated phase noise (the integrated phase noise from 0.1 Hz to 1 kHz for noise suppression at transmission distances of 220 km is almost 1.1 rad, see Fig. 8(a)). The long-term stability of 220 km optical frequency transmission reached a value of 7.1×10^{-20} at the averaging time of 20000 s. Comparing the achieved instability for this 220 km stabilized link with our previous measurements for over 100 km [14], we observe an excellent agreement with the scaling law ($\sigma_y \sim L^{3/2}$) derived in [24]. Thus, the new measurements support our prediction that we can achieve instability of 8.7×10^{-15} at 1 s for the optical transmission of a 1000 km link.

4. Conclusions

We proposed a high gain of OILA. Moving the AOM behind the slave laser not only reduces the attenuation of the light before it is injected into the slave laser, but also, more importantly reduces the additional phase noise induced during the injection locking process. An important conclusion is that the simpler the structure before injection locking, the lower is the noise of the injection locking process. Effects of operating current and temperature of the slave laser inside the OILA were also investigated. The optimized OILA provides an amplification capability equivalent to three EDFAs with a gain higher than 75 dB and ensures that the input carrier frequency stability can be as good as 8.2×10^{-20} at averaging time of over 100 s. The output power of OILA reaches 15 dBm, making this technology easily employable to cascaded-link technique [4], [9] and to the in-line extraction of an ultrastable frequency signal from a fiber link [25]. Moreover, the OILA is easy to fabricate as a photonic integrated circuit [26]–[28] that makes the repeater station smaller and more stable (easy to control temperature) compared with the repeater station in [4].

Further, experiments on the optical frequency transmission of the commercial NKT-X15 narrow-linewidth fiber laser carrier in the laboratory have tested the optimized OILA and obtained a transfer stability of 7.1×10^{-20} at 20000 s for a 440 km round-trip fiber link with a total attenuation of 106 dB. In the next study, we will use a cavity-stable laser to conduct experiment on an urban fiber link to further extend the length of the transfer. In addition, the OILA will be used in the optical clock network connected via free-space link [29] as the optical injection locking can erase the amplitude fluctuations of the injected signal providing a further benefit.

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