doi:10.3788/gzxb20184712.1214001

100 km 光纤远端复现超窄线宽激光

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摘　要:介绍了一种在光纤远端复现超窄线宽激光的方法.将两段50 km的光纤线路通过中继站级联在一起.用锁相跟踪法将中继站中的激光器频率锁定在50 km光纤远端传输光信号上,跟踪精度达到3.5×10^{-19}.为了保持高光谱纯度,两个光纤噪声补偿模块独立工作,用于补偿每段50 km光纤引入的相位噪声.这种级联方案能够确保噪声补偿具有较大的动态范围.经补偿后,100 km光纤引入的频率不稳定度达到5.9×10^{-17}(1 s平均时间),10 000 s后达到6.8×10^{-19}.实现了在100 km光纤远端复现超窄线宽激光,附加线宽低至1 mHz.

关键词:光学频率;超窄线宽激光;精密传输;光纤相位噪声;中继站
中图分类号:O43　　**文献标识码**:A　　**文章编号**:1004-4213(2018)12-1214001-6

Recovery of an Ultra-narrow Linewidth Laser over 100 km Fiber Link

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Abstract: It is demonstrated that an ultranarrow linewidth laser is recovered after transfer through a 100 km fiber link. The fiber link consists of two 50 km spolled fibers cascaded by a repeater station where a transceiver laser is phase-locked to the transferred light of the 50 km fiber with tracking precision of 3.5×10^{-19}. To maintain the high spectral purity, two fiber noise compensation modules are employed to compensate for the fiber-induced phase noise in each 50 km fiber. The cascaded scheme enables a large dynamic range for the noise compensation. The fractional frequency instability for the stabilized 100 km fiber is 5.9×10^{-17} at 1 s averaging time, reaching 6.8×10^{-19} at 10 000 s. The ultranarrow linewidth laser is recovered at the remote end of the 100 km fiber with additional linewidth of 1 mHz.

Key words: Optical frequency; Ultranarrow linewidth laser; Precision transfer; Fiber phase noise; Repeater station
OCIS Codes: 140.0140; 120.3930; 120.5050; 230.2285; 300.3700

0 Introduction

Ultranarrow linewidth lasers are indispensable tools in a variety of applications including optical atomic clocks[1], high resolution spectroscopy[2], tests of fundamental physics[3], gravitational wave

Foundation item: The National Natural Science Foundation of China (No. 61378037), the Fundamental Research Funds for the Central Universities (Nos. JUSRP51628B, 1142050205180920), and the Projects of International Cooperation and Exchanges NSFC (Nos. 61511130508, 61611130128)

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Received: Sep.28, 2018; **Accepted**: Nov.1, 2018

detection[4], and coherent optical frequency transfer[5]. Recent years, laser systems with subhertz linewidth have been established in different countries[6-10]. To achieve ultranarrow linewidth, the lasers are often servo-locked to the resonance of an ultrastable Fabry-Pérot reference cavity with high finesse by using Pound-Drever-Hall technique[11-12]. However, the complexity and expensiveness of the laser system limit its large-scale use.

An extremely promising alternative for obtaining a spectrally narrow light source is to distribute a ready-made ultranarrow linewidth laser to different sites via fiber links. The challenge in distribution of the ultranarrow linewidth laser lies in the power loss and fiber-induced noise which can broaden the linewidth of laser light and decrease the spectral purity. Both the two problems need to be resolved to recover an ultranarrow linewidth laser at the remote end. Conventional approach to the compensation for power loss is based on the Erbium-Doped Fiber Amplifier (EDFA)[13-15]. However, both the signal and noise are amplified simultaneously in the EDFA, and the power as well as signal-to-noise ratio of the input light are required in restricted ranges. For the fiber-induced noise compensation, many efforts have been made to establish actively stabilized fiber links in the coherent optical frequency transfer in the last decade[15-22]. Several researchers have reported the recovery of the transferred light with absolute linewidth at hertz level[23-24]. However, the recovery of spectrally narrow laser light though long-distance fiber link is still a challenging work because the servo bandwidth for suppressing fiber-induced noise is limited by the delay effect[25].

In this paper, it is demonstrated that an ultra-narrow linewidth laser is recovered via a 100 km cascaded fiber link. A repeater station is installed at the intermediate node to divide the fiber link into two segments. Each segment has a stabilized 50 km spooled fiber equipped with independent Fiber-induced Noise Compensation (FNC) module, which ensures a broader servo bandwidth than the conventional method. The transceiver laser in the repeater station is phase-locked to the output light from the first 50 km transfer with tracking precision of 3.5×10^{-19} at 1 s averaging time and used as a light source for the next 50 km transfer. As the FNC modules work, it presents a resolution-bandwidth (RBW)-limited additional linewidth of 1 mHz at the remote ends of both the 50 km fiber and 100 km fiber. The performance of the FNC modules and repeater station is also evaluated in the terms of frequency instability and fiber phase noise.

1 Experimental system setup

Fig.1(a) shows the system layout for recovery of ultranarrow linewidth laser over the 100 km fiber link which consists of two 50 km single-mode spooled fibers. A cavity-stabilized laser operating at 1 557 nm with subhertz linewidth[10] is taken as the light source for transfer. As depicted in the Fig.1(a), the two spooled fibers are connected with an intermediate repeater station. The transfer system except the two 50 km fibers is set up in sealed acrylic boxes to protect the optics in the two FNC modules and repeater station from air flow.

As the light transfers through the fiber link, the vibrational disturbance and temperature fluctuation result in phase noise on the carrier of the laser light which broadens the linewidth of the laser. To maintain spectral purity, the FNC module, which is a Michelson interferometer in essence, is introduced to compensate for the fiber-induced noise. As described in the Fig.1(b), the laser light is split into two orthogonal lights by a Polarization Beam Splitter (PBS). And a half-wave plate is used to adjust the light power distribution in the two paths. The light in the short arm acts as the local reference. It is reflected by the PBS and mirror (M_1) successively, and goes through the PBS by placing the quarter-wave plate with optical axis at a 45-degree angle to the polarization direction of the input light. The light in the long arm is frequency-shifted by +80 MHz on an Acousto-Optic Modulator (AOM_1) and coupled into a 50 km spooled fiber link. A coupler with coupling ratio of 30 : 70 is connected to the remote end of fiber link to distribute the light into two parts. One part (30%) is sent to a Faraday Mirror (FM) which reflects the light back to the fiber. The beat-note signal is obtained on a Photo Detector (PD_1) by heterodyne-beating the reflected light against the reference light. AOM_2(−110 MHz) serves to discriminate the light reflected by FM from the back-scattering light along the fiber. Thus, the beat-note signal indicating fiber noise can be obtained on the PD_1 at frequency of 60 MHz. Meanwhile, the FM rotates the polarization direction of light by 90° for a double-pass which ensures a maximum beat-note signal without polarization controller. The noise signal is extracted by comparing the beat-note signal with a Radio Frequency (RF) standard signal in a Double Balanced Mixer (DBM). And then the error signal from the DBM is sent to a Phase-Lock Loop (PLL) to generate a calibration signal applied on the AOM_1. Assuming that the fiber-induced noise is identical in both forward and backward paths, it can be compensated by the negative feedback control of the driving frequency of AOM_1. Because the phase variation accumulated along the 50 km fiber can pass across π and DBM can only distinguish phase variation in range of $\pm\pi$, a Frequency Divider (FD) is employed to divide the 60 MHz beat-note signal by 64 to improve the dynamic range and robustness of the PLL.

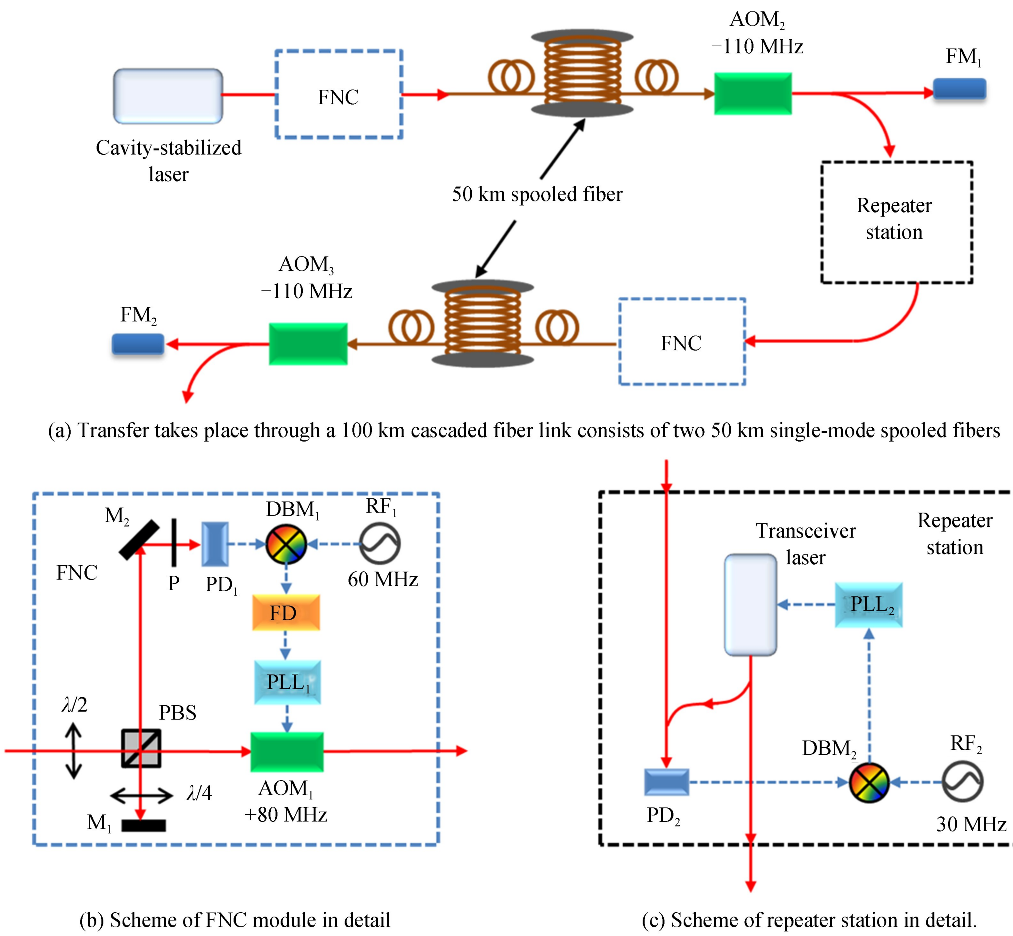

Fig.1 System layout for recovery of ultranarrow linewidth laser over the 100-km fiber link

2 Results and discussions

The additional linewidths of the transferred light through 50 km transfer with and without FNC are respectively measured on a spectrum analyzer by beating the transferred light against the local light on a photodiode. Fig.2(a) shows that the 50 km transfer induces a linewidth broadening of 391 Hz. When the FNC module works, the additional linewidth can be significantly narrowed down to 1 mHz limited by the resolution-bandwidth (RBW) of 0.5 mHz, as shown in the Fig. 2(b). Comparing with the subhertz linewidth of the laser source, the 1 mHz additional linewidth is negligible.

Besides the linewidth measurement, the performance evaluation of the FNC module are also carried out based on the measurements of residual phase noise Power Spectral Density (PSD) and fractional frequency instability of the transferred light. The residual phase noise PSD is measured on a Fast Fourier Transform (FFT) spectrum analyzer by demodulating the beat-note signal between the transferred light and the local light with a standard RF signal. As illustrates in the Fig.3, when the FNC module is off, the

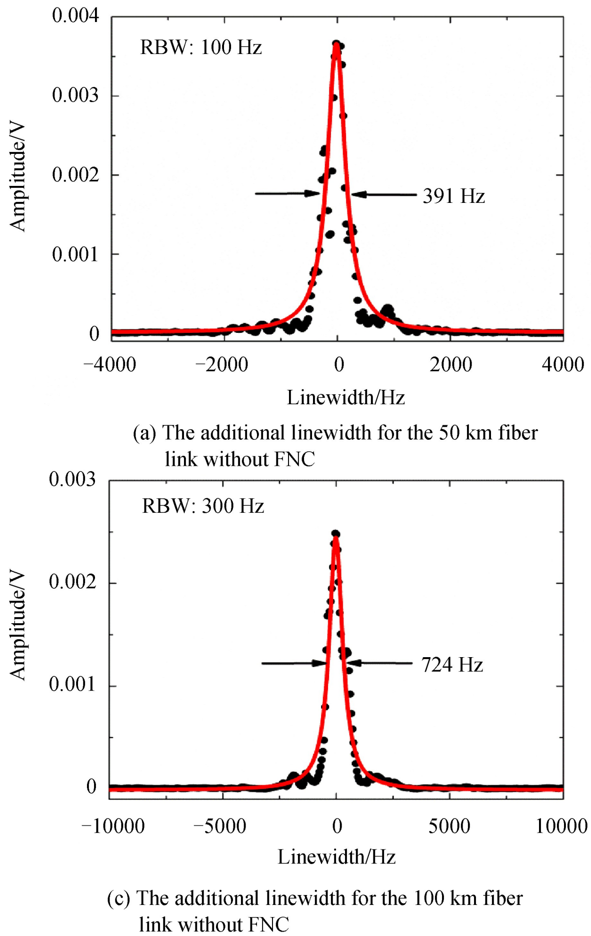

Fig.2 Linewidth measurements of the out-of-loop beat-note signal

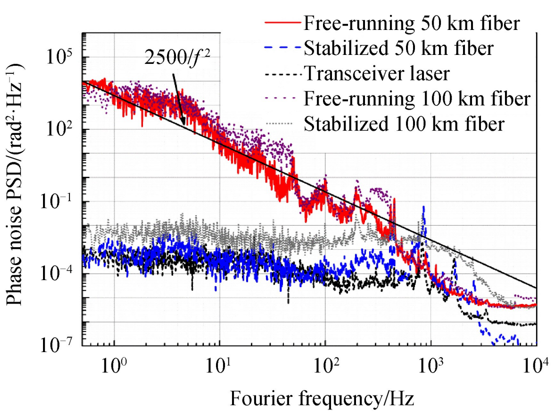

Fig.3 The phase noise PSD of the out-of-loop beat-note signals

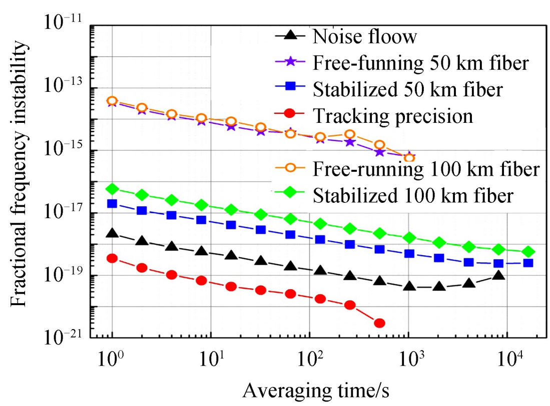

Fig.4 The fractional frequency instability of the out-of-loop beat-note signals

residual phase noise PSD follows the power-law dependence on Fourier frequency as h/f^2 below the cut-off frequency of 1 kHz, where f is the Fourier frequency, h is a coefficient varies for different fiber links and equals to 2 500 here. When the FNC module works, the residual phase noise PSD is significantly suppressed down to 10^{-3} rad^2/Hz level within the cut-off frequency, which confirms the result that the high spectral purity is maintained at the carrier of the transferred light. Moreover, the frequency of the out-of-loop beat-note signal is down-converted to 100 kHz and then recorded on a Λ-type counter (Agilent 53132A) with a gate time of 1 s. The fractional frequency instability is obtained by calculating the modified Allan deviation (ModADEV) based on the recorded data. As shown in the Fig.4, the frequency instability of the free-running 50 km fiber is 3.5×10^{-14} at 1 s averaging time and the frequency instability of the stabilized link is 2.0×10^{-17} at 1 s which averages down to 2.4×10^{-19} after 10 000 s. The noise floor of the transfer system is measured by replacing the 50 km fiber with a 2 m fiber. It presents a frequency stability one order of magnitude lower than that of the stabilized link which ensures the availability of transfer system.

Considering the fiber loss coefficient of 0.2 dB/km, the power attenuation of the transferred light after 50 km transfer makes it inadequate for further transfer. To address this problem, a repeater station is installed at the remote end of the 50 km fiber to regenerate a spectrally pure signal with sufficient power. Fig.1(c) shows the schematic diagram of repeater station. A portion of light from the transceiver laser beats against the transferred light on PD_2 and then the beat-note signal is compared with a standard radio frequency in the DBM_2. The error signal from DBM_2 is sent to PPL_2 to adjust the current modulation of laser, tracking the transceiver laser with the transferred light. To compensate for the frequency shift induced by the AOM_1 (+80 MHz) and AOM_2 (−110 MHz), the transceiver laser operates at the frequency 30 MHz higher than the incoming transferred light.

As the function of repeater station is to regenerate and amplify the incoming signal from the precious segment, the transceiver laser should inherit all the phase characteristics of the incoming signal. A series of evaluation experiments are carried out by comparing the transceiver laser with the transferred light. The beat-note signal between the two lights still exhibits an additional linewidth of RBW-limited 1 mHz. It indicates that a comparable subhertz linewidth laser source can be recovered at the remote repeater station. Moreover, the additional phase noise of the transceiver laser comparing with the original laser is measured. As shown in the Fig.3, the additional phase noise of the transceiver laser overlaps mostly with that of the transferred light. It proves that the transceiver laser completely inherits the high spectral purity from the transferred light. The beat-note signal between the transceiver laser light and transferred light is also down-converted and recorded. The ModADEV demonstrates that the repeater station performs excellently and provides a remarkable tracking precision of 3.5×10^{-19}(1 s), one order of magnitude lower than the noise floor of the FNC system.

After being phase-locked to the transferred light, the transceiver laser acts as an optical oscillator for the next 50 km transfer. Another FNC module is used to suppress the fiber-induce noise. For a free-running 100 km fiber, the fiber-induced noise leads to an additional linewidth of 724 Hz, as shown in Fig.2(c). While the two FNC modules as well as the repeater station work simultaneously, the linewidth broadening can be dramatically reduced to 1 mHz (RBW-limited), as shown in Fig.2(d). It is proved that the ultranarrow linewidth laser can be recovered through the 100 km cascaded fiber link.

In addition, the phase noises PSD of the 100 km fiber link with and without compensation are respectively measured, as shown in Fig.3. As the FNC modules and repeater station work, the phase noise is effectively suppressed within 1 kHz. In the higher-frequency range, the phase noises PSD rolls down and contributes little to the laser linewidth broadening.

The beat-note signal between the local light and the transferred light of the 100 km fiber link is recorded on a frequency counter with gate time of 1 s for more than 15 hours. For the free-running 100 km fiber link, the fractional frequency instability of the fiber link is 3.9×10^{-14} at 1 s averaging time. As the fiber-induced noise is suppressed, the ModADEV is 5.9×10^{-17} at 1 s averaging time, and scales down to 6.8×10^{-19} at 10 000 s averaging time.

3 Conslusion

In summary, the recovery of a subhertz linewidth laser through a 100 km cascaded fiber link is demonstrated. A transceiver laser is employed at the intermediate node to connect the two 50 km spooled fibers by phase-locking to the transferred light from the remote end with tracking precision of 3.5×10^{-19} at 1 s averaging time. To maintain the high spectral purity in the transferred light, two FNC modules are introduced to suppress the fiber-induced phase noise independently for each spooled fiber. The cascaded scheme enables the FNC modules to work in a larger dynamic range than the conventional approach. Thus, the additional linewidth can be suppressed to be RBW-limited 1 mHz at the remote ends of both 50 km and 100 km fiber links. The performances of the FNC modules and repeater station are evaluated based on the residual phase noise PSD and fractional frequency instability. The fiber-induced noise can be significantly reduced within the dynamic range which remains most of light power in the carrier. The residual frequency instability (ModADEV) of 5.9×10^{-17}(1 s) is achieved over the 100 km fiber link.

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引用格式：MA Chao-qun, CHEN Guo-qing, LI Lei, *et al*. Recovery of an Ultra-narrow Linewidth Laser over 100 km Fiber Link[J]. *Acta Photonica Sinica*, 2018, **47**(12): 1214001

马超群，陈国庆，李磊，等.100 km 光纤远端复现超窄线宽激光[J].光子学报，2018，**47**(12)：1214001