

Phase noise characteristics of narrow-linewidth fiber laser and laser diode in unbalanced interferometers

Huijuan Zhou (周会娟)¹, Wei Chen (陈伟)¹, Zhou Meng (孟洲)^{1*},
and Chongfeng Sun (孙崇峰)²

¹College of Opto-electronic Science and Engineering, National University of Defense Technology,
Changsha 410073, China

²Institute of Information Science and Engineering, Henan University of Technology, Zhengzhou 450001, China

*Corresponding author: zhoumeng6806@163.com

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The phase noises of two narrow-linewidth fiber laser and laser diode are measured by using unbalanced Michelson interferometers with various optical path differences (OPDs). The measured results indicate that the phase noises of the two lasers do not change linearly with the OPD over the range from 1 to 100 m. The laser diode exhibits phase noise levels higher than that of the fiber laser at OPDs longer than 10 m. However, the laser diode outperforms the fiber laser at OPDs shorter than 10 m. The results obtained can assess laser performance and determine the suitable laser for use in a particular application.

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Lasers with high coherence are widely used in applications such as coherent optical communication, interferometric fiber sensing including hydrophones, and accelerometers. Phase noise is a key parameter that is used to characterize highly coherent lasers. Laser phase noise limits the ultimate sensitivity of a wide variety of interferometric sensors. An unbalanced Michelson or Mach-Zehnder interferometer is usually adapted to measure laser phase noise^[1–6]. Phase noise at 1-m optical path difference (OPD), which is usually normalized from the value measured at a long OPD of several tens of meters, is used to assess the performance of a laser^[3].

Earlier investigations reported that the laser phase noise measured by the unbalanced interferometer is described as^[1,6]

$$\Delta\varphi = \frac{2\pi D}{c} \Delta\nu, \quad (1)$$

where D is the OPD of the unbalanced interferometer, c is the velocity of light in free space, and $\Delta\nu$ is the magnitude of the laser frequency fluctuation. Meng *et al* indicated that the phase noise of the diode-pumped Nd:YAG laser (Lightwave Electronics, Model 125) in an unbalanced interferometer did not vary linearly with the OPD over the range from 0 to 160 m^[6]. Equation (1) was no longer applicable for a diode-pumped Nd:YAG laser. The diode-pumped Nd:YAG laser is famous for its low phase noise. However, this type of laser is expensive and bulky.

The most widely used highly coherent lasers at present are narrow-linewidth fiber lasers and laser diodes. The low-frequency $1/f$ noise dominated the laser phase noise in the 1980s, which caused the phase noise of the single-mode laser diode to increase linearly with the OPD from 1 to 1000 mm^[1]. Commercially available single-mode laser diodes at present with reduced $1/f$ noise are starting to exhibit narrow-linewidth fiber laser performance^[4,5]. But the relationships between the phase noise and the OPD of narrow-linewidth fiber laser and laser diode, to our best knowledge, have not been

reported yet.

In this letter, we measure the phase noises of a distributed feedback (DFB) fiber laser (Basik module E15 from NKT Inc.) and an external-cavity laser diode (RIO ORION module from Redfern Inc.). Both laser represent the state-of-the-art laser technology at present. The NKT fiber laser has a linewidth of 95 kHz, whereas the RIO laser diode has a linewidth of 60 kHz^[5]. The phase noises of the two lasers at various OPDs are measured at low frequencies (less than 100 kHz) using unbalanced Michelson interferometers. Results indicate that the two lasers present different relative phase-noise levels at OPDs longer and shorter than 10 m.

Figure 1 shows the measurement setup. Light from the tested laser firstly passes through an optical isolator to prevent feedback. An unbalanced Michelson interferometer with Faraday rotating mirrors (FRMs) is used to avoid polarization fading and to ensure high interferometric visibility. A piezoelectric (PZT) fiber stretcher is incorporated into one of the interferometer arms to introduce phase modulation. Various OPDs from 1 to 100 m are obtained by changing the length of the delay fiber. The interferometer is packaged and shielded in a housing specifically designed for environmental acoustic and thermal noise isolation. An optical phase demodulator (OPD-4000 from Optiphase Inc.) is used to provide the sinusoidal modulation voltage and to demodulate phase noise based on phase-generated carrier (PGC) technique simultaneously. This approach can measure laser phase noise because of its low self noise (few $\mu\text{rad}/\sqrt{\text{Hz}}$)^[3].

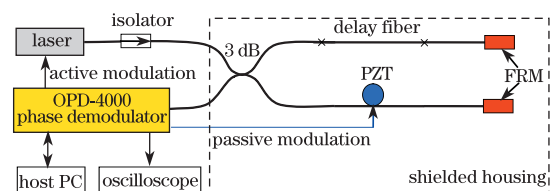


Fig. 1. Setup for laser phase noise measurement based on an

unbalanced Michelson interferometer.

Both lasers can receive direct optical frequency modulation (i.e., active modulation), which is useful for remote passive interrogation of interferometric sensing based on the PGC technique^[7]. Figure 2 illustrates the phase noises of the two lasers at active modulation frequency of 20 kHz, which are measured at OPDs of 1 and 100 m, respectively. Note that 0 dB/sqrt (Hz) is equal to 1 rad/sqrt (Hz). The fiber laser has lower phase noise levels at ultra-low frequencies (below 200 Hz) compared with the laser diode at OPDs of 1 and 100 m. However, the laser diode has a lower phase noise level at OPD of 1 m at high frequencies (beyond 200 Hz), whereas the fiber lasers behave better at OPD of 100 m. The lasers in the experiments are placed on the table unshielded, which makes these lasers susceptible to low-noise ambient disturbances. Furthermore, laser diodes are more sensitive to thermal disturbance than fiber lasers. The signal frequency of several interferometric sensors like fiber hydrophones is usually around 1 kHz. Thus, the phase noise level frequency of 1 kHz is adopted to obtain the relationship between laser phase noise and the OPD. The effects of low-frequency ambient disturbances on laser performance can be neglected at such a high frequency.

Figure 3 shows the phase noises at 1 kHz of the two lasers at various OPDs with measured data and fitted curves. The phase noises from the two lasers do not increase linearly with the OPD over the range from 1 to 100 m. Therefore, Eq. (1) is not applicable for these

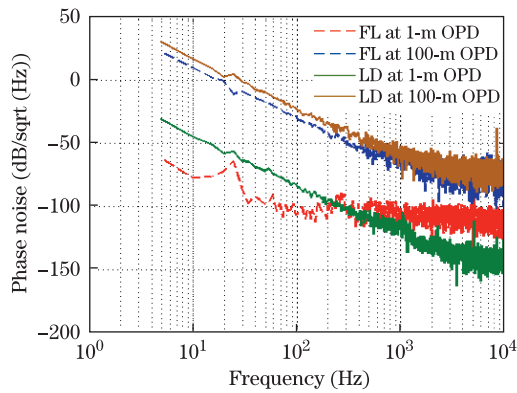


Fig. 2. Phase noise comparison of the two lasers at OPDs of 1 and 100 m, respectively. FL: fiber laser; LD: laser diode.

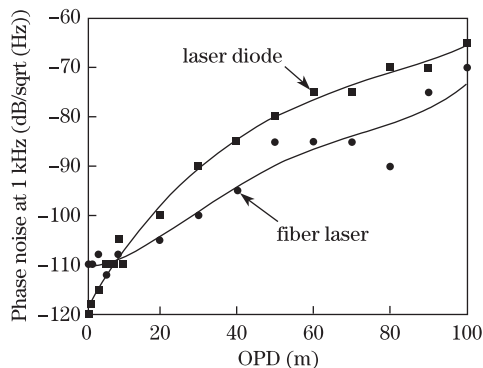


Fig. 3. Phase noises at 1 kHz of the two lasers versus the OPD with active modulation.

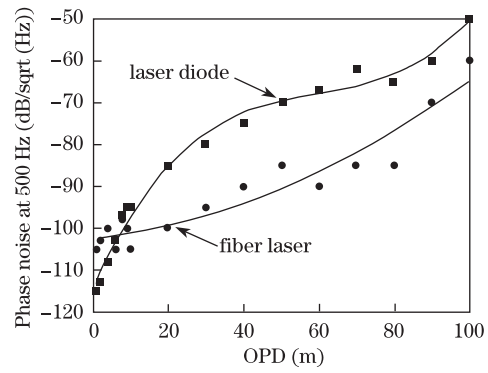


Fig. 4. Phase noises at 500 Hz of the two lasers versus the OPD with active modulation.

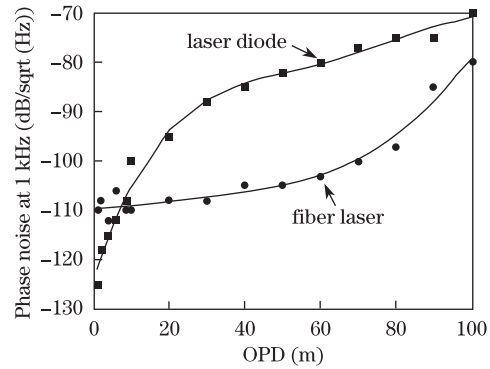


Fig. 5. Phase noises at 1 kHz of the two lasers versus the OPD with passive modulation.

narrow-linewidth lasers. The fiber laser denotes lower phase noises than the laser diode at OPDs longer than 10 m. On the contrary, the laser diode exhibits lower phase noises at OPDs shorter than 10 m. The phase noise of the laser diode increases almost linearly with an OPD shorter than 10 m, which is similar to previous measurements at an OPD shorter than 1 m^[1]. In contrast, the fiber laser maintains an almost constant phase noise level of -110 dB/sqrt (Hz) with an OPD shorter than 10 m.

The laser phase noise decreased at an approximate rate of $1/f^{1/2}$ over a frequency range from 10 Hz to 100 kHz^[6]. This result is confirmed in Fig. 2, which indicates that the laser phase noise at other frequencies have the similar results as those obtained at a frequency of 1 kHz. This result is verified by phase noises at 500 Hz of the two lasers in Fig. 4, using measured data and fitted curves.

The optical frequency modulation above is achieved by tuning the cavity length of the fiber laser and the drive current of the laser diode. The measured phase noises of the two lasers under active modulation are affected by their different modulation performances. Thus, the phase noise of the fiber laser fluctuates with the OPD as shown in Figs. 3 and 4. However, this result does not mean that the fiber laser is worse than the laser diode. Therefore, we used the PZT rather than the lasers to introduce the necessary modulation for the PGC technique (i.e., passive modulation) to assess the performance of the lasers accurately. The modulation frequency was recorded at 20 kHz. Figure 5 shows the phase noises at 1 kHz of the two lasers versus the OPD, with measured

data and fitted curves. These results are similar to those measured under active modulation. Figure 5 shows that the phase noise of the laser diode is -70 dB/sqrt (Hz) at an OPD of 100 m, which is normalized to a value of -110 dB/sqrt (Hz) at an OPD of 1 m based on Eq. (1). This value is 15 dB higher than the directly measured -125 dB/sqrt (Hz) at an OPD of 1 m. If the laser is assessed by using the phase noise normalized from that measured at 100-m OPD, the conclusion will be opposite to that directly measured at 1-m OPD. Thus, it is inaccurate to assess a laser based on the phase noise at OPD of 1 m that was normalized from the value measured at a longer OPD.

In conclusion, the phase noises of two narrow-linewidth fiber laser and laser diode at various OPDs are measured by using an unbalanced Michelson interferometers. The results measured under active and passive modulation indicate that the laser phase noise does not increase linearly with the OPD over the range from 1 to 100 m. The fiber laser has lower phase noises compared with the laser diode at OPDs longer than 10 m. However, opposite results are obtained at OPDs shorter than 10 m. The use of phase noise at 1-m OPD that is normalized from that measured at a long OPD cannot accurately assess laser performance. Selecting lasers for practical applications

should be based on the particular requirement, such as the OPD of the interferometric sensing system.

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