

# Distributed Vibration Sensor With Laser Phase-Noise Immunity by Phase-Extraction $\phi$ -OTDR

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**Abstract:** We have demonstrated a distributed vibration sensor based on phase-sensitive optical time-domain reflectometer ( $\phi$ -OTDR) system exhibiting immunity to the laser phase noise. Two laser sources with different linewidth and phase noise levels are used in the  $\phi$ -OTDR system, respectively. Based on the phase noise power spectrum density of both lasers, the laser phase is almost unchanged during an extremely short period of time, hence, the impact of phase noise can be suppressed effectively through phase difference between the Rayleigh scattered light from two adjacent sections of the fiber which define the gauge length. Based on the phase difference method, the external vibration can be located accurately at 41.01 km by the  $\phi$ -OTDR system incorporating these two lasers. Meanwhile, the average signal-to-noise ratio (SNR) of the retrieved vibration signal by using Laser I is found to be  $\sim 37.7$  dB, which is comparable to that of  $\sim 37.5$  dB by using Laser II although the linewidth and the phase noise level of the two lasers are distinct. The obtained results indicate that the phase difference method can enhance the performance of  $\phi$ -OTDR system with laser phase-noise immunity for distributed vibration sensing, showing potential application in oil-gas pipeline monitoring, perimeter security, and other fields.

**Keywords:** Distributed vibration sensing; optical time domain reflectometer; fiber sensor; phase noise

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## 1. Introduction

As one of the typical optical fiber sensors for distributed vibration sensing, a phase-sensitive optical time-domain reflectometer ( $\phi$ -OTDR) has been demonstrated as a promising technique due to its high sensitivity, wide monitoring range, and accurate locating capacity, and thus it is widely

applied in fields of oil-gas pipeline monitoring, perimeter security, and so on [1–4]. In particular, phase extraction of  $\phi$ -OTDR not only enables the accurate locating of external vibration, but also develops a linear measurement on external vibration signal [5–11]. Generally, an  $\phi$ -OTDR system has critical requirement of laser source because the phase noise of laser source could affect the phase

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measurement of external signal. Recently, the effect of phase noise of laser source on the performance of distributed vibration sensors has been extensively investigated. Alekseev *et al.* have experimentally verified that the presence of intensity noise caused by laser phase noise in  $\phi$ -OTDR fundamentally limits the sensitivity of the  $\phi$ -OTDR system to external phase vibration [12]. Moreover, optical phase suffers from phase noise originating from the finite coherence length of laser source even if a narrow linewidth laser is used in the  $\phi$ -OTDR system [13, 14]. Since phase noise can be accumulated over the entire round-trip, the associated growth of phase noise leads to a sharp decrease in signal-to-noise ratio (SNR), and as a result, the measurement range is limited [15, 16]. In a heterodyne detection  $\phi$ -OTDR, Pan *et al.* have calculated the phase difference by a pair of positions with a certain interval for locating the external vibration [5]. Remarkably, the presence of laser phase noise results in an unexpected phenomenon that the demodulated phase traces diffuse randomly from pulse to pulse. Overall, a narrow linewidth laser with low frequency drift and low phase noise is believed to be required for long-distance distributed sensing in the  $\phi$ -OTDR system. Inevitably, such critical requirement of laser source increases the total cost of  $\phi$ -OTDR system.

In order to mitigate the influence of laser phase noise on the performance of the  $\phi$ -OTDR system, a number of techniques have been explored [6, 8, 10]. Liang *et al.* used the Wiener filter to reduce the phase fluctuation caused by the laser phase noise and additive noise successfully [6]. Tu *et al.* proposed a statistics based calculating method to reduce the uncertainty in phase-measuring, and the differential phase of two nearby interrogated fiber separations instead of two adjacent positions was defined to represent the phase change induced by vibration [8]. Recently, in order to compensate the total phase noise which consists of laser phase noise and phase extraction error, several auxiliary weak

reflection points are set at specific positions along the sensing fiber. Thus, additional phase signals from reflection points were introduced as reference phases to correct the Rayleigh backscattering light phase signals and phase variance-distance trace showed a significant decreasing trend around weak reflection points after phase noise compensation [10]. However, this method is relatively complicated since additional components are required to generate weak reflection and the degree of weak reflection needed to be strictly controlled. Therefore, a simple and direct method without the supplementary of optical components and complex algorithm is expected to minimize the influence of laser phase noise on system performance.

In this work, the influence of laser phase noise on the  $\phi$ -OTDR system performance has been investigated, and the immunity of laser phase-noise for distributed vibration sensing has been achieved. Two laser sources with different noise characteristics and noise power spectral densities are utilized. The linewidth of Laser I is 0.1 kHz, while that of Laser II is 2.2 kHz. Since the laser phase changes a little during an extremely short period of time, we have found that the influence of phase noise can be mitigated effectively through phase difference between the Rayleigh scattered light from two adjacent sections of the fiber which define the gauge length. By using such a phase differentiating technique, the location of external vibration by using two lasers can be obtained accurately at 41.01 km. Meanwhile, the average SNR of the retrieved signal is found to be  $\sim 37.7$  dB by using Laser I, which is comparable to that of  $\sim 37.5$  dB by using Laser II. Therefore, the performance enhancement of  $\phi$ -OTDR system with immunity of laser phase noise for distributed vibration sensing is achieved without any supplementary of optical components and complex algorithm. The obtained results show a general guidance for choosing a proper narrow linewidth laser source in distributed vibration sensing systems based on  $\phi$ -OTDR.

## 2 Principle of enhancing laser phase-noise immunity in $\phi$ -OTDR system

The optical field output of a single-frequency laser source can be expressed as

$$E(t) = E_0 \exp[j(2\pi f_0 t + \varphi(t))] \quad (1)$$

where  $E_0$  is the optical amplitude which can be assumed to be constant, and  $f_0$  and  $\varphi(t)$  refer to central optical frequency and random phase fluctuation representing the phase noise, respectively. As  $\varphi(t)$  is the random process, the phase noise level is characterized by the power spectral density (PSD) of  $S_\varphi(f)$  [17, 18], which provides statistical properties in the frequency domain. The phase noise of a single-frequency laser source essentially includes  $1/f$  noise at low frequencies and white noise at high frequencies [19–24], and the single-sideband phase noise PSD is given in a polynomial form as [25]

$$S_\varphi(f) = \frac{\delta_v}{\pi f^2} + \frac{k_f}{f^3} + \frac{k_r}{f^4} \quad (2)$$

where  $\delta_v$  represents the Lorentzian spectral linewidth of the laser, and  $k_f$  and  $k_r$  are constant coefficients of  $1/f$  frequency noise and random walk frequency noise, respectively. The total phase noise could be estimated by an integration of  $S_\varphi(f)$  over the all frequency range.

A phase difference  $\Delta\varphi(t)$  with a time delay of  $\tau$  is introduced to suppress the phase noise which is given as

$$\Delta\varphi(t) = \varphi(t) - \varphi(t - \tau) = \varphi(t) \otimes h(t) \quad (3)$$

where  $h(t)$  is the impulse response expressed as follows:

$$h(t) = \delta(t) - \delta(t - \tau). \quad (4)$$

The convolution of a random process and an impulse response produces an output PSD ( $S_{\Delta\varphi}(f)$ ) as

$$\begin{aligned} S_{\Delta\varphi}(f) &= H(f) \times H^*(f) \times S_\varphi(f) \\ &= (1 - e^{-j2\pi f\tau}) \times (1 - e^{j2\pi f\tau}) \times S_\varphi(f) \end{aligned} \quad (5)$$

when the factors of  $e^{-j\pi f\tau}$  and  $e^{j\pi f\tau}$  are taken out, we can get as follows:

$$S_{\Delta\varphi}(f) = [2 \sin(\pi f\tau)]^2 S_\varphi(f) \quad (6)$$

where  $S_{\Delta\varphi}(f)$  is determined by both  $S_{\Delta\varphi}(f)$  and  $[2 \sin(\pi f\tau)]^2$ . For a small value of  $\tau$  (for example,  $\tau = 0.3 \mu\text{s}$ ), the PSD  $S_{\Delta\varphi}(f)$  at frequency lower than 500 kHz will be suppressed, and thus the total phase noise can be significantly reduced. In this work, the mechanism of enhancing laser phase noise immunity is based on the phase difference that the total phase noise is comparable with an extremely short  $\tau$  even though the laser sources have different noise levels.

## 3. Experimental setup

Figure 1 shows the experimental setup of distributed vibration sensing system based on  $\phi$ -OTDR. The optical output power of each laser source is 20mW and is separated into two branches by a 90:10 coupler, 90% of the light as the probe light and 10% of the light as the local reference light. The probe light is modulated into a pulse form with a frequency shift of 200MHz by the acoustic-optic modulator (AOM). The pulse width is 100 ns, and the repetition rate is 1.5 kHz. An erbium-doped fiber amplifier (EDFA) is set in optical path to increase the peak power of the pulse light for enhancing the intensity of Rayleigh backscattering light along the sensing fiber. External vibration source is simulated by a piezo transducer (PZT) that is coiled with sensing fiber. An electrical signal generator (ESG) drives the PZT. The Rayleigh backscattering light is mixed with the local reference light in the optical coupler. The beat signal is then injected into a balanced photo-detector (BPD). The output signal of BPD is sampled by a high-speed data acquisition (DAQ, 8-bit, 1 GS/s). The signal processing is completed in a personal computer and the in-phase-quadrature (I/Q) demodulation enables the extraction of the phase of Rayleigh backscattering light. A two-channel arbitrary function generator (AFG) is used to drive the AOM and provides radio frequency (RF) signal to trigger the DAQ for synchronized acquisition.

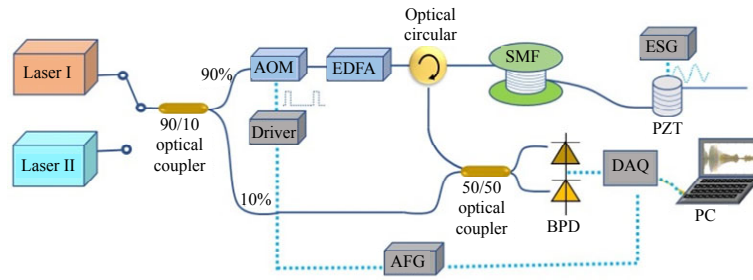


Fig. 1 Experimental setup of  $\phi$ -OTDR: acoustic-optic modulator (AOM), arbitrary function generator (AFG), erbium-doped fiber amplifier (EDFA), single-mode fiber (SMF), electrical signal generator (ESG), piezo transducer (PZT), balanced photo-detector (BPD), data acquisition (DAQ), and personal computer (PC).

Before conducting vibration sensing experiments, we compare the PSD of the applied two commercial laser sources. Laser I has linewidth of about 0.1 kHz that is greatly narrower than that of Laser II which is 2.2 kHz at wavelength of 1550.12. Since the coherence length of laser source is inversely proportional to the linewidth, the coherence length is estimated to be  $\sim 3000$  km and  $\sim 136$  km for Laser I and Laser II, respectively. Figure 2 shows the PSD of Laser I and Laser II, which is measured by unbalanced Michelson interferometer composed of a  $3 \times 3$  optical fiber coupler [17]. The range of Fourier frequency extends from 1 Hz to 1 MHz limited by the detectable bandwidth of the test system. From Fig. 2, the noise feature of Laser I is better than that of Laser II at frequency larger than 1 kHz.

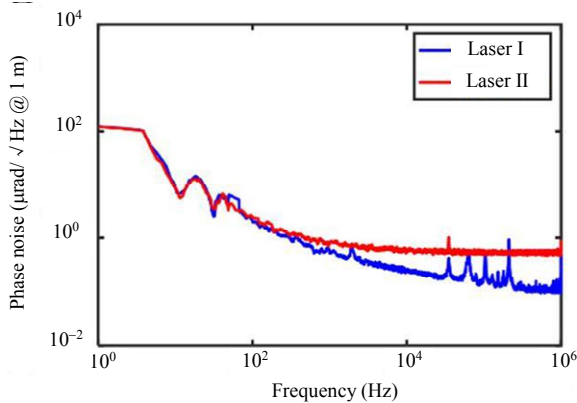


Fig. 2 Measurements of the phase noise PSDs of Laser I with the linewidth of 0.1 kHz and Laser II with the linewidth of 2.2 kHz.

#### 4. Experimental results and discussion

In the experiment, the length of sensing fiber is about 45 km. To simulate the external disturbance, a

PZT located at 41.01 km is driven by a cosine voltage signal of 80 Hz while 2-m-long fiber is wrapped on it. 75-consecutive Rayleigh backscattering traces are acquired. Under the same conditions, Laser I and Laser II are used to verify the proposed theory successively. By using the orthogonal demodulation method, the amplitude and the phase can be extracted [11]. The phase difference  $\delta\phi(z)$  of the demodulated phase at two neighboring locations ( $\delta z$ ) along the sensing fiber is calculated as follows:

$$\delta\phi(z) = \phi(z) - \phi(z + \delta z). \quad (7)$$

The external vibration can be found at location of  $z$  where a peak exists at the differential phase trace,  $|\delta\phi(z)| > 0$ , while  $\delta\phi(z) \approx 0$  if there is no vibration. In this experiment,  $\delta z = 10$  cm based on the sampling rate of DAQ is used to calculate the phase difference  $[\delta\phi(z)]$  for locating the external vibration. Figures 3(a) and 3(b) show the standard deviation (SD) of phase difference  $\delta\phi(z)$  for 75-consecutive traces of Laser I and Laser II, respectively. The peaks at 40.01 km are recognized as the vibration peaks by the comparison of the demodulated phase before and after these peaks [11]. A few undesired peaks are observed due to the fading effect, but they can be effectively ignored by our proposed fading-discrimination method [11].

After locating the external vibration, the phase information of vibration signal is further obtained by the phase difference. The phase change within a gauge length ( $\Delta z$ ) can be expressed as

$$\Delta\varphi(z) = \varphi(z + \Delta z/2) - \varphi(z - \Delta z/2) = \theta_r(z) \quad (8)$$

which is linearly associated with the strain induced by the external vibration. Since there is a phase accumulation process when the pulse light passes through the vibration area, gauge length must be larger than the sum of perturbation area (2 m) as well as the region influenced by the perturbation. As the space occupied by a probe pulse is 20 m, the region influenced by the perturbation covers from 10 m before the perturbation area to 10 m after the perturbation area, and thus  $\Delta z$  should be taken more than 22 m. Figure 4(a) plots the vibration signals extracted from the  $\varphi$ -OTDR system incorporating two different lasers when  $\Delta z = 30$  m that is an equivalent of time delay of  $\sim 0.15 \mu\text{s}$ . Each temporal phase difference trace presents a clear sinusoidal variation over time. Figure 4(b) shows the corresponding fast Fourier

transformation (FFT) of the two vibration signals, showing all two peaks appear at 80 Hz. In order to compare the quality of the extracted vibration signal by phase difference method for two different laser sources, their SNRs are calculated. Here the SNR is defined as the amplitude ratio between the signal peak amplitude and the background noise level according to the spectrum of signal  $SNR = 20\lg(A_s/A_n)$ , where  $A_s$  is the amplitude of the signal and  $A_n$  is the root mean square of the signal of the background noise) [9, 26]. The SNRs are calculated to be 37.1 dB and 38.9 dB for Laser I and Laser II, respectively. Such comparable SNR indicates that the phase difference method could enhance the performance of  $\varphi$ -OTDR with laser phase-noise immunity for distributed vibration sensing without the supplementary of optical components and complex algorithm.

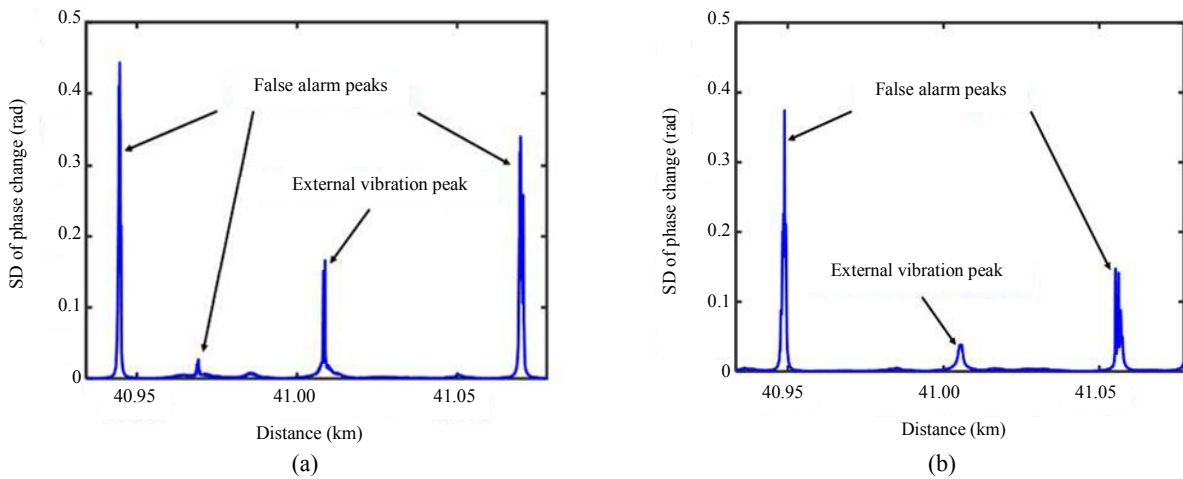


Fig. 3 Location information by calculating the standard deviation (SD) of phase difference for 75-consecutive traces of (a) Laser I and (b) Laser II.

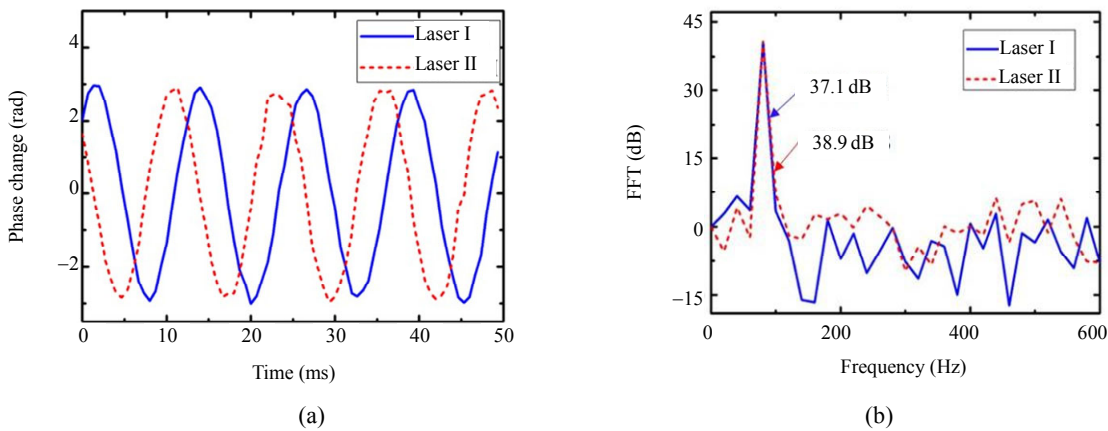


Fig. 4 Comparison of recovered external vibration signal of Laser I and Laser II ( $\Delta z = 30$  m): (a) the time domain waveforms and (b) the corresponding FFT of the vibration signals.

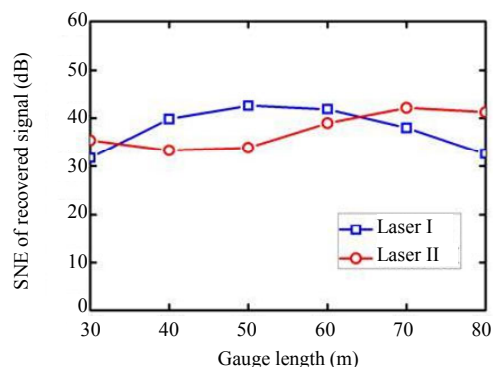


Fig. 5 SNR variation arising from gauge length with a range of 30 m–80 m.

In order to prove the enhancement of laser phase-noise immunity by the phase difference method, we have investigated the  $\phi$ -OTDR system incorporating two different lasers by extending the gauge length to 80 m that is a few times longer than the distance occupied by the probe pulse and the vibration event. As shown in Fig. 5, the SNRs are all above 30 dB and they are comparable for Laser I and Laser II at the same gauge length. For  $30\text{ m} < \Delta z < 80\text{ m}$ , the average SNRs of Laser I and Laser II are about 37.7 dB and 37.5 dB, respectively. The experimental results confirm that the phase noise can be suppressed efficiently by the phase difference method for a relatively wide range of gauge length. In the circumstances, the cross talk from temperature fluctuation exists, and the gauge length can be chosen with a relatively small value so that the phase accumulation originated from temperature within the gauge length is mitigated by the phase difference method. Moreover, in some practical applications such as the broader fence, the frequency change of temperature behaves differently from that of vibration, as the former is generally a slow change and the latter is a fast change. Therefore, a high-pass filter following the phase difference algorithm can be included in order to extract the phase accurately. Based on the proposed effective method for enhancing laser phase-noise immunity, the cost of the  $\phi$ -OTDR system is expected to be greatly reduced, and the method could be compatible to all  $\phi$ -OTDR system, showing

potential application in oil-gas pipeline monitoring, perimeter security, and other fields.

## 5. Conclusions

In conclusion, we have demonstrated an  $\phi$ -OTDR system with laser phase-noise immunity based on phase extraction for distributed vibration sensing. By analyzing the phase noise characteristics of laser source, we have found that the phase noise changes slightly during a very short period of time. The influence of phase noise of laser source is mitigated efficiently by the phase difference method. An external vibration at 41.01 km is located accurately, and the average SNR of the restored signal by using the laser source with a linewidth of 0.1 kHz is about 37.7 dB compared with the SNR of 37.5 dB with a linewidth of 2.2 kHz. Compared with previous works [8, 10], neither complex calculation nor any additional components are required. The obtained results provide a useful guidance for choosing a proper narrow linewidth laser source in the actual engineering applications.

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