# Influences of frequency drift of laser source on phase sensitivity optical time domain reflectometer

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**Abstract:** The influences of frequency drift of laser source on phase sensitivity optical time domain reflectometer($\varphi$-OTDR) was investigated. One-dimensional pulse-response model of Rayleigh backscattering in a single-mode fiber was employed to analyze the trace-to-trace fluctuations induced by frequency drift. In laboratory test, an unbalanced Mach-Zehnder interferometer (MZI) with path-length difference of 100 m was employed to monitor the frequency drift real-time, and the performances of φ-OTDR system using three lasers with different frequency drift rate were compared to testify the theoretical analysis. Both the theoretical and the experimental results show that the frequency drift of laser source is an important source for the fluctuations of $\varphi$-OTDR waveform, and the trace-to trace fluctuations increase as the growing of frequency drift. Moreover, it is difficult to distinguish the fluctuations induced by frequency drift and the fluctuations induced by intrusion event in time-domain when the frequency drift is up to several hundreds of MHz/min. However, the differences between them are more evident in frequency-domain. The conclusion is useful for choosing laser sources and improving the performance of $\varphi$-OTDR.

**Key words:** frequency drift; phase sensitivity optical time domain reflectometer($\varphi$-OTDR); fiber-optic distributed disturbance sensor(FDDS)

**CLC number:** TN29 **Document code:** A **Article ID:** 1007-2276(2016)01-0091-05

# 激光器频率漂移对相位敏感光时域反射计性能影响研究

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**摘 要:** 针对激光器频率漂移对相位敏感光时域反射计($\varphi$-OTDR)的性能影响,文中采用后向瑞利散射的一维脉冲响应模型对其进行了理论分析。在实验室测试中,搭建了臂长差为 100 m 的非平衡 MZ 干涉仪来实时监测激光器的频率漂移;并通过测试三种不同频率漂移的激光器下的 $\varphi$-OTDR 系统性能验证了理论分析的正确性。理论分析及实验结果表明,激光器的频率漂移是引起 $\varphi$-OTDR 曲线波动的重要因素,频率漂移越大,其引起的 $\varphi$-OTDR 曲线波动就越大;当频率漂移高达几百 MHz/min 时,在时域上已难以区分出是频率漂移引起的扰动还是入侵事件引起的扰动,但仍能在频域中将频率漂移噪声分辨出来。

**关键词:** 频率漂移; 相位敏感光时域反射计($\varphi$-OTDR); 光纤分布式扰动传感器

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**收稿日期:** 2014-05-20; **修订日期:** 2014-06-22

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## 0 Introduction

Fiber-optic distributed disturbance sensor (FDDS) is regarded as an excellent technology for perimeter security of border and pipeline due to its advantages such as long sensing range, high sensitivity, electromagnetic interference immunity, low cost and working without field power[1-2]. The FDDS based on $\varphi$-OTDR attracts a lot of interests in recent years as it can locate multiple intrusion events simultaneously.

$\varphi$-OTDR has been widely investigated since it is proposed in 1993[3]. Park demonstrated the effectiveness of $\varphi$-OTDR with semiconductor laser and acousto-optic modulator (AOM), the sensing range is 6 km and spatial resolution is 400 m[4]. Later, by using frequency stabilized Er-doped fiber Fabry-Perot laser, the sensing range had been improved to 19 km with spatial resolution of 100 m[5-6]. Bidirectional Raman amplification technology is adopted to extend the sensing range to 62 km at the spatial resolution of 20 m[7]. A system based on all-polarization maintaining configuration was reported, by using the heterodyne detection technology and signal processing of moving averaging and moving differential, the spatial resolution had been improved to 1 m and detectable frequency range is increased to 2.25 kHz with sensing range of 100 m[8-9].

Configuration of $\varphi$-OTDR is similar to conventional OTDR except the laser. In conventional OTDR, a laser with very broad line width (gigahertz-to-terahertz range) is used to avoid fluctuations in the return signal owing to interference of backscattered components from different parts of the fiber. In contrast, $\varphi$-OTDR is designed to enhance coherent effects rather than avoid them. As a result, a laser with narrow line width is critical for $\varphi$-OTDR. Due to the enhanced coherent effects, frequency drift of the laser causes trace-to-trace fluctuations in the $\varphi$-OTDR waveform and can obscures the effect of an intrusion event. In this paper, one-dimensional pulse-response model of Rayleigh backscattering in a single-mode fiber is employed to analyze the fluctuations induced by the frequency drift of laser source and the laboratory tests are established by three lasers with different frequency drift rate to testify the theoretical analysis.

## 1 Principle

In a $\varphi$-OTDR system, light pulses are injected into one end of a fiber, and Rayleigh backscattering light returned from the fiber is monitored with a photodiode. As shown in Fig.1, suppose the light pulses are monochromatic light with rectangular pulses, and the coherent time of the laser is much longer than the pulse width. According to the one-dimensional pulse-response model of Rayleigh backscattering in a single-mode fiber[10], the field amplitude of the Rayleigh backscattering light can be represented by

$$e(t)=\sum_{i=1}^{N} a_i \exp\left(-\frac{\alpha}{2}\frac{c\tau_i}{n}\right)\exp[\mathrm{j}2\pi\upsilon(t-\tau_i)]\mathrm{rect}\left(\frac{t-\tau_i}{w}\right) \quad (1)$$

where $N$ is the number of scattering center, $a_i$ is the amplitude of backscattering wave with the code number of $i$, $\alpha$ and $n$ are attenuation coefficient and refractive index of the fiber, $c$ is the velocity of light in vacuum, $\tau_i=2nl_i/c$ is the time delay of backscattering wave with the code number of $i$. Then the optical power of the Rayleigh backscattering light $I(t)$ can be described as:

$$I(t)=I_c(t)+I_v(t) \quad (2)$$

$$I_c(t)=\sum_{i=1}^{N} a_i^2 \exp\left(-\alpha\frac{c\tau_i}{n}\right)\mathrm{rect}\left(\frac{t-\tau_i}{w}\right) \quad (3)$$

$$I_v(t)=2\sum_{i=1}^{N}\sum_{j=i+1}^{N} a_i a_j \exp\left[-\frac{\alpha}{2}\frac{c(\tau_i+\tau_j)}{n}\right]\cos[2\pi\upsilon(\tau_i-\tau_j)]\cdot \mathrm{rect}\left(\frac{t-\tau_i}{w}\right)\mathrm{rect}\left(\frac{t-\tau_j}{w}\right) \quad (4)$$

where $I_c(t)$ represents the sum of the optical power of every independent backscattering center, which provides the conventional OTDR waveform, $I_v(t)$ is induced by the interference of different backscattering center in pulse width. In conventional OTDR, $I_v(t)$ is ignored ordinarily because of the broad spectrum width of the laser.

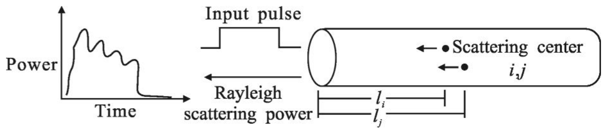


Fig.1 Schematic of Rayleigh backscattering power based on φ-OTDR technology

However, in φ-OTDR system, in which a highly coherent laser is used, $I_v(t)$ produces saw-tooth fringe in backscattering waveform. The saw-tooth fringe comes from the cosine functional item $\cos[2\pi\upsilon(\tau_i-\tau_j)]$. $\varphi_{ij}=2\pi\upsilon(\tau_i-\tau_j)$ is the phase difference of two backscattering waves with code number of $i$ and $j$, $\varphi_{ij}$ can also be described as

$$\varphi_{ij}=2\pi\upsilon(\tau_i-\tau_j)=4\pi\upsilon n(l_i-l_j)/c \quad (5)$$

From Eq. (5), we can see that the phase difference relates to the light frequency $\upsilon$ and the attenuation coefficient $n$. When an intrusion event occurs near the sensing fiber, $n$ varies due to the elasto-optical effect, then the phase difference is changed, it can be wrote as $\varphi_{ij}=4\pi\upsilon(n+\Delta n)(l_i-l_j)/c$. The change of $\varphi_{ij}$ results in the change of $I_v(t)$.

Nevertheless, $I_v(t)$ varies even if no intrusion event occurs because of frequency drift of the laser. If the frequency drift is $\Delta\upsilon$, the phase difference change can be wrote as $\varphi_{ij}=4\pi\Delta\upsilon n(l_i-l_j)/c$. In φ-OTDR system, pulse width is usually from several hundreds of nanoseconds to several microseconds, then the $(l_i-l_j)_{max}$ is from tens to hundreds of meters. It means that several MHz shift, even several hundreds of kHz shift of light frequency may result in π phase difference. Therefore the frequency drift of the laser is a very important parameter for φ-OTDR, it can obscures the effect of an intrusion event, even result in failure of the system.

## 2 Experiment

Different frequency drift is employed in the laboratory tests, and an unbalanced MZI with path length difference of 100 m is used to monitor the frequency drift real-time. Trace-to-trace fluctuations in the φ-OTDR waveform caused by frequency drift are analyzed, respectively, and compared with the fluctuations induced by intrusion event.

### 2.1 Experiment configuration

The setup of φ-OTDR with unbalanced MZI is shown in Fig.2. Light from the CW laser source is split into two parts through a 95:5 coupler. 95% part is modulated by an acoustic-optic modulator (AOM) with 200 MHz frequency shift. The pulses with a 10 kHz repetition and 5 μs pulse width is gated into sensing fiber via a circulator. The backscattered light from the sensing fiber pass through the circulator and is detected by photodiode 2 (PD2). Another part is gated into an unbalanced MZI with path length difference of 100 m and then detected by PD1. Finally, the signals from PD1 and PD2 are imported into data processor.

Unbalanced MZI is used to monitor the frequency drift $\Delta\upsilon$, as $\Delta\upsilon$ results in phase difference $\Delta\Phi=2\pi\Delta\upsilon n\Delta l/c$ with $\Delta l$ being the path length difference. In the present case, $\Delta l=100$ m so that one fringe (radian phase shift) corresponds to a 2 MHz frequency change[5].

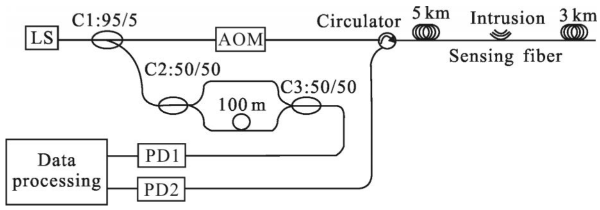


Fig.2 Experimental setup for φ-OTDR with unbalanced MZI. LS: Laser source; AOM: acoustic optical modulator; PD1, PD2: photodiode 1 and 2.

The sensing fiber consists of two spools of single-mode fiber (5 and 3 km) with a single-mode fiber optic cable of 3 m. Two spools of sensing fiber and the MZI are insulated from acoustic effects by placing them in sealed chests with multiple layers of foam board, respectively. Intrusion event is simulated by beating the fiber cable of 3 m.

### 2.2 Experiment results

Three narrow line width laser sources with different frequency drift are used in the experiment, respectively. Laser 1 is the Rock Fiber Laser Module produced by NP Photonics, the output wavelength is 1 550.8 nm and the line width is 5 kHz. Laser 2 is the Rock Fiber Laser Source produced by NP Photonics, the output wavelength is 1 549.9 nm and the line width is 5 kHz. Laser 3 is the Basik Module produced by NKT Photonics, the output wavelength is 1 550.1 nm and the line width is 1 kHz.

Frequency drift of not very high in general (1.5 fringes in 2 s corresponds to 90 MHz/min) but shaking drastically in detail is generated by Rock Fiber Laser Module which is produced in NP Photonics. The total frequency drift is up to several hundreds of MHz/min. The drastic frequency drift results in heavily fluctuations in the $\varphi$-OTDR waveform and obscures the effect of an intrusion event, as shown in Fig.3. However, distinctions of the intrusion event are still discovered in frequency domain, especially in the range of about 20–80 Hz, as shown in Fig.4.

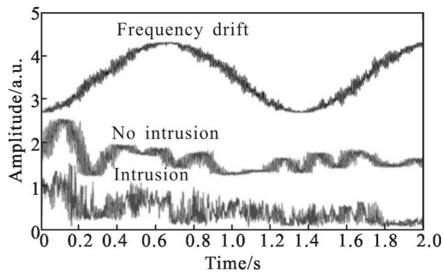


Fig.3 Frequency drift and the response of $\varphi$-OTDR over a time period of 2 s at range of 5 km with and without disturbance when using the first laser

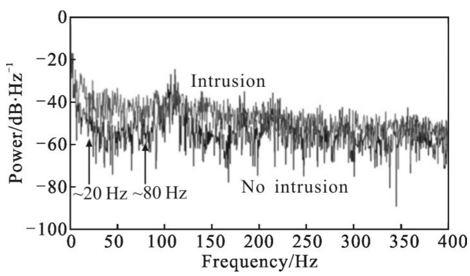


Fig.4 Frequency response at range of 5 km with and without disturbance when using the first laser

Instability frequency drift is generated by Rock Fiber Laser Source which is produced in NP Photonics. From Fig.5, it can be seen that the frequency drift varies from several tens to several hundreds of MHz/min. Instability frequency drift results in unstable fluctuations of the $\varphi$-OTDR waveform, which are quite different with the fluctuations induced by intrusion event. The frequency range of fluctuations caused by frequency drift is lower than 50 Hz while another is up to hundreds of Hz, as shown in Fig.6.

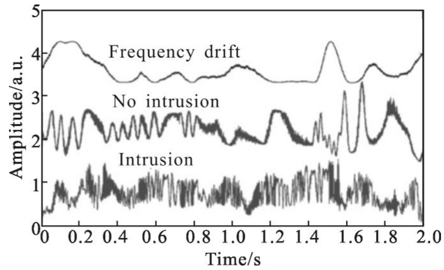


Fig.5 Frequency drift and the response of $\varphi$-OTDR over a time period of 2 s at range of 5 km with and without disturbance when using the second laser

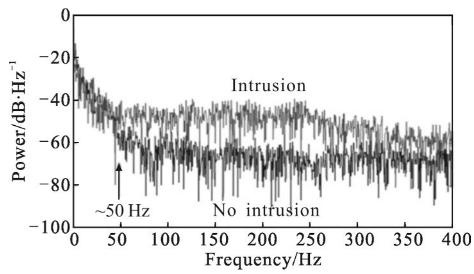


Fig.6 Frequency response at range of 5 km with and without disturbance when using the second laser

Very stable frequency is generated by the Basik Module which is produced in NKT Photonics. The frequency is so stable that only a fraction of a temporal fringe can be observed in 2 s by the unbalanced MZI with path length difference of 100 m, as shown in Fig.7. We estimate the frequency drift is just

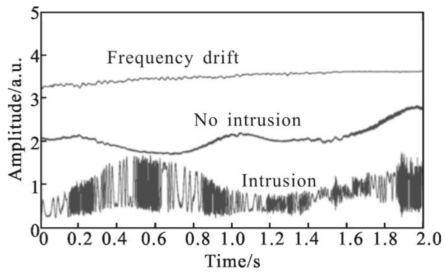


Fig.7 Frequency drift and the response of $\varphi$-OTDR over a time period of 2 s at range of 5 km with and without disturbance when using the third laser

several MHz/min. Due to the low frequency drift, the $\varphi$–OTDR trace is very stable, the band of fluctuations caused by frequency drift is reduced to about 20 Hz, as shown in Fig.8.

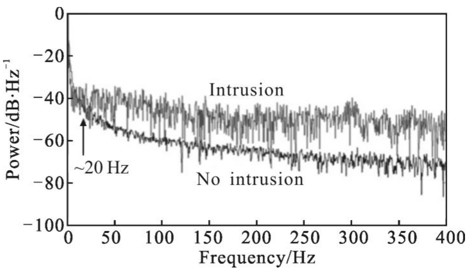


Fig.8 Frequency response at range of 5 km with and without disturbance when using the third laser

## 3 Conclusion

One-dimensional pulse-response model of Rayleigh backscattering in a single-mode fiber is employed to analyze the influences of frequency drift of the laser on $\varphi$–OTDR. Different kinds of frequency drift (drift of 90 MHz/min in general but shaking drastically in detail, instability drift from several tens to several hundreds of MHz/min, drift of low and stable) are generated respectively in laboratory tests. Experimental results show that, trace-to-trace fluctuations decrease with the reduction of frequency drift. Differences still can be found in frequency domain even the frequency is up to several hundreds of MHz/min. However, a laser with low frequency drift is still very important for $\varphi$–OTDR to achieve high signal to noise ratio, especially in the application of perimeter security for natural gas and oil pipeline where the sensing fiber is buried in soil.

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