Laser frequency drift noise reduction in fiber-optic system based on Φ-OTDR through a novel location algorithm

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Abstract: In the distributed fiber-optic disturbance sensor system based-on Φ-OTDR, the frequency drift of laser directly results in low signal to noise ratio (SNR) of the system and further influences system location. In order to reduce the disturbance location error induced by laser frequency drift, a location algorithm was proposed through analyzing the error mechanics, which combines spectrum analysis with characteristic frequency selection. The characteristic frequency for location was achieved by comparing the SNR of the system owing to different frequency. Laboratory tests were established and the results indicate that the algorithm is efficient to disturbance location for the location and the performance of system has been enhanced.

Key words: frequency drift; distributed fiber-optic disturbance sensor system based-on Φ-OTDR; spectrum analysis; location algorithm

CLC number: TN29 **Document code:** A **Article ID:** 1007-2276(2015)07-2150-06

一种新型的光纤相位 OTDR 系统频漂误差抑制算法的研究

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摘 要: 激光器的频率漂移对相位敏感光时域反射计的定位有重要的影响，其直接导致定位的信噪比下降。提出一种频谱分析结合选取特征频段的定位算法,在算法中通过选取合适的特征频段,对影响系统定位的激光器频漂进行误差抑制。特征频段的选取通过实验信噪比的高低决定。通过实验验证,结果显示该算法提高了系统定位性能并进一步提高了信噪比。

关键词: 频率漂移； 相位敏感光时域反射计； 频谱分析； 定位算法

收稿日期: 2014-11-05； **修订日期:** 2014-12-03

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0 Introduction

Distributed fiber optic sensor has advantages of wide disturbances monitoring range, high sensitivity, low cost without field power and so on. Besides those, the achieving of multi-point location makes the distributed fiber-optic disturbance sensor system based-on Φ-OTDR attract more and more attention in the development of the distribution fiber optic sensors [1]. Up to now, it is widely applied in perimeter security, pipeline transportation and communication lines fields. It executes protections for some important objects, such as aerospace bases, weapons and ammunition depots, oil and gas pipelines, boundary lines, airports, prisons, warehouses and so on[1-2].

Distributed fiber-optic disturbance sensor system based-on Φ-OTDR requires a narrow line width and minimal frequency drift laser to work as a light source. It locates the disturbance by detecting the coherent change of the backscattered Rayleigh light to interfere within the pulse duration[3]. Due to the usage of the backscattered Rayleigh light to interfere within the pulse duration in the disturbance sensing system to achieve location, it requires the light source with a very narrow line width and minimal frequency drift. Since the narrow line width laser enhance coherent effects of the system. Minimal frequency drift of laser is to avoid the fluctuation of Rayleigh backscattering waveform which could obscure the changes caused by disturbance[4], so it is a critical parameter for the system location.

With the higher performances of the system required in application, in order to inhibit the influence induced by the laser frequency drift on system location, a number of academics and institutions proceeded researches on low frequency drift of laser. They attempt to solve the frequency drift from the source where it is generated and through employing technology of frequency stabilization and optical circuit design to eliminate[5-6] it, so their research costs are relatively high. Some studies use Wiener filtering to inhibit the influence induced by the laser frequency drift on system location[5], but it is not a special method targeting the frequency drift of the laser. After all, most studies of the frequency drift are focused on the influence on the distributed fiber-optic disturbance sensor system based on Mach-Zehnder interferometer, the frequency drift problems of distributed fiber-optic disturbance sensor system based-on Φ-OTDR are rarely reported. So the paper prompts a novel location algorithm using the technology of selecting characteristic frequency to inhibit the influence induced by the laser frequency drift on system location. The technology is relatively simple and has been verified efficient through tests of the distributed fiber-optic disturbance sensor system based on Φ-OTDR.

1 Theoretical analysis

1.1 Locating mechanism

The working principle of the distributed fiber-optic disturbance sensor system based-on Φ-OTDR is to measure the index of refraction changes. It locates through measuring the delay time between the input pulse and the received pulse. When a disturbance occurs in the fiber due to the invasion and elasto-optical effect, the refractive index of the sensing fiber will change in the corresponding position, which will result in an optical phase change and fluctuation in backscattering waveform[7]. The configuration of Φ-OTDR is shown in Fig.1.

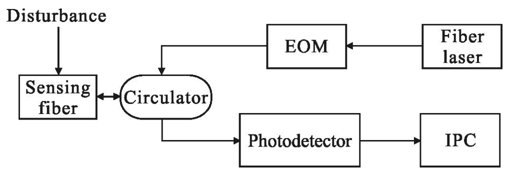

Fig.1 Location of the distributed fiber-optic disturbance sensor system based-on Φ-OTDR

1.2 Modeling analysis

After the light of narrow line width laser is modulated, the optical pulses are launched into sensing fiber, and then they issue scattering of light in all directions. In the single-mode fiber, more than double Rayleigh backscattering is ignored, it is seen as a one-dimensional pulse response model[2] as in Fig.2.

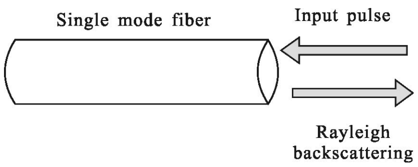

Fig.2 One-dimensional pulse response model

The field amplitude of the Rayleigh backscattering light can be represented[2,6] by:

$$y(t)=\sum_{k=1}^{N} E_s(t-\tau_k)\cdot a(\tau_k)\cdot \exp\left(-\alpha\frac{c\tau_k}{n}\right)\cdot \mathrm{rect}\left(\frac{t-\tau_k}{\omega}\right) \quad (1)$$

Where $E_s(t)$ represents the input optical signal wave function, τ_k and $a(\tau_k)$ are the k-th time delay and amplitude of the scattering respectively, ω represents the pulse width modulated, α is the fiber attenuation constant, c is the velocity of light in vacuum, n is the refractive index of the fiber, N is the total number of scatters. rect $(\cdot)$ is rectangular function, which can be described as:

$$\mathrm{rect}\left(\frac{t}{\omega}\right)=\begin{cases}1, \text{ while } 0\leqslant\frac{t}{\omega}\leqslant 1\\ 0, \text{ otherwise}\end{cases} \quad (2)$$

The optical power of Rayleigh backscattering[2,6] is:

$$p(t)=\langle|y(t)^2|\rangle=p_1(t)+p_2(t)=$$
$$\sum_{i=1}^{N} Ia^2(\tau_i)\exp\left(-2\alpha\frac{c\tau_i}{n}\right)\mathrm{rect}\left(\frac{t-\tau_i}{W}\right)+$$
$$2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} Ia(\tau_i)a(\tau_j)\exp\left[-\alpha\frac{c(\tau_i+\tau_j)}{n}\right]\cdot$$
$$\mathrm{rect}\left(\frac{t-\tau_i}{W}\right)\mathrm{rect}\left(\frac{t-\tau_j}{W}\right)\cos[(\omega_s+\alpha_f t)(\tau_j-\tau_i)] \quad (3)$$

Where $\langle\cdot\rangle$ means averaging, $I=|Es(\mathrm{t})|^2$ is the input light power, which is composed of two parts. $p_1(t)$ represents the summary of the optical power of every independent backscattering center, providing a conventional OTDR wave; $p_2(t)$ indicates the result of the interference of different backscattering center within pulse width, which has a saw-tooth waveform.

a_f is frequency drift of the laser, assuming that it changes linearly with time, τ_i, τ_j represents the transmission time to backscattering center i and j. Formula (3) is the one-dimensional pulse response model of the system.

In formula (3) the optical phase change ϕ_{ij} is crucial to system location, while ϕ_{ij} can also be described[2] as:

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

Theoretical analysis indicate that the changes of the optical phase can be induced by the locating mechanism based on elasto-optical effect or the frequency drift of laser, as shown in formula (3) and (4). And eventually the optical phase change leads to change of Rayleigh backscattering waveform. Characteristics extraction method for waveforms of the signal based on the time domain is mainly about amplitude, the square of the mean, peak, the variance and kurtosis. These characteristics cannot specify whether the fluctuation of Rayleigh backscattering waveform is induced by the disturbance or the frequency drift of laser, but the frequency difference of them can be dissociated in frequency domain for further disposal, so we prompt a novel location algorithm employs frequency domain analysis.

2 Location algorithm

2.1 Theoretical analysis of location algorithm

Through analyzing the Rayleigh backscattering signal of in frequency domain, the frequency of disturbances and laser frequency drift in distributed fiber-optic disturbance sensor system based-on Φ-OTDR is in diversity. The frequency drift of laser is in low frequency while the disturbance is in high frequency. Once different types of signals in the frequency domain have a clear variance, the spectral analysis of the signal is an effective characteristics extraction method.

By spectral analysis, if we directly accumulate the data in different position to calculate the power spectrum, we will not get any information of disturbance for there is more than one peak value in the graph.

Since different characteristic frequency has a great influence on the SNR of the system, in order to select the appropriate characteristic frequency, a priori and numbers of experimental data is needed. And if the characteristic frequency which could characterize the disturbance information is properly selected, the location algorithm will effectively inhibit the influence induced by the laser frequency drift on system location.

2.2 Flow chart of location algorithm

Assume matrix $y(t)$ represents all the date we stored from the experiments, its length is n_0. We reconstitute $y(t)$ in a form that period points n_t multiplied by the number of periods n_s to facilitate subsequent processing, as shown in formula (6). n_t can be used as a known quantity from (5), where f_s is the sampling rate, ω is the pulse width of the modulated period.

$$n_t=\omega\cdot f_s \tag{5}$$

$$y(t)_{n0}=y(t)_{nt\times ns} \tag{6}$$

Since the light which is propagating in the optical fiber fades down with the length of transmission distance, there is a great attenuation in backscatter waveform. So $y(t)$ is a exponential attenuation waveform. In order to improve the SNR of the system, attenuation compensation for attenuation of the waveform is necessary. In formula (7) the parameters have introduced before. $y'(t)$ means the matrix $y(t)$ after it is compensated.

$$y'(t)=y(t)\cdot\exp\left(\alpha\frac{c\tau_k}{n}\right) \tag{7}$$

Optical power of different positions is of great difference. mk is obtained as the mean of the same position in different periods to balance the optical power of different positions. And if the primary date of every period divides the mean value of mk in the corresponding position, the optical power of each position is equalized. $y''(t)$ means the matrix $y'(t)$ after its optical power is equalized.

$$y''(t)=y'(t)/mk \tag{8}$$

The overall algorithm flow chart is shown in Fig.3.

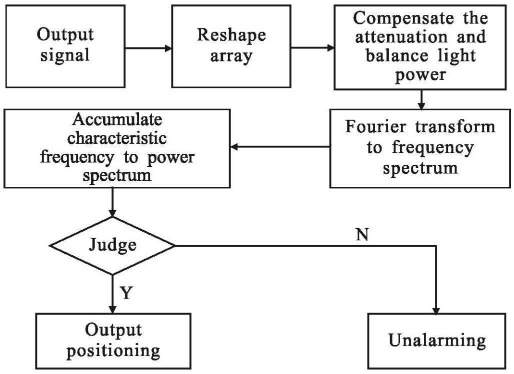

Fig.3 Flow chart of location algorithm

In the location algorithm, the Fast Fourier Transformed FFT spectrum is computed for every point beyond the disturbing point. The size of FFT is n_t. The spectrum of signal is the collection of spectrum of signal in the sensing fiber and it is composed of all the frequency of the components. The spectrum of the amplitude spectrum is the general spectral measurements which often changes with the change of frequency.

Disturbances are able to be distinguished by the peak readings of the spectrums. So we select the appropriate characteristic frequency and accumulate the characteristic frequency to analyze the power spectrum. From the value of the power spectrum, it can significantly distinguish the disturbance and location. That is to say, in the flow chart of the location algorithm if the judgment is yes, the location algorithm output disturbance position and alarm for it.

3 Experiments and results

3.1 Laser frequency drift test

Fringes based on a Mach-Zehnder interferometer are observed to estimate the laser frequency drift. When the frequency drift of the laser is Δv, the phase shift caused by it is $\Delta\varphi$, $\Delta\varphi=2\pi\Delta v\tau$[7-8]. Where, $\tau=n\Delta L/c$. If the arm length difference ΔL is 100 m, the time difference τ is approximately 0.5 μs. Accordingly, the phase shift interference results can be observed to monitor the laser frequency drift, as shown in Fig.4. Assuming the laser frequency drift modifies in a linear change, therefore we can estimate the frequency drift rate is approximately 190 MHz/min.

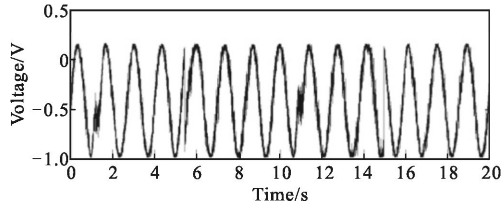

Fig.4 Frequency drift waveform of the laser in test

3.2 Location algorithm test

The fixed frequency drift of laser is used to build acquisition system of the distributed fiber-optic disturbance sensor system based on Φ-OTDR, whose main components are as follows: a narrow line width laser, electro-optic modulator, circulator, the sensing fiber, photodetector, sample cards, and IPC. The main parameters are: light source center wavelength is 1 550 nm, the sampling rate is setup to 10 MHz, pulse width is 1 μs, the modulation period is 100 μs, the sensing fiber is 8 km. Experimental knock is conducted at 3 km of the sensing fiber as a disturbance signal. Acquisition system based on Labview is responsible for collecting ten groups of data stored and processed in locating algorithm.

As shown in Fig.5 are n_s cycles of the Rayleigh backscattering waveform of the distributedfiber-optic disturbance sensor system based on Φ -OTDR. Experimental waveform perturbation already contains the combined effect of the laser frequency drift and the disturbance.

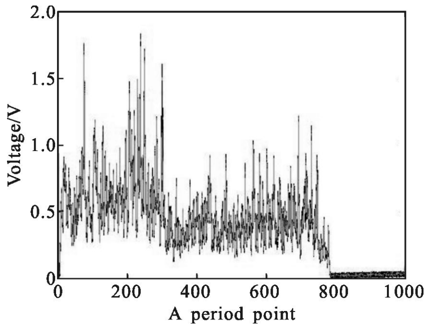

Fig.5 Waveform of Rayleigh backscattering

The FFT spectrum is computed for every point beyond the disturbing point. Four positions selected from the whole positions can be seen in Fig.6. From Fig.6, disturbance position 3 km is at the higher frequency and its Fourier components are relatively larger.

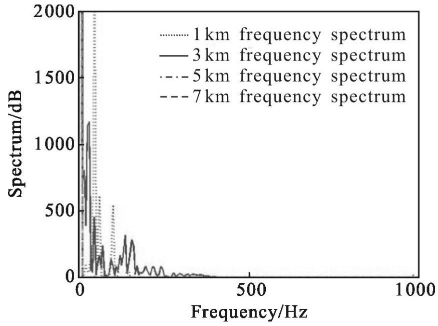

Fig.6 Frequency spectrum graph

But in Fig.6 some value of data in the position of 1 km exceed the data in disturbance position of 3 km. In contrast, if directly accumulate all the data, no disturbance can be located as shown in Fig.7 since there are more than one peaks. By selecting the appropriate characteristic frequency and accumulate them to analyze the power spectrum we can achieve the correct locating, as shown in Fig.8.

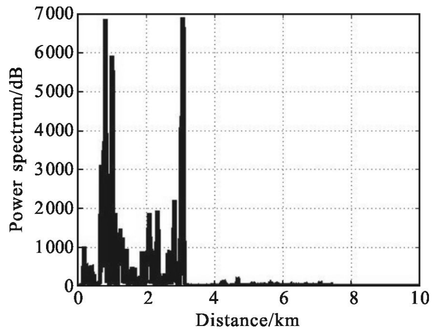

Fig.7 Failure of location

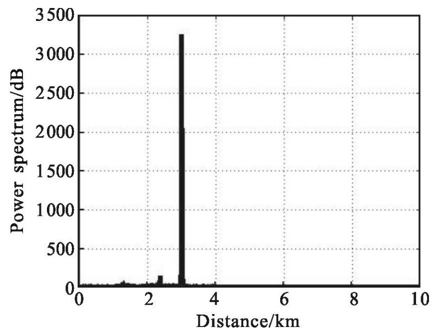

Fig.8 Optimal location

Through analyzing and processing of ten groups of data, which has two sets of data not accurately located, one is in 2.46 km and the other is in 0.53 km. SNR is defined as the ratio of the maximum value in characteristic frequency and the maximum value of the other frequency. The remaining eight groups of data locate between 2.90 km and 3.10 km, the SNR of which is relatively high, thus verifying the validity of the location algorithm. By comparison, the frequency 1 is the appropriate characteristic frequency of the test for its universal property. Data analysis results are displayed in Fig.9.

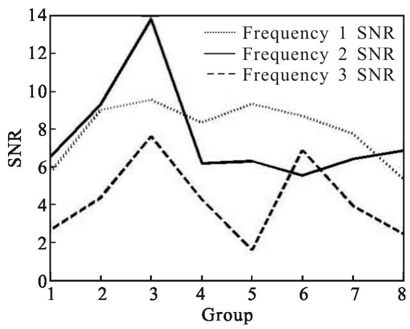

Fig.9 SNR of different frequencies

4 Conclusion

Through the analysis and description of the frequency drift due to differences in the disturbance frequency, the selection of characteristic frequency is feasible to inhibit the influence induced by the laser frequency drift on system location. Experimental results verify the validity of location algorithm using the technology of selecting characteristic frequency and reach a high SNR. Because the appropriate characteristic frequency can characterize the frequency of the disturbance signal which is different with the laser frequency drift, we can inhibit the influence induced by the laser frequency drift on system location and improve the accuracy of the location.

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