Influences of laser on fiber-optic distributed disturbance sensor based on Φ-OTDR

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Abstract: Fiber-optic distributed disturbance sensor based on Phase-sensitive Optical Time-Domain Reflectometry (Φ-OTDR) can achieve real-time intrusion detection on a large scale. As a critical component of the sensor, the parameters of the laser affect the monitoring length and the spatial resolution. In this paper, the theoretical analysis and the experiments about the influences of the laser source on the system was described. The investigation results indicate that the monitoring length increases with the rising of optical power of the laser, the pulse width and the modulation period; the spatial resolution decreases with the decline of pulse width. Based on the above analysis, the preferred selection of the laser parameters with different monitoring length is proposed. The theoretical analysis are proved by the experiments.

Key words: fiber-optic distributed sensor; monitoring length; spatial resolution; laser parameters; Φ-OTDR

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Φ-OTDR 的分布式光纤扰动传感系统光源参数影响

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摘 要:基于 Φ-OTDR 的分布式光纤扰动传感系统利用一根传感光纤可实现长距离的入侵实时监测。光源作为该系统的关键器件之一,其参数直接影响到系统的监测距离和定位精度等性能指标。文中针对光源参数对系统性能的影响做了理论分析和实验研究。理论分析和仿真表明:增加光源功率、提高脉冲宽度和提高调制周期可提高监测距离;减小脉冲宽度可提高定位精度。在上述分析的基础上,提出了针对不同监测距离的光源参数优选方案,并通过实验验证了理论分析的正确性。

关键词:分布式光纤传感; 监测距离; 定位精度; 光源参数; Φ-OTDR

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0 Introductions

Fiber-optic disturbance sensor system based on Φ-OTDR has many advantages such as distribution, high sensitivity, high spatial resolution, long monitoring length and so on. There has been a growing interest in the sensor with a promising application on the intrusion detection[1-3]. The prior studies of the sensor focus on the schemes and the location algorithms, which lack the study of the influences of the laser source on the system. This paper presents the theoretical analysis and demonstrates the influences of the optical power, pulse width and modulation period. Also, the relationships of the location precision and the spatial resolution are discussed and experimented.

1 Theory

1.1 Operation principle

The schematic illustration of the fiber-optic distributed disturbance sensor based on Φ-OTDR is shown in Fig.1.

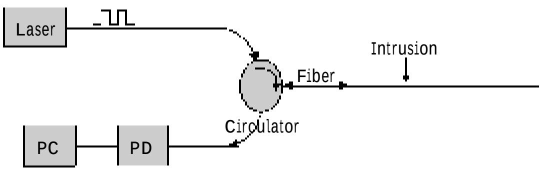

Fig.1 Schematic illustration of fiber-optic distributed disturbance sensor based on Φ-OTDR

The light pulses are injected into one end of the sensing fiber through the circulator. A narrow line-width laser causes the Rayleigh backscattered light waves to interfere within the pulse duration and the interferenced light waves pass through the circulator are detected by the photo detector. When there is an intrusion on the buried fiber, the refractive index of the fiber on the intrusion position will change. These variations cause the phase of the Rayleigh backscattered light to change and influence the power of the signal. By monitoring the variations we can obtain the intrusion information and the location of the disturbance[4-5].

The interferences of the backscattered light within the pulse duration are assumed to be an F-P interferometer, as shown in Fig.2.

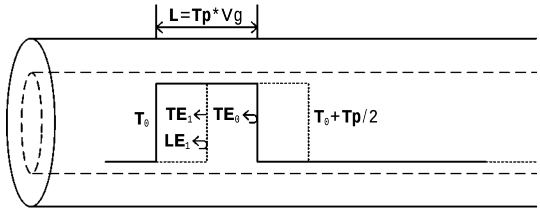

Fig.2 Model of F-P interferometer

In Fig.2, the light pulse TE_1 and LE_1 have interference at time $T_0+T_p/2$, where T_p is the pulse width. In this model, the power of interferenced light is expressed as:

$$\mathbf{P}_{RB}=\mathbf{P}_i 2\mathbf{R}(1+\cos\Phi) \tag{1}$$

Where P_{RB} is the power of the backscattered light, $\mathbf{P}_i$ is the power of source light when it transmits $\mathbf{T}_0$ from the first end, R is the backscattered Rayleigh coefficient, $\mathbf{R}=\mathbf{F}\alpha_s\mathbf{T}_p\mathbf{V}_g/2$, Φ is the phase between rising edge and trailing edge of light pulse, $\Phi=4\pi\mathbf{n}l/\lambda$, **n** is the refractive index of fiber, l is the length of sensing fiber, λ is the wavelength of laser[6].

Regardless of the dispersion, the phase between two edges of the light pulse is invariable when there are no disturbances or stresses. The Rayleigh backscattered power will change along with the sensing fiber. When there is a disturbance f(t) on the sensing fiber, where the stress or strain can be regarded as the disturbance, the phase induced by the disturbances can be given by[7-8]:

$$\Delta\Phi(t)=\mathbf{B}\cdot f(t) \tag{2}$$

The optical power of the backscattered light can be shown as follows:

$$\mathbf{P}'_{RB}(t)=\mathbf{P}_i\mathbf{F}\alpha_s\mathbf{T}_p\mathbf{V}_g\{1+\cos[\Phi+\Delta\Phi(t)]\}=\mathbf{P}_0\exp(-2\alpha\mathbf{z})\mathbf{F}\alpha_s\mathbf{T}_p\mathbf{V}_g\{1+\cos[\Phi+\mathbf{B}\cdot f(t)]\} \tag{3}$$

where $\mathbf{P}_0$ is injected peak power of the light pulses.

So, the disturbance information can be attained through measuring the power changes of the backscattered interferenced light.

1.2 Influences of pulse width on spatial resolution

The spatial resolution as an important parameter reflecting the orientation capability of the system. It indicates the shortest distance between the two disturbance positions that can be distinguished. Ignoring any other influencing factors, the relationship of the spatial resolution Δz and the pulse width T_p can be shown as:

$$\Delta z=\frac{D}{2}=\frac{1}{2}\cdot T_p v_g=\frac{1}{2}\cdot T_p\cdot c/n \tag{4}$$

Where T_p is the pulse width, n is the refractive index of fiber, c is the velocity of light in vacuum and $c=3.0\times10^8$ m/s. The refractive index of the fiber is 1.468. According to this formula, when light pulse width is 2 μs, 4 μs and 5 μs, the corresponding spatial resolution will be 204 m, 409 m, and 511 m. Regardless of any other influence factors, the spatial resolution that corresponds to pulse width is shown in Fig.3. It indicates that the spatial resolution can be increased by reducing the pulse width.

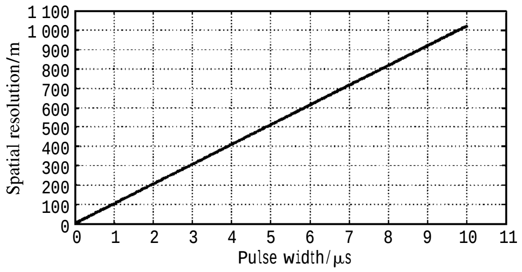

Fig. 3 Relationship of the spatial resolution with pulse width

1.3 Influences of pulse width, light source power, and modulation period on monitoring length

The monitoring length indicates the longest sensing scale of the system. It is an important parameter for securing perimeter and monitoring oil pipelines. The longest detection distance is mainly influenced by the pulse width, light source power, and modulation period and so on. Photo-detector has its own sensitivity, when the light power is less than this level it can not be detected. To realize longer monitoring distance, system should provide higher backscattered power. The equation $P_{RB}=F\alpha_s T_p v_g P_0 e^{-2\alpha L}/2$ shows that the backscattered power is in proportion to injected light power, and the light pulse width attenuates exponentially along with the transmitting length[9]. In a word, the intrusion detection distance can be enhanced by increasing the light source power, widen the pulse width and the modulation period.

In practical application, the signal-to-noise ratio (SNR) of the signal should above a value. Otherwise, the intrusion signals will be difficult to be detected and located. Considering our experimental conditions, the efficacious minimal backscattered optical power is regarded as 20 nW.

Regardless of Raman scattering, Brillion scattering, higher-order Rayleigh scattering and any other external influences, the relationship of the backscattered power with the power of laser is shown in Fig.4, where pulse width is 1 μs, modulation period is 100 μs and insertion loss of the optical components in the system is 7.3 dB.

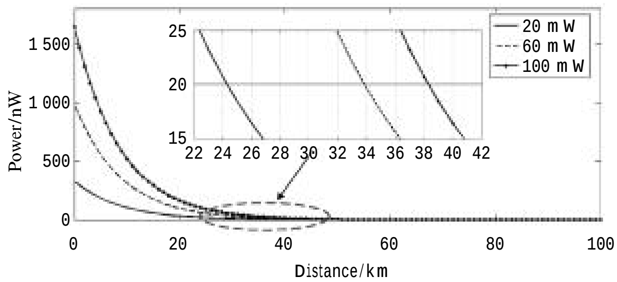

Fig. 4 Backscattered Rayleigh light power curves of different light source power

As illustrated in Fig.4, we can conclude that the backscattered power will increase along with the light source power when the light pulse width is fixed. If the light source power is 20 mW, the monitoring length can up to 24 km.

The backscattered light power curves of different light pulse width are shown in Fig.5, where the light source power is 60 mW and the modulation period is 100 μs.

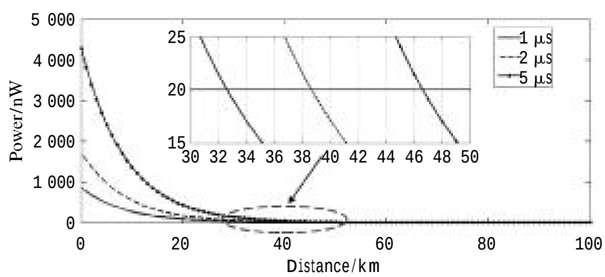

Fig.5 Backscattered light power curves of different light pulse width

From Fig.5 we can find out that backscattered light power will decrease with the improving of spatial resolution when the light source power is fixed. If the intrusion monitoring length is demanded to reach 46 km, the spatial resolution would not be higher than 500 m, on condition that light source power is 60 mW.

$$L_{max} \leqslant \frac{cT}{2n} \quad (5)$$

The length of fiber decides the transition time of light pulse in the fiber. Modulation period must be greater than the transition time, otherwise the neighborhood pulses will overlap each other and the system will be incapable of sensing and locating the disturbance. Thus, the modulation period will influence the longest intrusion detection distance. Modulation period and fiber lengh ought to meet Eq.(5), where T is modulation period.

1.4 The restriction between monitoring length and spatial resolution

The backscattered light power will increase with the improving of source optical power when the light pulse width is fixed. There is a restriction between the spatial resolution and the longest monitoring distance. A balance between these two parameters is attempted to be proposed as follows. The longest monitoring distance of different source optical power and different spatial resolution is shown in Fig.6, on condition that allowable minimum backscattered light power is 20 nW.

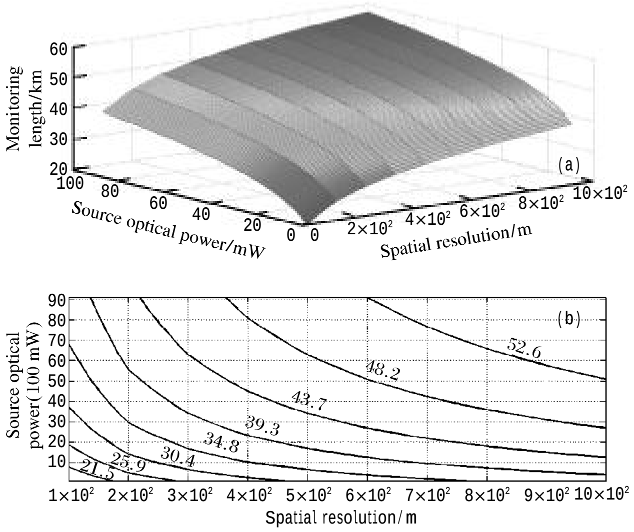

Fig.6 Longest monitoring distance of different optical source powers and different spatial resolutions

On condition that source optical power is 60 mW, the longest monitoring distance would achieve near 34.8 km while spatial resolution is 100 m, and the monitored length reaches 52 km if spatial resolution is 1 km. Nonlinearity effects must be considered when source optical power is too high or sensing fiber is too long.

In addition, the system's spatial resolution would be influenced by frequency shift, noise level, extinction ratio of modulator, sampling rate of acquisition card and some other factors. The spatial resolution is required to be moderate as too higher resolution will decrease the SNR. Reducing light pulse width will increase the spatial resolution when source optical power and modulation period are fixed. However, it will deteriorate the SNR due to the lower backscattered power. We need to choose an appropriate pulse width to make a balance between spatial resolution and SNR so as to satisfy our demands on these two parameters.

2 Experimental result and discussion

The experimental setup is shown in Fig.7.

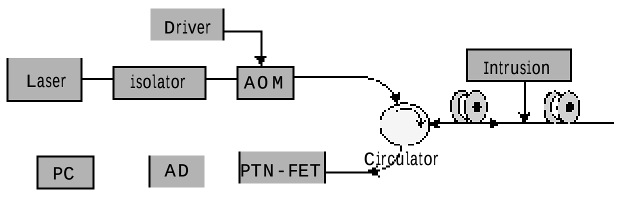

Fig.7 Experimental setup

Continuous wave emitted by 3.6 kHz narrow line-width laser is modulated by acousto-optic modulator (AOM) then injected into the one end of the sensing fiber through a circulator. Between two loops of fiber there is a piece of 5 m fiber where a stress is applied. The data received by acquisition card is analyzed by Matlab.

2.1 Experiments on the effects brought by pulse width to system

In this experimental setup, the sensing fiber is consisted of two circles, measured 5.1 km and 2.9 km in length respectively. Optical power of the source is 60 mW. Applying a stress near 5.1 km, the intrusion signals of different light pulse width are shown in Fig.8, when pulse period is 100 μs.

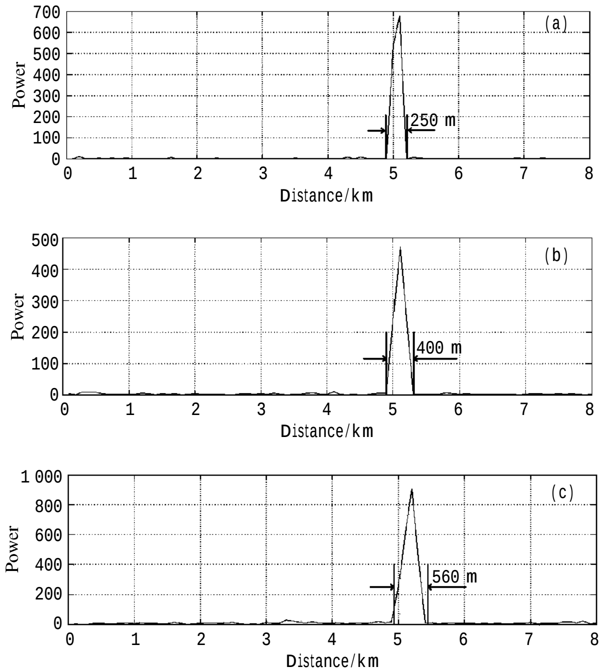

Fig.8 Fig. (a), (b) and (c) are intrusion signals when pulse width is 2 μs, 4 μs and 5 μs

In engineering applications, the width of intrusion signals could be regarded as a direct response to the spatial resolution. This experiment indicates that while pulse width is 2 μs, 4 μs and 5 μs, the corresponding spatial resolution is 250 m, 400 m and 560 m, whose theoretical spatial resolution is 204 m, 409 m and 511 m. Just as described in the section 1.4, the spatial resolution is influenced by some other factors. The experimental results are consistent with theoretical analysis in range of allowable error. It shows that improving the light pulse width will increase the spatial resolution.

2.2 Experiments on the effects brought by light source power to system

A comparable experiment of different source optical power has been done while pulse period is 100 μs, pulse width is 5 μs, and fiber length is 8 km. Backscattered light power curves is shown in Fig.9.

When the optical power of the source is 60 mW, backscattered light power has increased by 2 times compared with 30 mW. Experimental result indicates that improving the light source power will increase the SNR of backscattered Rayleigh light, then enhance monitoring

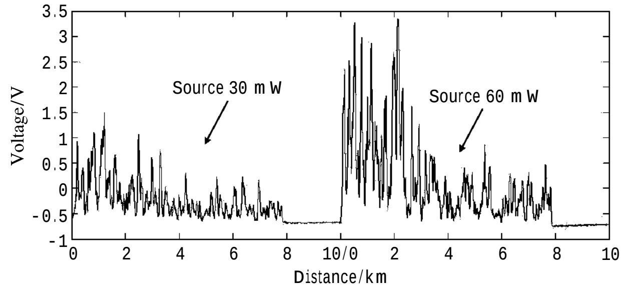

Fig.9 Backscattered light power curves of different light source power

distance and improve spatial resolution.

2.3 Experiments on the effects brought by modulation period to system

While the source optical power is 60 mW, the detected backscattered power curves of different modulation period are shown in Fig.10.

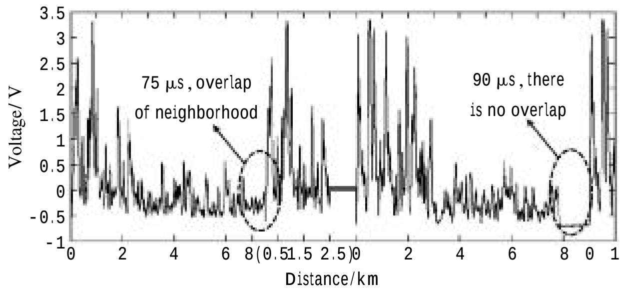

Fig.10 Backscattered power curves of different modulation period

As displayed in Fig.10, while modulation period is 75 μs, the neighborhood will overlap each other and system will be incapable of sensing and location on the last 500 m. However, if modulation period is 90 μs, the longest allowable sensing fiber length is 8 km.

This experiment shows that if the modulation period is increased the space between two adjacent backscattered power curves will be wider, and the monitored length will be higher. On the contrary, if modulation period is shorter than the transition time, the neighborhood will overlap each other.

2.4 Verification experiment on the long distance application

According to the simulation result, the longest monitoring distance would reach about 34 km when optical power of the source is 60 mW and the spatial resolution is 100 m. In this experiment, the sensing fiber used above is replaced by other two circles whose length is 29.6 km and

3.5 km, 33.1 km in total. The detected intrusion signal near 29.6 km is shown in Fig.11, where source optical power is 60 mW, modulation period is 350 μs and pulse width is 1 μs.

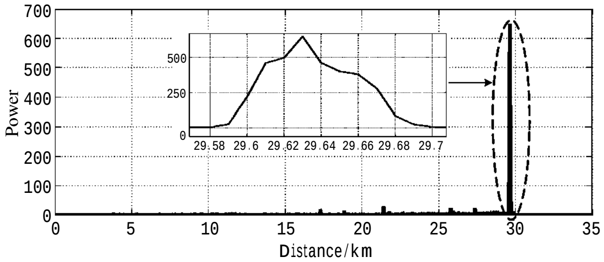

Fig.11 Detected intrusion signals

In this experiment, system has achieved monitoring length of 33.15 km, spatial resolution of 120 m and intrusion signal's SNR of 13.64 dB. The theoretical resolution is 102 m and the experimental result is consistent with the conclusion of theoretical analysis in range of allowable error.

3 Conclusions

In this paper, detailed analysis and the corresponding experiments about the influences brought by light source on minitoring length and spatial resolution have been done. The conclusions can be demonstrated as follows: I when modulation period and light pulse width are fixed, improving light source power will increase monitoring length; II when light source power and modulation period are fixed, narrowing light pulse width will decrease monitoring length and enhance spatial resolution; III when light source power and light pulse width are fixed, increasing modulation period will increase the monitoring length.

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