Long-distance intrusion sensor based on phase sensitivity optical time domain reflectometry

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Abstract: The influences of stimulated Brillouin scattering (SBS) on the sensing range of the phase sensitivity optical time domain reflectometry (φ-OTDR) was investigated and the limiting sensing range under different detection sensitivities of photodiodes was proposed. As the SBS threshold decreases along with the increasing of the fiber length, a novel scheme was presented to extend the sensing range. Circulators were employed in the scheme to divide the sensing fiber into several sections and the Rayleigh backscattering of different sections were detected by photodiodes, respectively. As a result, Stokes radiation of different sections would not affect each other such that the SBS become more difficult to build up. Therefore, the power injected into the sensing fiber increased and much longer sensing range was realized. In laboratory tests, three circulators were used to divide the sensing fiber into 3 sections, and 66.92 km sensing range was realized. The sensing range can be extend further by adding more circulators.

Key words: stimulated brillouin scattering(SBS); phase sensitivity optical time domain reflectometry (φ-OTDR); fiber-optic distributed disturbance sensor (FDDS)

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基于相位敏感光时域反射计的长距离入侵探测系统

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摘 要: 根据受激布里渊散射(SBS)对相位敏感光时域反射计(φ-OTDR)的监测距离的限制,分析了在使用不同灵敏度的光电探测器时 φ-OTDR 系统的监测距离,并根据 SBS 阈值随着光纤长度的增加而下降的特点,提出了一种新的光路结构以提升系统的监测距离。该光路结构采用环行器将敏感光纤分为多个部分,并对各部分的后向瑞利散射光分别进行探测,避免了各部分光纤产生的斯托克斯光相互叠加,从而提高了 SBS 阈值,进而实现了提升系统监测距离的目的。在实验室测试中,使用 3 个环行器将敏感光纤分为了 3 个部分并实现了 66.92 km 的监测距离。通过增加环行器的数量,系统的监测距离可以进一步提高。

关键词: 受激布里渊散射(SBS); 相位敏感光时域反射计(φ-OTDR); 光纤分布式扰动传感器

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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]. φ–OTDR based FDDS attracts a lot of interests in recent years as it can locate multiple intrusion events simultaneously.

φ–OTDR has been widely investigated since it was proposed in 1993 [3]. Park demonstrated the effectiveness of φ–OTDR with semiconductor laser and acousto–optic modulator (AOM), the sensing range was 6 km and spatial resolution was 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]. 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 was increased to 2.25 kHz with sensing range of 100 m[7-8].

As the signal of φ–OTDR is Rayleigh backscattering light, which is very weak, high input power is critical. In addition, the input power should increase with the raise of sensing range because of the attenuation of fiber. So the stimulated Brillouin scattering (SBS) is very easy to build up in φ–OTDR system, especially the SBS threshold decreases with the raise of fiber length. Bidirectional Raman amplification technology is adopted to solve the problem. By equalizing the optical power in sensing fiber, high input power at the beginning of the fiber is not necessary, so the sensing range is extended to 62 km [9]. However, the technology also brings some disadvantages. First, signal to noise ratio (SNR) drops. What's more, bidirectional pumping is unavailable sometimes in the applications of border and pipeline.

In this paper, the influence of SBS on the sensing range of φ–OTDR is analyzed and a novel scheme is presented to extend the sensing range. The configuration has some advantages such as simple architecture, low cost and feasible in different applications.

1 Principle

The principle of φ–OTDR system is shown in Fig. 1. Light pulses are injected into one end of a fiber, and Rayleigh backscattering light returned from the fiber is monitored with a photodiode. As with the conventional OTDR, the φ–OTDR trace is a plot of returned optical power versus time. The effect of phase changes resulting from intrusion event are sensed by subtracting an φ–OTDR trace from an earlier stored trace. The time at which changes in the φ–OTDR trace occur are proportional to the range at which intrusion event occurs.

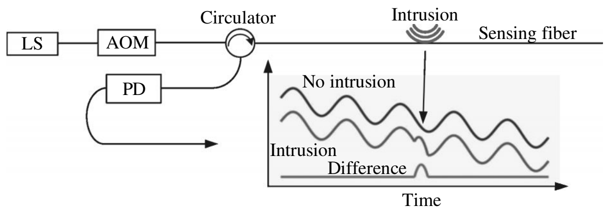

Fig.1 Schematic diagram of φ–OTDR

The power of Rayleigh backscattering in the end of the fiber can be calculated by[10]

$$P_s \approx T_p \eta P_i \exp(-2\alpha L) \tag{1}$$

where T_p, P_i are the pulse width and the peak power of the light pulse, η is the coefficient of Rayleigh backscattering, α and L are the attenuation and total length of the sensing fiber.

From Eq.(1), we can see that P_s decreases along with the raise of sensing fiber length. In φ–OTDR system, we demand $P_s \geqslant 10\ P_{ds}$ (P_{ds} is the detection sensitivity of photodiode) to ensure the detection of the optical power perturbation in the end of the sensing fiber. Then Eq.(1) can be described as

$$P_i T_p \geqslant \frac{10 P_{ds}}{\eta \exp(-2\alpha L)} \tag{2}$$

Suppose the pulse frequency is f, the average power of input light can be represented by

$$\overline{P}_i = P_i T_p * f \geqslant \frac{10 P_{ds} f}{\eta \exp(-2\alpha L)} \tag{3}$$

However, the demanded high pump power of φ-OTDR could cause SBS. SBS is a nonlinear optical process, which leads to most of input power transfer to backward Stokes when the input power exceeds the threshold in a fiber. Because of the low threshold of inherent power, SBS becomes an important limiting factor of the sensing range of φ-OTDR. The SBS threshold can be calculated by[10]

$$P_{th} = \frac{G A_{eff}}{g_0 L_{eff}} \tag{4}$$

where G is the gain coefficient, A_{eff} is the effective mode area, g_0 is peak value of the Brillouin gain coefficient of fiber, and $L_{eff}=[1-\exp(-\alpha L)]/\alpha$ is the effective fiber length, such that Brillouin threshold can be represented by

$$P_{th} \geqslant \frac{\alpha G A_{eff}}{g_0[1-\exp(-\alpha L)]} \tag{5}$$

Eq.(3) shows the incident light power should increase with the raise of the fiber length. However, Eq.(5) shows that the SBS threshold decreases with the raise of the fiber length. The contradiction limits the sensing range of φ-OTDR.

A simulation is performed for the ordinary single mode fiber, of which the η=10 W/J, α=0.25 dB/km=0.0576/km, $G\approx 21$, $A_{eff}\approx 77.7$ μm^2 and $g_0=2\times10^{-11}$ m/W. In addition, the modulation frequency is set to 1.43 kHz, in other words, the pulse interval is 700 μs, to ensure the successive returns do not overlap. Figure 2 shows the demanded input power and the Brillouin threshold alter with the fiber length. It is clear that the sensing range increases with the raise of detective sensitivity, and is limited to 43 km, 57 km, and 70 km when the detective sensitivity of photodiode is 1 nW, 5 nW and 25 nW.

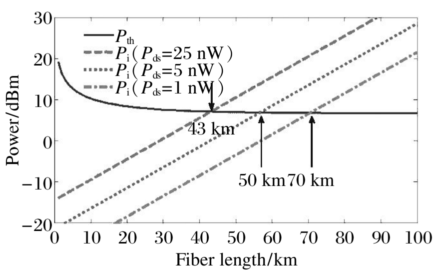

Fig. 2 Demanded input power and the SBS threshold vs fiber length

2 Experiment

2.1 Experiment setup for SBS threshold measurement

The configuration shown in Fig. 3 is used to measure the SBS threshold. Light from the CW laser source is amplified by Er-doped fiber amplifier (EDFA) and then split into two parts through a 99:1 coupler. An optical power meter (OPM1) is employed to measure the power of 1% part to calculate the input power injected into the testing fiber. Another part is gated into the testing fiber through a circulator, and the backscattered light pass through the circulator and is detected by OPM2. The input power is adjusted by tuning the drive current of EDFA, then the relationship of input power and backscattered light power can be established. Then the point namely SBS threshold, at which the power of backward Stokes increases rapidly can be found.

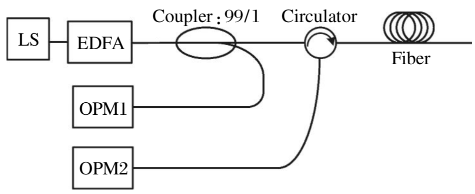

Fig. 3 Experimental setup for measurement of SBS threshold (LS: Laser source; EDFA: Er-doped fiber amplifier; OPM1, 2: optical power meter 1, 2)

SBS thresholds of seven pools of fiber with different lengths are measured, as shown in Fig. 4. We can see that the experiment values matches quite well with the theoretical values.

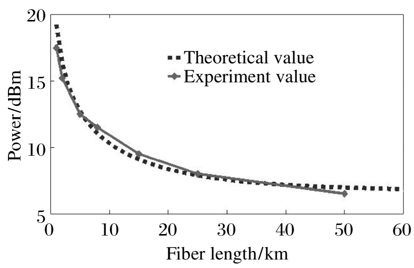

Fig.4 Brillouin threshold with different fiber lengths

2.2 Experiment setup for long distance φ-OTDR system

The setup of long distance φ-OTDR system is shown in Fig.5. Light from the CW laser source, of which the output wavelength is 1 550.8 nm and the line width is 5 kHz, is modulated by an AOM with 200 MHz frequency shift. The pulses with a 700 μs pulse interval and 5 μs pulse width is amplified by EDFA and then gated into sensing fiber via a circulator. The total length of sensing fiber is 66.92 km, and is divided into 3 sections. The fiber length of each section is 5.04 km, 11.28 km and 50.60 km in turn. The sensing fiber of the third section consists of two spools of single-mode fiber (25.28 and 25.32 km) with a single-mode fiber optic cable of 3 m. Intrusion event is simulated by beating the fiber cable. The Rayleigh backscattering light of different sections is detected by photodiode 1, 2, and 3, respectively. The detection sensitivity of the photodiode is about 5 nW.

In this configuration, Stokes radiation of latter sections will not introduced in frontal sections such that SBS threshold is determined by the fiber length of each section rather than the total length. Therefore, much higher power can be injected into the sensing fiber to realize much longer sensing range.

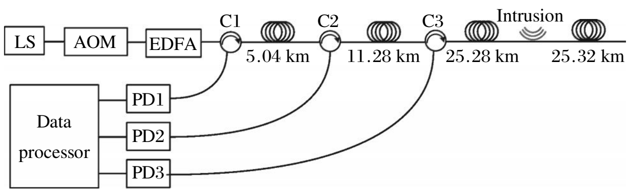

Fig.5 Experiment setup of long distance φ-OTDR system (LS: Laser source; AOM: acoustic optical modulator; EDFA: Er-doped fiber amplifier; C1, C2, C3: circulator 1, 2, and 3; PD1, PD2, PD3: photodiode 1, 2 and 3)

The input power can be adjusted by tuning the drive current of EDFA. In laboratory test, we set the average power of input pulse light to 10dBm, which is much larger than SBS threshold of 50 km fiber (the theoretical value is 7.0 dBm) and lower than the threshold of 5 km fiber (the theoretical value is 12.7 dBm). Therefore, the SBS will not build up in first section. The optical power injected into the second section is reduced to about 8.0 dBm because of the attenuation of fiber and circulator, which is much lower than the SBS threshold of 11 km fiber (the theoretical value is 10.0 dBm). Then the optical power injected into the third section is reduced to about 4.5 dBm, which is also lower than the SBS threshold of 50 km fiber. Thus, we realize a sensing range of 66.92 km without exciting SBS, which is much longer than the theoretical value of limiting sensing range when the detection sensitivity is about 5 nW (57 km as shown in Fig.2).

The Rayleigh backscattering trace is shown in Fig. 6. The top waveform shows the first section of 5.04 km, the middle waveform shows the second section of 11.28 km, and the bottom waveform shows the third section of 50.60 km. The intrusion point can be derived by subtracting an φ-OTDR trace with intrusion event from an earlier stored trace without intrusion event, as shown in Fig.7. The top three waveforms are the differences of the three sections in turn, and the bottom waveform is the sum of above three traces. From the bottom trace of Fig. 7, we can see that the intrusion event is occurred at the range of 41.61 km when the actual point is 41.60 km (5.04 + 11.28+25.28 km), the location error is only 10 m.

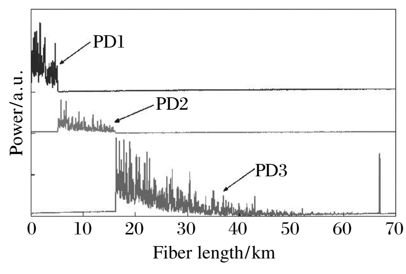

Fig.6 φ-OTDR traces of three sections

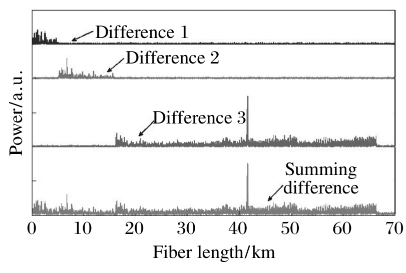

Fig.7 Differences of φ-OTDR traces of three sections

3 Conclusion

The influence of SBS on the sensing range of φ-OTDR is analyzed and a novel scheme is presented to extend the sensing range. Circulators are employed in the scheme to divide the sensing fiber into several sections so that Stokes radiation of different sections can not affect each other and the SBS become more difficult to build up. Therefore, much higher power can be injected into the sensing fiber to realize much longer sensing range. In laboratory tests, 66.92 km sensing range is realized with three circulators, which exceeds the limiting length of theoretical value of ordinary φ-OTDR. The proposed scheme has some advantages such as simple architecture, low cost and feasible in different applications and the sensing range can be extend further by adding more circulators.

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