122km single-end phase-sensitive optical time domain reflectometer based on post signal processing method

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Abstract. Phase sensitive optical time domain reflectometer able to detect vibration information. However, when it comes to ultra-long detection, the vibration signal is overwhelmed due to noise level and polarization fading. In this paper, a method is used to compensate noise and fading phenomenon based on post signal processing scheme, including sectional amplification, amplitude demodulation and adaptive matched filtering. On the basis of the theoretical analysis of the detection method, the feasibility is verified by experiment. Vibration information from 122km can be detected.

1. Introduction

The phase sensitive optical time domain reflectometer (Φ-OTDR) is one of the novel distributed optical sensing techniques. It is widely used in distributed acoustic sensing system[1-5], due to its high resolution and resistance to electromagnetic interference[6-10]. However, in the scenario of ultra-long distance vibration detection, the birefringence effect caused by fiber and environment becomes complicated, which leads to severe polarization fading phenomenon. Moreover, the optical signal attenuation increases rapidly as the fiber length grows, which leads to the decrease of SNR. As a result, the vibration information is overwhelmed and hard to be located.

Several researches have been made to locate the ultra-long distance vibration information. Optical signal amplifying is a conventional way and several amplification schemes were proposed. An optical repeater structure was proposed by Zhu, where an erbium-doped fiber amplifier (EDFA) and a Raman amplifier was combined and connected between sensing fibers[11]. Zhou proposed a remotely pumped erbium doped fiber amplification scheme, where an erbium-doped fiber was connected between sensing fibers and injected by pump waves to achieve the amplification[12]. Hugo proposed a URFL cavity which consisted of a Raman pump laser, WDMs and FBGs to achieve Raman amplification as well as eliminate noise caused by the amplification process.[13] Tian used several bi-directional fiber amplifiers between the sensing fibers to amplify the optical signal[14]. However, the optical signal amplification needs extra optical components, thus increasing the cost. Besides, most of them are not single-end detecting scheme. Amplification components should be connected between sensing fibers, which is usually not realizable in practical application.

In this paper, a single-end detecting system is proposed on the basis of post signal processing method. Sectional amplification, amplitude demodulation and adaptive matched filter will be used on the electronic signal detected by the photonic detector to compensate polarization fading phenomenon as well as the SNR loss. No optical components are connected in the middle of the sensing fiber, which
saves the cost and has great practical value. On the basis of the analyzation of the detection method, experiment was made and vibration information was successfully detected on the distance of 122km.

2. Principle

2.1. System principle
The principle structure of heterodyne Φ-OTDR is shown in Fig.1. The narrow linewidth light emitted by the laser is divided into probe light and local oscillator light by the optical coupler (OC). The probe light is modulated to pulses and frequency-shifted by Acoustic Optical Modulator (AOM). The modulated pulses and shift frequency are generated by signal generator (SG). The modulated signal launches into fiber under test (FUT) through the circulator (Cir). The backscattered light is interfered with local oscillator light in the optical coupler. The interference light is detected by photonic detector (PD) and converted into electrical signal. Signal processing methods are used to process the electrical signal.

![Principle structure of heterodyne Φ-OTDR](image)

2.2. Post signal processing method principle
In Φ-OTDR system, optical pulses are generated in a certain repetition rate by the AOM. Each pulse goes through the sensing fiber and the relevant backscattered light is coherent with local oscillator light. The optical field of backscattered light can be expressed as

\[ E_s(t) = E_s \exp(j2\pi(f + f_m)t + \theta_s), \]  

where \( E_s \) is the backscattered optical field amplitude, \( f \) is the optical frequency, \( f_m \) is the shift frequency generated by AOM, \( \theta_s \) is the modulated phase. Similarly, the optical field of local oscillator light can be expressed as

\[ E_{lo}(t) = E_{lo} \exp(j2\pi ft), \]  

where \( E_{lo} \) is the local oscillator optical field amplitude. After the interference, the detected optical current can be expressed as

\[ I(t) = |E_s(t) + E_{lo}(t)|^2 = E_s E_{lo} \cos(2\pi f_m t + \theta_s), \]  

which is called Φ-OTDR trace. Because of the optical attenuation, \( E_s E_{lo} \) decreases rapidly as the distance grows. As a result, the sensing distance is limited when \( E_s E_{lo} \) is lower than noise level. Sectional amplification is ought to be used to amplify the long distance optical signal amplitude. In Φ-OTDR system, spatial location \( z \) and \( t \) has the relationship \( t = \frac{2nz}{c} \), where \( n \) is refractive index of fiber, \( c \) is the velocity of light. Sectional amplification method finds the specified location according to \( t \), divides the Φ-OTDR into two parts, and amplifies them with different amplification gains. After sectional amplification, \( I(t) \) becomes
\[ I(t) = AE_xE_Lo \cos(2\pi f_m t + \theta_x) = AE_xE_Lo \cos(4\pi f_m nz / c + \theta_x), \]  

(4)

where \( A \) stands for the amplification gain, which differs according to spatial location \( z \).

In the practical system, due to the birefringence phenomenon, the state of polarization (SOP) is different between backscattered light and local oscillator light. As a result, the detected optical current should be rewritten as

\[ I(t) = AE_xE_Lo \cos(\theta_p(t)) \cos(2\pi f_m t + \theta_x), \]  

(5)

where \( \theta_p(t) \) represents the relative polarization angle between backscattered light and local oscillator light. As the sensing distance grows, the SOP difference becomes complicated. As a result, at certain position \( \cos(\theta_p(t)) \) becomes too low to detect the vibration information, causing polarization fading problem. Inspired from polarization diversity method which adds polarizer to separate the coherent light into S-state light and P-state light to compensate each other, amplitude demodulation is used on the detected electrical signal to acquire its orthogonal signal. By compensating the original signal with its orthogonal signal, the polarization fading phenomenon can be decreased rapidly, particularly on the position where the signal amplitude is influenced severely by the SOP difference.

After sectional amplification and amplitude demodulation, the adaptive matched filtering method can be used to enhance the SNR and extract the vibration information[15]. Assuming consecutive \( N \) \( \Phi \)-OTDR traces are acquired, the signal on the specified location \( z \) of the sensing fiber can be expressed as

\[ x_z = [x_{z,0}, x_{z,1}, \ldots, x_{z,N-1}]^T, \]  

(6)

where \( x_{z,n} \) stands for the data acquired by the \( (n+1)^{\text{th}} \) \( \Phi \)-OTDR trace representing the location \( z \). On non-vibration position, the signal can be expressed as

\[ H_0 : x_{z:H_0} = n_{o,z} + n_{e,z}, \]  

(7)

where \( n_{o,z} \) represents the fluctuating optical noise and \( n_{e,z} \) represents the environment noise. On vibration position, the signal can be expressed as

\[ H_1 : x_{z:H_1} = \sigma_p s(\omega) + x_{z:H_0}, \]  

(8)

where \( \sigma_p \) represents the vibration amplitude and \( s(\omega) \) represents the steering vector which can be expressed as

\[ s(\omega) = [1, e^{2\pi i \omega}, e^{4\pi i \omega}, \ldots, e^{2\pi i (N-1) \omega}]^T, \]  

(9)

where \( \omega \) represents the normalized frequency. The system SNR is

\[ \text{SNR} = \frac{P_0||s(\omega)||^2}{C}, \]  

(10)

where \( P_0 = \sigma_p^2 \) and \( C \) stands for noise covariance matrix. According to the matched filtering theory, the filter coefficient can be acquired by

\[ w_{\text{opt}} = C^{-1}s(\omega), \]  

(11)

Under this circumstance the system SNR becomes

\[ \text{SNR} = \frac{P_0||w^H s(\omega)||^2}{w^HCw}, \]  

(12)

In the practical system, the cross correlation matrix can’t be got because of the uncertainty of the noise environment and should be estimated by signal input. The filter coefficient expression should be rewritten as

\[ w = (R_x + \Delta)^{-1}s(\omega), \]  

(13)
where \( \mathbf{I} \) is the diagonal matrix and \( \delta \) is the parameter. The diagonal matrix is induced to satisfy the matrix reversibility requirement. \( \mathbf{R}_i \) is expressed as

\[
\mathbf{R}_i = \frac{1}{N} \sum_{n=1}^{N} \mathbf{x}_{n/H} \mathbf{x}_{n/H}^T, \quad i = \begin{cases} 1, \text{ vibration position} \\ 0, \text{ non-vibration position} \end{cases}
\]

The system SNR becomes

\[
\text{SNR} = \frac{P_0 \left| \mathbf{s}(\omega)^H (\mathbf{R}_s + \delta \mathbf{I})^{-1} \mathbf{s}(\omega) \right|^2}{\mathbf{s}(\omega)^H (\mathbf{R}_s + \delta \mathbf{I})^{-1} \mathbf{C}(\mathbf{R}_s + \delta \mathbf{I})^{-1} \mathbf{s}(\omega)},
\]

By substituting actual signal into Eq.(14) to get cross correlation matrix, then use Eq.(13) to get filter coefficient and filter the signal, the system SNR can be enhanced rapidly and the vibration location can be easily detected from the post signal processing result.

3. Experiment results and analysis

The ultra-long distance \( \Phi \)-OTDR vibration detecting system is shown in Fig.2. A narrow linewidth laser is deployed as the optical source and connected with a 90:10 optical coupler which divides the optical signal into probe light (containing 90% of the laser power) and local oscillator light (containing 10% of the laser power). The probe light is modulated by an AOM with a pulse length of 200ns and a frequency shift of 100MHz. The AOM is driven by a signal generator. The modulated probe light is amplified by an EDFA and filtered to eliminate the amplifier spontaneous emission (ASE) noise caused by the EDFA. Then the probe light is launched into fiber under test through the circulator. A piezo-electric transducer (PZT) is connected to the end of the fiber, creating the vibration signal. In the experiment, the length of the sensing fiber is 122km.

![Figure.2 Experimental structure of ultra-long distance \( \Phi \)-OTDR](image)

The Rayleigh backscattered light from sensing fiber is coherent with local oscillator light. The coherent light is detected by the balanced photonic detector (BPD) and converted into electronic signal. The electronic signal is mixed with 90MHz sinusoid signal. Then the high frequency part is filtered and the rest is sectional amplified where signal after 70km is amplified with higher amplification gain. The sectional amplified signal is detected by DAQ to convert into digital signal. The digital signal goes through amplitude demodulation and adaptive matched filter to get the vibration information.

The waveform of electrical signal after sectional amplification is shown in Fig.3. Three consecutive traces are shown in Fig.3. After sectional amplification, the second-half part of each trace is amplified with higher amplification gain. The waveform is acquired by oscilloscope because the signal has not been acquired by DAQ. The signal after amplitude demodulation is shown in Fig.4. Amplitude demodulation process generates the orthogonal signal to compensate the original signal in order to compensate the polarization fading phenomenon. Signal is changed from bipolar signal into unipolar signal because of amplitude demodulation process. The signal after adaptive matched filter is shown in Fig.5. With the optical fluctuating noise and environment noise filtered and system SNR enhanced, an
obvious peak can be found, which corresponds to the actual vibration location. The corresponding location of the peak according to the experiment is 121.7km, which is slightly different from the theoretical location. The error can be ignored under the circumstance of such long sensing distance.
4. Conclusion
In this paper, a post signal processing method of ultra-long distance Φ-OTDR has been studied. By using sectional amplification, amplitude demodulation and adaptive matched filtering, noise and polarization fading phenomenon has been compensated, thus enhancing the SNR and extracting the vibration information. The sensing distance can be increased rapidly. In the experiment, the vibration at 122km can be located.

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