Acquiring the large phase jumping beyond π with phase unwrapping assisted by auxiliary light in Φ -OTDR

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Abstract: The absolute difference (phase jumping) between two adjacent phases should be less than π in order to accurately recover the phase signal with traditional phase unwrapping algorithm, which limits the capability of quantitative measurement for traditional Φ -OTDR. In this article, a new process of phase unwrapping with an auxiliary light in coherent Φ -OTDR is proposed, so the resolvable phase jumping is extended to a larger value beyond π and the capability of phase unwrapping is improved. In this Φ -OTDR system, wrapped differential phases between a reference position and the subsequent positions of fiber are firstly acquired for all probe light pulses. And wrapped differential phases of interleaving pulse sequence are unwrapped using the traditional phase unwrapping algorithm. Then, positions where the differential phases are correctly unwrapped are obtained from the discontinuously linear profile of the phase change curves of the original probe light. Based on these positions, the information of perturbation can be correctly retrieved. In experiment, the new process of phase unwrapping with the auxiliary for Φ -OTDR is executed and a perturbation signal which induces a maximum phase jumping of 3.7154 rad is well reconstructed. More experimental results all demonstrate the validity of the proposed method.

Index Terms: Phase jumping; Φ -OTDR; quantitative measurement; auxiliary light.

1. Introduction

In phase optical time domain reflectometer (Φ -OTDR), when a highly coherent laser pulse injects into the optical fiber, the Rayleigh backscattering effect will generate speckle-like OTDR traces. If an external perturbation acts on the fiber, OTDR traces will change. Usually, people can acquire the phase of Φ -OTDR from the changed OTDR traces [1-5]. In theory, the phase change of Rayleigh backscattering signal in Φ -OTDR is linearly proportional to the perturbation [5]. Therefore, a series of methods such as three-port detection, double-pulse interference, holographic demodulation, pulse coding, double wavelengths, etc. have been proposed to retrieve the phase information [7-18].

In the process of estimating the phase, arc tangent function is usually involved. If the phase signal exceeds the range $[-\pi, \pi]$, the result of the arc tangent function must be wrapped. In order to obtain the correct phase signal, the process of phase unwrapping is inevitable. However, the traditional phase unwrapping algorithm requires that the absolute phase difference between two adjacent values which are correctly unwrapped should be less than π [18-20]. This absolute phase difference between two adjacent values is called phase jumping in order to discriminating with other differential results. In practical applications, it's common to encounter a phase jumping larger than π when a large perturbation occurs. In traditional Φ -OTDR system, increasing the sampling rate by reducing the pulse period can decrease the phase jumping. However, the pulse period is limited by the fiber length. Then we need to resolve two problems. The first is how to know a phase jumping larger than π exists. Because the traditional phase unwrapping process may regard the wrongly unwrapped result as the correct one. The second is how to accurately demodulate the phase signal whose phase jumping exceeds π .

For the first problem, this paper proposes a simple distinguishing method by the linear characteristic of phase changes before and behind the perturbation. For the second problem, we propose a novel phase unwrapping method by introducing an auxiliary light which has a different frequency with the original probe light into Φ -OTDR. Since the initial phases at the same position of the fiber are different for different frequency lights and they vary with the fiber length, the auxiliary light cannot increase the sampling rate directly. Instead, the auxiliary light in the new process of phase unwrapping is for assisting the original probe light to realize the correct phase unwrapping based on the traditional phase

unwrapping algorithm at some positions.

In this paper, the characteristic of phase change of the original probe light in the coherent Φ -OTDR with and without the auxiliary light will be analyzed in detail. Based on these characteristics in Φ -OTDR, the phase unwrapping when the phase jumping exceeds π will undergo an unconventional process and the corresponding phase signal will be acquired.

2. Principle

In the coherent Φ -OTDR system, the detected current in the AC mode can be expressed as:

$$I_D(t, z) \propto A_S A_{LO} \cos[2\pi\Delta f \cdot 2nz/c + \varphi(t, z) + \varphi_n(t, z) + \varphi_0(t) - \varphi_{LO}(t)] \quad (1)$$

where t is the moment of the optical pulse entering the sensing fiber, z is the distance of the position away from the input end, A_S and A_{LO} are the amplitudes of signal light and reference light, Δf is the frequency shift introduced by the modulator, n is the effective fiber refractive index, c is the velocity of light in vacuum, φ is the phase change induced by the external perturbation, φ_n is the phase fluctuations due to the nonuniform characteristic of refractive index along the fiber, φ_0 and φ_{LO} are the initial phases of the probe signal light and reference light.

Then the statistical phase of Φ -OTDR can be written as:

$$\Phi(t, z) = \varphi(t, z) + \varphi_n(t, z) + \varphi_0(t) - \varphi_{LO}(t) = \arctan[I(t, z)/Q(t, z)] + h(t, z)\pi = \phi(t, z) + h(t, z)\pi \quad (2)$$

where I and Q are the results of IQ demodulation from Eq. 1, ϕ is the wrapped statistical phase, h is an integer determined by the phase unwrapping algorithm in the temporal direction at each position of fiber. In the practical application, the difference between φ_0 and φ_{LO} is random due to the accumulated phase noise before the input end of sensing fiber. In order to eliminate this randomness, a reference position in the front part of the sensing fiber is chosen. Then the differential operation between the reference position and each subsequent position is executed. So the spatial differential phase can be expressed as:

$$\theta(t, x) = \Phi(t, z) - \Phi(t, z_r) = \phi(t, z) - \phi(t, z_r) + [h(t, z) - h(t, z_r)]\pi = \psi(t, x) + k(t, x)\pi, x = z - z_r \quad (3)$$

where z_r represents the reference position, ψ is the wrapped differential phase between the wrapped statistical phases of z and z_r , k is an integer and decided by the phase unwrapping algorithm.

For convenience of analysis, Eq. 3 can be rewritten as $[\varphi(t, z) - \varphi(t, z_r)] + [\varphi_n(t, z) - \varphi_n(t, z_r)]$. Usually, the reference position is chosen in a stable region of fiber. So $\varphi(t, z_r)$ is ideally zero. However, the random fluctuation of the item $\varphi_n(t, z) - \varphi_n(t, z_r)$ may still introduce error to the extraction of the phase change $\varphi(t, x)$. Therefore, in order to remove the impact of $\varphi_n(t, z) - \varphi_n(t, z_r)$ on the phase signal, a differential operation between each differential phase curve and a reference one is required. Furthermore, to reduce the error induced by a single differential phase curve, the reference curve to be subtracted is substituted by the average of differential phase curves obtained by all probe pulses at different times. If the pulse period is T , the phase change curve can be obtained by:

$$\beta(t, x) = \theta(t, x) - [\sum_{p=0}^{N-1} \theta(pT, x)] / N \quad (4)$$

Theoretically, the phase change $\beta(t, x)$ in the quiet region has the same value along the fiber, which is simply shown in Fig. 1(a).

Fig.1. Demonstration of calculated phase change for a perturbation with a (a) small and (b) large phase jumping in the traditional process of phase unwrapping

In Fig. 1(a), we assume that a perturbation exists in the region AB and the corresponding phase jumping is less than π . The position O corresponds to the reference position z_r in Eq. 3. Before the event region, the phase changes along the fiber are all zero. When the optical pulse encounters the perturbation, the phase change begins to vary. With the

increase of the overlapped length between the optical pulse and the event region, the amplitude of the phase change increases steeply. Then, with the leaving of the optical pulse from the region AB, the phase change reaches to another stable value. However, in practical applications, the phase of one position contains the accumulated noises from all the preceding positions. Consequently, the differential result $\beta(t, x_B) - \beta(t, x_A)$ (where x_A and x_B are the coordinates corresponding to position A and position B in Fig. 1(a), respectively) can reduce the impact of the accumulated noises as much as possible and it is an optimal result to represent the phase signal induced by the perturbation.

However, because the wrapped differential phase $\psi(t, x)$ varies with the fiber length, if the phase jumping induced by the external perturbation is increased to a value beyond π , it would lead to random unwrapped phases for different positions. Consequently, the differential phase after the perturbation position will vary randomly along fiber, resulting in that the phase change curve DE derived from Eq. 4 has a chaotic profile in the region BC after the perturbation position as shown in Fig. 1(b). So the external event cannot be correctly retrieved for such situation. This phenomenon also indicates that the phase jumping induced by the perturbation exceeds π .

Fig.2. Scheme of pulse train with the original probe light and the auxiliary light for new process of phase unwrapping

In order to obtain the perturbation information whose phase jumping exceeds π , we introduce an auxiliary light to the coherent detection system. Correspondingly, the interleaving pulse sequence is shown in Fig. 2. The red sequence is the original probe light pulse for measuring the external perturbation and the blue sequence is the auxiliary light pulse. The original probe light and the auxiliary light have the same interval T . The parameter τ is the temporal interval between the original probe light and the auxiliary light. In this Φ -OTDR, the electrical signal received by the detector can be expressed as:

$$I_{D_{i2}}(t, z) \propto \sum_{i=1}^2 A_{Si} A_{Loi} \cos[2\pi \Delta f_i \cdot 2nz / c + \varphi_i(t, z) + \varphi_{ni}(t, z) + \varphi_{0i} - \varphi_{Loi}] \quad (5)$$

where $i=1, 2$ represents the original probe sequence and the auxiliary sequence, respectively.

Since Δf_1 and Δf_2 are different, $I_{D1}(t, z)$ and $I_{D2}(t, z)$ can be easily separated from $I_{D_{i2}}(t, z)$ via two bandpass filters. Then the statistical phase $\Phi_i(t, z)$ of each frequency component can be written as:

$$\Phi_i(t, z) = \varphi_i(t, z) + \varphi_{ni}(t, z) + \varphi_{0i} - \varphi_{Loi} = \arctan[I_i(t, z) / Q_i(t, z)] + h_i(t, z)\pi = \phi_i(t, z) + h_i(t, z)\pi \quad (6)$$

Continuously, the differential phases of the original probe sequence and the auxiliary sequence are obtained and can be written as:

$$\theta_i(t, x) = \Phi_i(t, z) - \Phi_i(t, z_r) = \phi_i(t, z) - \phi_i(t, z_r) + [h_i(t, z) - h_i(t, z_r)]\pi = \psi_i(t, x) + k_i(t, x)\pi, x = z - z_r \quad (7)$$

In Eqs. 5-7, the variable t is equal to $mT + [\text{mod}(i+1, 2)] \cdot \tau$, where m is an integer and mod denotes the module operation. Then, by rearranging phase sequence $\psi_1(t, x)$ and $\psi_2(t, x)$ in an interleaving way, a new combined sequence $\psi_{1x2}(t, x)$ can be obtained which is expressed as $\psi_i(mT + [\text{mod}(i+1, 2)] \cdot \tau, x)$. Since $\psi_{1x2}(t, x)$ is a sequence of wrapped differential phase, after phase unwrapping, the differential phase $\theta_{1x2}(t, x)$ of the interleaving sequence can be written as $\psi_{1x2}(t, x) + j(t, x)\pi$, where j is an integer determined by the traditional phase unwrapping algorithm. Furthermore, the differential phase and the phase change of the original probe pulse can be expressed as Eq. 8 and Eq. 9, respectively.

$$\theta_1(t, x) = \theta_{1x2}(t, x) \Big|_{t=mT} \quad (8)$$

$$\beta_1(t, x) = \theta_1(t, x) - \left[\sum_{q=0}^{N-1} \theta_1(qT, x) \right] / N \quad (9)$$

In the coherent Φ -OTDR system with a single frequency light, the linear characteristic of phase change after the perturbation position will be lost if the phase jumping exceeds π as shown in Fig. 1(b). But by the new process of phase

unwrapping with the auxiliary light in coherent Φ -OTDR system, the distribution of phase change of the original probe light does not simply show a whole linear profile or a whole chaotic profile. Instead, the phase change curve has many discontinuous regions which are mainly divided into two kinds of regions: linear region which is contributed by the correctly unwrapped phases and the chaotic region which is mainly induced by the wrongly unwrapped phases. To explain this result further, four typical relationships of the phase difference between the original probe signal and the auxiliary signal at a certain position are shown in Fig. 3.

Fig.3. Phase distribution with four pulses (a) ideal state (b) (c) wrong unwrapping (d) correct unwrapping

In Fig. 3, the red dots represent the differential phase θ_1 derived by the original probe light pulse sequence and the blue dots represent the differential phase θ_2 derived by the auxiliary light pulse sequence. They are aligned according to the time interval between the original probe light pulse and the auxiliary light pulse. For convenience, we assume that the phase change induced by the external perturbation increases linearly with time and here τ is just half of T in Fig. 3. Moreover, we assume that the absolute phase difference between the adjacent differential phases induced by the original probe light (as well as the auxiliary light) is more than π . In Fig. 3(a), it ignores the difference of the integrated phase along the fiber induced by the different light frequency. All the differential phases only contain the phase changes induced by the external perturbation. Therefore, the differential phases obtained by the original probe light and by the auxiliary light are all in the same line. However, in the practical application, since the phase integrals along a same length of fiber for different frequency lights are different, the interleaving results between the differential phases of the original probe light and the auxiliary light may exhibit many kinds of states as shown in Fig. 3(b), Fig. 3(c) and Fig. 3(d). Although the auxiliary light is introduced, the absolute phase difference between $\theta(0)$ and $\theta(\tau)$ in Fig. 3(b) and the one between $\theta(\tau)$ and $\theta(T)$ in Fig. 3(c) are still larger than π . So the traditional phase unwrapping algorithm for these states will still output wrong results, which results in a chaotic profile to the phase signal along these positions. Fortunately, the interleaving results at some positions also exhibit the state like Fig.3(a) and Fig. 3(d) in which the absolute phase difference between any adjacent pulses in the new combined sequence is less than π . For these positions, although the phase jumping of the original probe light has not been changed, the interim phase jumping in the new sequence is reduced and the traditional phase unwrapping algorithm can be correctly executed. Because the phase difference induced by the frequency difference between the original probe light and the auxiliary light changes slowly along the fiber, each linear region or chaotic region will last for a certain distance as shown in Fig. 4.

Fig.4. Demonstration of phase change for an arbitrary original pulse in the new process of phase unwrapping

Then the phase change induced by the large perturbation can be accurately demodulated based on the discontinuously linear regions. Similar to the coherent Φ -OTDR system with the single frequency light, the finally retrieved phase signal can be directly written as $\beta_1(t, x_B) - \beta_1(t, x_A)$.

3. Experimental setup and Result

Fig.5. Schematic diagram of the coherent Φ -OTDR system with/without the auxiliary light

The schematic diagram of the experimental setup for verifying our proposed method is shown in Fig. 5. Laser LD is a highly frequency-stabilized light source with the linewidth of less than 100 Hz. Its output light is divided into two parts by the first coupler OC1 with 90:10 splitting ratio. The light with 90% energy in the upper branch serves as the probe light, and the light in the lower branch serves as the local reference light. The upper light is then divided into two equal probe lights through the second coupler OC2. Then the two probe lights are modulated into two probe pulses with a 40 MHz acousto-optic modulator (AOM) and an 80 MHz AOM, respectively. In experiment, the probe pulse with the 40 MHz frequency shift serves as the original probe light and the other probe pulse with the 80 MHz frequency shift serves as the auxiliary light. The repeat frequencies of the two probe pulses are both 50 kHz, the pulse widths are both 200 ns and their temporal interval is about 9 μ s. Afterwards, the two pulses are combined through the 50:50 coupler OC3. The combined probe pulses are then amplified by an EDFA and injected into the test fiber by a circulator. A piezoelectric transducer (PZT) driven by a signal generator is set at about 1.25 km from the input end to simulate vibration signal. The Rayleigh scattering light returned from the fiber is mixed with the local reference light through a 50:50 coupler OC4 and is then received by a balanced photodetector BPD. VA is an amplifier. The sampling rate of the data acquisition card in PC is 312.5 MSa/s.

Fig.6. Superposition of (a) intensities and (b) phase changes at different times when the amplitude of driving signal is 2.5V in Φ -OTDR only using the original probe light

A sinusoidal signal with a frequency of 600 Hz and amplitude of 2.5V is applied to the PZT to simulate a small perturbation which induces phase jumpings less than π . If the Φ -OTDR works only with the original probe light, the intensity $\sqrt{I^2(t,z) + Q^2(t,z)}$ is plotted in Fig. 6(a). In this figure, we can see that the intensity in the region near 1.25 km are thicker than that in other regions. So there must be an event in this region. Fig. 5(b) shows the distribution of phase change when the reference position is chosen at 121.6 m. Obviously, at about 1.25 km, the amplitude of phase change is changed dramatically. And, before and behind the event region, the amplitude of phase change has no obvious change. The distribution of Fig. 5(b) is very consistent with that of Fig. 1(a). The final phase signal can be easily obtained which is not shown in this paper. Among 999 phase jumpings of this phase signal, its maximum value is 2.5796 rad. It proves that the whole linear phase change profile before and behind the event region means all phase jumpings of the phase signal are less than π and the phase signal can be correctly retrieved in the Φ -OTDR system based on the traditional phase unwrapping process with only one single frequency probe light.

Then the amplitude of the PZT driving signal is increased from 2.5 V to 5 V. The intensity and the phase change distribute obtained only with the original probe light are shown in Fig. 6(a) and Fig. 6(b), respectively.

Fig.7. Superposition of (a) intensities and (b) phase changes at different times when the amplitude of driving signal is 5V in Φ -OTDR only using the original probe light

Comparing Fig. 7(a) with Fig. 6(a), we find that they are similar with each other. However, in Fig. 7(b) the phase change curve behind the event region is quite chaotic, which is significantly different with that in Fig. 6(b). We cannot recover the accurate driving signal anymore. According to Fig. 1, it indicates that the phase jumping induced by the 5V PZT driving signal must exceed π .

Therefore, we use the proposed new process of phase unwrapping in this paper to retrieve this phase signal. According to Eqs. 5-9, by the aid of the auxiliary light (the 80 MHz frequency shift light), the phase change of the original probe light (the 40 MHz frequency shift light) is acquired and depicted in Fig. 8(a).

Fig.8. (a) Superposition of phase changes of the original probe light at different times when the amplitude of driving signal is 5V in the Φ -OTDR assisted by the auxiliary light and (b) the phase signal retrieved from (a) according to the proposed method.

From Fig. 8(a), we can find that the distribution of phase changes still has the discontinuous pattern. In the linear regions, the interim phase jumpings for the interleaving pulse sequence must be less than π . So the wrapped differential phases in these positions can be unwrapped correctly with the traditional phase unwrapping algorithm. Based on the phase changes in these linear regions, the final phase signal from the original probe light is retrieved as shown in Fig. 8(b). In Fig. 8(b), we can extract 999 phase jumpings from the difference between adjacent retrieved phases. For these results, there are 180 values which are greater than π , and the largest one is 3.7154 rad. Consequently, the chaotic profile in Fig. 7(b) is induced. However, the perfect result in Fig. 8(b) indicates that the phase jumping beyond π can be acquired by the proposed method.

4. Discussion and Conclusion

In experiment, the external perturbation simulated by the PZT driving signal is sinusoidal. Enlarging either the amplitude or the frequency of the sinusoidal signal can increase the maximum phase jumping of the measured phase signal.

Fig.9. The correctly recovered maximum phase jumping by the proposed method for different driving (a) frequency and (b) amplitude

When the amplitude of PZT driving signal is fixed at 5 V and its frequency is increased with a step of 100 Hz, the measured phase signal by the new proposed method is acquired and its maximum phase jumping is depicted in Fig. 9(a). Obviously, with the increase of the PZT driving frequency, the maximum phase jumping is increased from 0.8531 rad to 4.4601 rad. Then, the frequency of PZT driving signal is fixed at 700 Hz and its amplitude is decreased with a step of 0.5 V. Correspondingly, the maximum phase jumping of the measured phase signal is decreased from 4.4601 rad to 2.6271 rad, which is shown in Fig. 9(b). In a word, the measured phase jumping is increased gradually with the increase of the frequency/amplitude of the PZT driving signal. It also demonstrates that the measurable range of the external perturbation (e.g. driving frequency and amplitude in Fig. 9) is widened.

In conclusion, we have introduced the auxiliary light into the coherent Φ -OTDR system for enhancing the phase jumping to a higher value beyond π . To the best of our knowledge, it is the first time to discriminate the state of phase jumping by the profile of phase change in Φ -OTDR. In the new process of phase unwrapping, the original probe light pulse and the auxiliary light pulse are combined as a new pulse sequence. Then, according to the new combined pulse sequence, the traditional phase unwrapping algorithm can correctly work at some positions. These positions can form discontinuously linear regions. Based on these linear regions, the final phase signal whose phase jumping exceeds π can be acquired. In experiment, we first demonstrate the ability of the proposed method to judge and recover the phase jumping larger than π , so a sinusoidal waveform has been retrieved accurately by the new process of phase unwrapping. More experiments also show that more and larger phase jumpings up to 4.4601 rad can be recovered.

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