Improved location algorithm for multiple intrusions in distributed Sagnac fiber sensing system

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Abstract: An improved algorithm named “twice-FFT” for multi-point intrusion location in distributed Sagnac sensing system is proposed and demonstrated. To find the null-frequencies more accurately and efficiently, a second FFT is applied to the frequency spectrum of the phase signal caused by intrusion. After Gaussian fitting and searching the peak response frequency in the twice-FFT curve, the intrusion position could be calculated out stably. Meanwhile, the twice-FFT algorithm could solve the problem of multi-point intrusion location. Based on the experiment with twice-FFT algorithm, the location error less than 100m for single intrusion is achieved at any position along the total length of 41km, and the locating ability for two or three intrusions occurring simultaneously is also demonstrated.

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References and links

1. Introduction

Distributed optical fiber intrusion sensor is an important branch of the optical fiber sensing technology. With its characteristics of high sensitivity, passive components and one-dimensionally continuous distribution, it has been applied in many civil and industrial fields, such as regional security, oil and gas pipeline leaking monitoring, structural health monitoring and prevention along the communication chain [1–4].

Recently, a plenty of fiber structures have been proposed to detect and locate intrusion, which could be divided into two main kinds including the interferometric systems [5–7] and backscattering systems [8–10]. Even though the backscattering based techniques can realize a very high locating accuracy of several meters or less, the dynamic intrusion signals acting on the sensing fiber within a very short time could not be detected from the weak scattering lights, because of their time consumption and complex data processing. Oppositely, the interferometric system has very high real-time performance in detecting the intrusion signals by the strong interferometric light. In general, Mach-Zehnder, Michelson and Sagnac based interferometers are used to establish the monitoring system.

Comparing with other interferometers, Sagnac is insensitive to temperature variation and is of low expectation for light source, which makes it more practical and cheaper. A plenty of sensors has been proposed such as circle Sagnac, non-balanced Mach-Zehnder/Sagnac and dual-Sagnac [11–13]. In these structures, most of them locate intrusion events by searching null-frequencies in the frequency spectrum of the intrusion. However, the method of searching the null-frequencies is usually to be very difficult due to the low signal-noise-ratio of the frequency spectrum. A traditional way is to smooth the null-frequency curve first by a complex power estimation and wavelet transform technology. Then remove the down trend of the curve. At last find the minimal values of the null-frequency curve with a proper threshold. Although this method could find these null-frequencies in most cases, it is still complex and fallible in denoising and finding the accurate dips, especially in the cases that the intruders’ position is close to the reflector due to the low signal-noise-ratio [14–17]. As the result, the system would be in trouble with a high locating error and instability. Furthermore, the traditional locating method could not work when multiple intrusions take place simultaneously, due to the disorder of the frequency spectrum curve. Since multi-point intrusions occur easily at the same time along the long fiber with the length of several tens of kilometers in practical applications, it is necessary to investigate the reliable location algorithm for multiple intrusions in distributed optical fiber sensing system.

In this paper, an improved location algorithm named twice-FFT for distributed Sagnac optical fiber intrusion system is proposed. By applying a second FFT algorithm to the
frequency spectrum of the intrusion, the period of the frequency response curve could be obtained which determines the intrusion position. After that, a Gaussian fitting was used to improve the accuracy of the peak response frequency. Due to the twice-FFT algorithm is focus on the overall distribution of the frequency response curve rather than several specific dips, the intrusion position could be obtained more efficiently and more accurately. In addition, for multiple intrusions occurring simultaneously, each peak frequency in twice-FFT curve responding to certain intrusion still could be picked out independently, and thus all the intrusions could be extracted in sequence and their locations could be calculated out easily.

2. Sensing configuration and principle

2.1 Sensing -configuration

The non-balanced Mach-Zehnder/Sagnac structure, which enables the light to transmit along a single fiber by using a reflector at the end of the sensing fiber, provides simpler structure as well as stronger anti-ambient interference ability than other interferometric intrusion detection systems. It is selected to be the sensing structure in this paper as depicted in Fig. 1. Light from the broadband light source (BBS) is injected into an imbalanced Mach-Zehnder interferometer (IMZI) through a 3 × 3 coupler, and the third output port of the coupler is handled with large-bending loss to prevent the reflected light caused by the end face. From the output of 3dB coupler, the light injects into the sensing fiber. After reflected by the Faraday rotation mirror (FRM) at the end of the sensing fiber, the light will go back through the sensing fiber and IMZI, and then received by photo detectors (PD). When intrusion occurs on the sensing fiber, the phase of the light transmitting in the fiber will change according to the elasto-optical effect. Due to the lengths of the two arms of IMZI are different, the modulated phase would be different when the two beams of light propagate to the intrusion position through the two arms of the IMZI. It should be noted that the BBS of very low degree of polarization (DOP)(<2%) as well as the FRM could greatly decline the phenomenon of polarization-induced fading in the interferometer sensor system [18, 19].

2.2 The locating principle of twice-FFT for single-point intrusion

There are four light routes in the system, which are I: A-B-D-E-F-E-D-C-A; II: A-C-D-E-F-E-D-B-A; III: A-B-D-E-F-E-D-B-A; and IV: A-C-D-E-F-E-D-C-A. Since the length of the delay fiber is much longer than the coherent length of the source, only the signal light in the route I and II are able to interfere with each other. Then the light through route III and IV could be considered as the direct current light to be eliminated easily.

Assuming that single intrusion is applied on the sensing fiber, the intrusion signal could be described as the superposition of various sine waves with different frequencies and magnitudes. The phase change of the signal light could be given as:

\[
\varphi(t) = \sum_{i=1}^{W} \psi_i \sin (\omega_i t + \phi_i) \tag{1}
\]

where \(\psi_i\), \(\omega_i\) and \(\phi_i\) are the amplitude, frequency and initial phase of each single sine component, \(W\) is a positive integer. Then the phase difference between route I and route II caused by the intrusion could be described as:
\[
\Delta \varphi(t) = \sum_{i=1}^{M} \{ \psi_i \sin[\omega_i (t - \tau_i) + \phi_i] + \psi_i \sin[\omega_i (t - \tau_i) + \phi_i] \\
- \psi_i \sin[\omega_i (t - \tau_i) + \phi_i] - \psi_i \sin[\omega_i (t - \tau_i) + \phi_i] \}
= 4 \sum_{i=1}^{M} \psi_i \sin(\omega_i \frac{nL_i}{2c}) \cos(\omega_i \frac{nL}{c}) \cos[\omega_i (t - \frac{n(2L_0 + L_d)}{2c}) + \phi_i]
\]

where \(\tau_1, \tau_2\) are the time consumption that the signal light travel through E-D-C-A and E-F-E-D-C-A in route I, respectively, and \(\tau_3, \tau_4\) refer to the time consumption the signal light transmitted through E-D-B-A and E-F-E-D-B-A in route II, respectively; \(L_0\) and \(L_d\) are the length of sensing fiber and the delay fiber, respectively; \(L\) is the distance between the intrusion point and FRM; \(n\) and \(c\) are the refractive index of the fiber and the light speed in vacuum. From Eq. (2), if the frequency of certain sine component \(f_{null}\) satisfies:

\[
f_{null} = \frac{\omega_i}{2\pi} = \frac{(2k-1)c}{4nL}, k=1,2,3\ldots
\]

\(\Delta \varphi(t)\) will be constant to be zero, when \(L_d\) is short enough and the effect of the sine item could be ignored. In this case, these eigenfrequencies are called null frequencies.

Thus, by applying FFT to \(\Delta \varphi(t)\) demodulated from the interference intensity [20–22], the frequency spectrum with obvious period signal could be obtained. After picking out these null-frequencies, the intrusion location could be got from Eq. (3). However, suffering from the limitations of the intrusion frequency components, optical transmission loss and low SNR resulted from the PD and environmental noise, the null-frequency curves are always rough and irregular, as shown in Fig. 2. Obviously, it is very hard to find the accurate null-frequencies, which increases the locating difficulty and error. Thus, an improved data processing method in searching the null-frequencies exactly and quickly has become a key issue in the distributed Sagnac intrusion sensing system.

Fig. 2. The actually obtained null-frequency curve with the intrusion position \(L = 17690\)m.

To solve this problem, we proposed a locating method called “twice-FFT”, i.e. the second time Fast Fourier Transform locating algorithm. Supposing the interval of the adjacent null frequencies is \(\Delta f_{null}\), from Eq. (3), we can obtain

\[
L = \frac{c}{2n\Delta f_{null}}
\]

Thus, by applying FFT to the rough frequency spectrum of \(\Delta \varphi(t)\), a new frequency spectrum called twice-FFT curve could be obtained, in which the frequency of the main peak is equal to the reciprocal of \(\Delta f_{null}\). Then the intrusion location could be calculated from Eq. (4). Owing that the FFT could effectively eliminate the noise of the narrow-band signal, even though the SNR of the frequency spectrum of \(\Delta \varphi(t)\) is low, the second FFT analysis could extract the period of the null-frequencies directly and exactly, without the need of finding the null-frequencies one by one.
The flow diagram of the twice-FFT algorithm is shown in Fig. 3, and the basic procedures are listed below:

(1) Start;
(2) Collect the interference data from the data acquisition card;
(3) Intercept the effective fragment of the two time-domain interference signal from the first point above the setting amplitude threshold, which are defined as: $I_1(t)$ and $I_2(t)$;
(4) Demodulate the phase change $\Delta \phi(t)$ caused by intrusion from $I_1(t)$ and $I_2(t)$ through phase demodulation method, for example synthetic-heterodyne interferometric demodulation method [21];
(5) Apply the first FFT to $\Delta \phi(t)$, and obtain the frequency spectrum curve, $H_0(f) = \text{FFT}[\Delta \phi(t)];$
(6) Intercept the effective fragment of $H_0(f)$ with clear periodicity, $H_1(f)$.
(7) Fit $H_1(f)$, and obtain its down trend of contour curve, $H_2(f)$.
(8) Remove the down trend of $H_1(f)$ by subtracting $H_1(f)$ and $H_2(f)$ in order to reduce the useless low frequency of the curve, and then obtain the normalized curve $H_3(f)$;
(9) Apply the second FFT on $H_3(f)$ and the period of the curve contour could be extracted. The new frequency response curve is called twice-FFT curve, $H_4(f)$;
(10) Estimate the peak frequency $f_{\text{peak}}$ in the twice-FFT curve by Gaussian fitting, which has a relationship with the original null-frequency interval $\Delta f_{\text{null}}$ of $f_0$. 

Fig. 3. The flow diagram of the twice-FFT algorithm.
\[ f_{\text{peak}} = \varepsilon / \Delta f_{\text{null}} \]  \hspace{1cm} (5)

where \( \varepsilon \) is the ratio of sampling rate and data length which could be seen as a constant.

(11) Calculate the length \( L \) through Eq. (4) and (5)

\[ L = \frac{c f_{\text{peak}}}{2n\varepsilon} \]  \hspace{1cm} (6)

(12) End.

We take the frequency spectrum in Fig. 2 as the example. The processing results of step (5)-(10) are shown in Figs. 4(a)-4(f), respectively. We obtain twice-FFT curve with high SNR and distinct frequency peak. In our experiment, the ratio \( \varepsilon \) is equal to 40/3. The Gaussian fitting peak frequency \( f_{\text{peak}} \) is 0.002309Hz. From Eq. (6), a null-frequency interval of 5774.5Hz and the intrusion position of 17695m with an error of 5m can be acquired.

![The process results of twice-FFT algorithm with the intrusion position \( L = 17690m \): (a) \( H_0(\omega) \). (b) \( H_1(\omega) \). (c) \( H_2(\omega) \). (d) \( H_3(\omega) \). (e) \( H_4(\omega) \). (f) the peak frequency in twice-FFT curve with Gaussian fitting.](image)

From above, even though the null-frequencies could not be found easily in its original frequency spectrum, the twice-FFT algorithm could find the period of null-frequencies effectively and easily. Thus, the twice-FFT algorithm can greatly improve the system stability and location reliability.

2.3 The locating principle of twice-FFT for multi-point intrusion events

In practical applications, the length of the sensing fiber could be more than several tens of kilometers. Multiple intrusions are likely to occur at the same time. From section 2.1, the traditional locating method depends on a clear null-frequency curve. If several intrusions at different positions are applied on the sensing fiber simultaneously, the phase change of the signal light would disorder compared with the initial periodical curve according to Eq. (2). Thus, the system could not locate any intruder. However, the twice-FFT algorithm can solve this problem properly.

To simplify the multi-point intrusion process, the condition of two intrusions is firstly discussed. Supposing two intrusions are applied onto the points P and Q simultaneously, as shown in Fig. 5. The total modulated phase difference \( \Delta \phi_{P,Q}(t) \) between route I and route II caused by the two disturbances should be:
\[
\Delta \phi_{P,Q}(t) = \Delta \phi_P(t) + \Delta \phi_Q(t)
\]
\[
= 4 \sum_{i=1}^{M} \psi_1 \sin(\omega_1 \frac{n L_1}{2c}) \cos(\omega_1 \frac{n L_1}{c}) \cos[\omega_1 (t - \frac{n(2L_0 + L_d)}{2c})] + \phi_1]
\]
\[
+ 4 \sum_{j=1}^{N} \psi_2 \sin(\omega_2 \frac{n L_2}{2c}) \cos(\omega_2 \frac{n L_2}{c}) \cos[\omega_2 (t - \frac{n(2L_0 + L_d)}{2c})] + \phi_2]
\]

where \(\Delta \phi_P(t)\) and \(\Delta \phi_Q(t)\) are the phase difference introduced by the first and second intrusion independently; \(L_1\) and \(L_2\) are the distance between each intrusion and FRM respectively; \(\psi_1, \omega_1, \Phi_1\) are the amplitude, frequency and initial phase of each single sine component of intruder at P; \(\psi_2, \omega_2, \Phi_2\) are the amplitude, frequency and initial phase of each single sine component of the intruder at Q. \(M, N\) are the positive integer corresponding to the number of frequency components of each intrusion respectively.

Fig. 5. The schematic diagram of multi-point intrusion along the sensing fiber.

From Eq. (7), the phase difference between the light transmitting in route I and II is no longer dependent on one single intrusion source. The null-frequency curve of each intrusion would be interacted with each other and there is no regular null-frequencies remaining. However, Fourier transform is a linear transformation, so the spectrum of the \(\Delta \phi_{P,Q}(t)\) could be considered as the sum of \(\Delta \phi_P(t)\) and \(\Delta \phi_Q(t)\)’s spectra. By employing twice-FFT algorithm, the original interval of the adjacent null frequencies \(\Delta f_{\text{null-P}}\) and \(\Delta f_{\text{null-Q}}\) still could be conveniently obtained. Figures 6(a) and (b) show a typical null-frequency curve and its twice-FFT curve when two intrusion events applied on the fiber simultaneously. It can be seen that the frequency spectrum of \(\Delta \phi_{P,Q}(t)\) is seriously disordered in Fig. 6(a), while two main peaks \(f_{\text{peak-1}}\) and \(f_{\text{peak-2}}\) in Fig. 6(b) corresponding to the two intrusions are clear and could be extracted easily. Based on Eq. (6), the accurate position of each intrusion should be calculated as:

\[
L_i = \frac{cf_{\text{peak-i}}}{2n\epsilon}, \quad i = 1, 2
\]

Fig. 6. The locating results when two intrusions occur on the sensing fiber simultaneously: (a) the disordered null-frequency curve. (b) twice-FFT curve.

Similarly, as \(k\) intrusion events occur simultaneously on the fiber, the accurate positions for each intrusion point can be obtained through the following equation:

\[
L_k = \frac{cf_{\text{peak-k}}}{2n\epsilon}, \quad k = 1, 2, 3\ldots
\]
where $f_{\text{peak}-k}$ is the frequency of the $k$th peak of the twice-FFT curve.

3. Experimental results and discussion

The experimental setup of the distributed optical fiber intrusion sensing system is shown in Fig. 1. An erbium doped fiber amplifier (EDFA) with a maximum power of 10mW, ranged from 1525 nm to 1565 nm, is used to illuminate the interferometer as the BBS. A section of 1km standard single mode fiber was used as the delay fiber. A total length of 41km standard single mode fiber which is combined by five fiber plates is used in the system as the sensing fiber. Two photodiodes are employed to receive the interferer light and the converted electronic signals are collected by the data acquisition card. LabVIEW software is used to process the data including phase demodulating module, twice-FFT algorithm module, displaying and alarming module.

3.1 The locating results of twice-FFT for single-point intrusion

In the experimental process, five joint points of the fiber plates are selected as the intrusion positions. The distances between each point and FRM are 10586m, 11642m, 17690m, 37741m and 41707m, respectively. A wide-band vibration generator is adopted to simulate the intruder at every test point. The typical twice-FFT curves of them are given in Fig. 7. Although each null-frequency curve of Fig. 7(a) shows periodicity pattern, it is still very hard to obtain the null-frequencies from these rough curves. However, a very clear peak frequency could be found in each twice-FFT curve of Fig. 7(b). Due to the searching process of the peak frequency in Fig. 7(b) is much simpler and more precise, the twice-FFT algorithm would be more efficient and stable.

Fig. 7. (a) The original null-frequency curves and (b) twice-FFT curves for different intrusion points: (1) $L = 10586\text{m}$; (2) $L = 11642\text{m}$; (3) $L = 17690\text{m}$; (4) $L = 37741\text{m}$; (5) $L = 41707\text{m}$.

In order to compare the stability of the twice-FFT algorithm with the traditional null-frequency searching method, 30 times intrusion events are imposed on each test point, and the data are processed by the two methods in real time. The experimental results are presented in Figs. 8(a) and 8(b) respectively.
In Fig. 8(a), the traditional null-frequencies searching method performs well only when the distance between intruder and FRM is very long. The locating error would rapidly increase while the distance is reducing. For $L = 10586m, 11642m$ and $17690m$, the locating errors for the traditional null-frequency searching method always fluctuate within several hundreds meters and sometimes the max locating error could reach to tens of kilometers which means positioning failure. The main reason is that there are only few null-frequencies in the curve when the distance is short, and the misjudging error would be amplified according to Eq. (4).

![Fig. 8. The locating results for 30 times intrusion events at five different points: (a) by traditional null-frequencies searching method; (b) by twice-FFT algorithm.](image)

In Fig. 8(b), the locating position by twice-FFT algorithm is much more concentrated to the real intrusion position than the results in Fig. 8(a). The maximal locating error is less than 100m at the five different points. Because the twice-FFT algorithm pays attention to the curve contour rather than the accurate null-frequencies, the misjudging error could be avoided properly and the influence of $L$ would also become much smaller than the traditional null-frequency searching method. Thus, higher stability and accuracy of twice-FFT algorithm could be achieved.

### 3.2 The locating results of twice-FFT for multi-point intrusion events

Firstly, two intruders are applied on $L_1 = 11642m$ and $L_2 = 41707m$ simultaneously, and the original null-frequency curve is shown in Fig. 9(a). By using twice-FFT algorithm, two peak frequencies $f_{peak-1}$ and $f_{peak-2}$ can be picked out easily as depicted in Fig. 9(b) corresponding to...
the intrusion positions of $L_1 = 11570\text{m}$ and $L_2 = 41841\text{m}$ with locating errors of 72m and 134m, respectively.

Furthermore, three intruders experiment is also implemented. Three points of $L_1 = 11642\text{m}$, $L_2 = 17690\text{m}$ and $L_3 = 41687\text{m}$ are selected to be tested. The original null-frequency curve and twice-FFT curve are shown in Fig. 10. According to Eq. (9), the location of the intruders are calculated to be $11573\text{m}$, $17605\text{m}$ and $41679\text{m}$ with the errors of 69m, 85m and 8m, respectively.

At last, multiple groups of experiments are accomplished to demonstrate the reliability and stability of twice-FFT algorithm. The results are listed in Table 1, with the locating errors of less than 150m and 200m for two-points and three-points intrusion, respectively. Although the locating error for multi-point intrusion is a little larger than the single point intrusion because of the crosstalk among the different components, these results still approve that the twice-FFT algorithm could detect and locate the multi-point intrusion events effectively. In addition, by increasing sampling rate or employing more accurate frequency estimation methods could further improve the locating accuracy.

Table 1. Locating Results in Multiple Groups of Experiments Using Twice-FFT Algorithm

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4. Conclusions

We have proposed a novel locating algorithm called twice-FFT for distributed Sagnac optical fiber intrusion sensing system. Through a second FFT against the original rough null-frequency curve, the accurate null-frequency interval and the intrusion position could be obtained. Compared with the traditional null-frequencies directly searching method, the twice-FFT algorithm doesn’t need the complex and fallible dips searching mathematical operation. Thus, it could be more efficient and avoid the large error caused by the misjudging of the null-frequencies and enhance the locating stability of the system. Furthermore, according to the analysis from the frequency domain, the twice-FFT algorithm has another advantage of multi-point intrusion locating, which is very valuable for the distributed optical fiber intrusion sensing system. A plenty of experiments have been accomplished with a small locating error of less than 100m for single point intrusion up to the total length of 41km. The results demonstrate that the locating accuracy is free from the distance between the intruder and the sensing fiber end, and the strong stability of the locating ability has been proved. The multi-point intrusion experiments results demonstrate this algorithm can demodulate each intruder effectively and conveniently.

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