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Macheng Lai
Kuan Peng
Yiyang Luo
Xiaolei Li
Yanpeng Li
Fan Ai
Deming Liu
Qizhen Sun
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Macheng Lai, Kuan Peng, Yiyang Luo, Xiaolei Li, Yanpeng Li, Fan Ai, Deming Liu, and Qizhen Sun

School of Optical and Electronic Information, National Engineering Laboratory for Next Generation Internet Access System, Huazhong University of Science and Technology, Wuhan 430074, China

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Abstract: An ultra-long distance distributed intrusion detecting system assisted with power amplification and sensitivity enhancement is proposed and demonstrated. First, through introducing multiple bidirectional amplifiers into the unbalanced Mach–Zehnder/Sagnac interferometer-based fiber sensing link, the sensing distance is remarkably extended, and second, the signal-to-noise ratio of this sensing system is significantly improved from less than 2 to 6–8 dB by coating the sensing fiber with organic silicone polymer. Furthermore, the high-order downtrend fitting function is adopted to implement the intrusion locating of ultralong distance sensing; the zero-padding fast Fourier transform algorithm and multiple-averaging method are jointly utilized for the improvement of the locating accuracy. Experimentally, a proof-of-concept distributed intrusion detecting system is constructed with the employment of bidirectional amplification. In particular, the ultra-long sensing distance up to 226.337 km is implemented, which is the reported longest distributed sensing system to the best of our knowledge.

Index Terms: Fiber-optic distributed sensor, intrusion detecting, ultra-long sensing distance, bi-directional amplification, polymer package.

1. Introduction
Distributed optical fiber intrusion detecting systems have attracted intensive research due to their versatile applications, such as the residential protection, the security defense in optical communication link and the pipeline invasion monitoring [1]. From the first implementation of distributed optical fiber intrusion detecting through monitoring the optical intensity change [2], various mechanisms have been proposed and demonstrated, including fiber-optic scattering and interferometry, etc. [3]. Recently, with the development of fiber sensing techniques and the demand of large-coverage monitoring, scientific interest is shifted into the extension of sensing distance.

In particular, to realize the ultra-long distance distributed intrusion detecting, phase sensitive optical time-domain reflectometry (Φ-OTDR) is adopted. By injecting a pulse of highly coherent light into a conventional single-mode fiber, the detected optical power trace, which is produced by
the coherent interference of the light reflected from different scattering centers, shows variations synchronized with the vibration frequency [4]–[6]. The longest sensing distance of the Φ-OTDR up to 175 km was reported by Wang et al. in 2014 [7], through introducing the combination of co-pumping 2nd-order Raman amplification based on random fiber lasing, counter-pumping 1st-order Raman amplification, and counter-pumping Brillouin amplification scheme. Meanwhile, Brillouin optical time-domain analyzer (BOTDA) based on the detection of frequency of stimulated Brillouin scattering (SBS) is also used to realize the ultra-long distance distributed intrusion detecting [8]–[10]. In 2016, Qian et al. achieved the BOTDA sensing system with the sensing distance up to 157.68 km, with the combination of random fiber laser Raman pumping and low-noise laser-diode-Raman pumping scheme [11]. Also, polarization optical time domain reflectometry (P-OTDR) can also realize long-distance intrusion sensing through detecting birefringence change along sensing fiber [12]. By using second-order Raman amplification pumped by a long fiber laser formed by two fiber Bragg gratings (FBGs) located at both ends of the fiber, a P-OTDR intrusion detecting system with the distance of 106 km was demonstrated by Peng in 2013 [13]. However, the aforementioned sensing systems possess slow response and high cost, which extremely limits their practical applications [14], [15].

Alternatively, the interferometric mechanism based distributed sensing systems characterized by numerous advantages, such as high sensitivity, large dynamic range and wide response frequency band [16], pave another way for ultra-long distance intrusion detecting. Moreover, composite interference structures [17]–[20] and novel locating algorithms [21]–[24] reported in recent years have made great progress in this sensing scheme. By employing dual-Sagnac interference structure, a 50 km intrusion detecting system is realized by Yuan et al. with time delay estimation to locate intrusions [25]. Particularly, with the unbalanced Mach–Zehnder/Sagnac interference (MZI-SI) structure, a 41 km distributed optical fiber intrusion sensing system was carried out by our research group in 2014 and the twice fast Fourier transform (2-FFT) algorithm was introduced to greatly reduce the locating error [23]. More recently, to realize a sensing distance of 130 km, the similar MZI-SI structure and harmonic peak locations based on the 2-FFT algorithm are implemented by Zhao et al. in 2016 [24]. However, the limited sensing distance can not meet the demands in some long distance occasions, for instance, the border patrol. Therefore, further increasing the sensing distance is of great significance.

In this paper, an ultra-long distance distributed intrusion detecting system is proposed and demonstrated. By introducing dual-stage bi-directional amplification, the sensing distance is significantly extended, which is the reported longest intrusion detecting system to the best of our knowledge. Meanwhile, by employing the organic silicon polymer as the packaging material encircling the sensing fiber, the signal-to-noise ratio (SNR) is greatly improved. Furthermore, with the help of the modified 2-FFT algorithm by employing the high order downtrend fitting function, the zero-padding fast Fourier transform algorithm and multiple-averaging method, the intrusion locating with higher accuracy for long distance sensing link is realized.

2. Working Principle

The schematic diagram of the sensing system is illustrated in Fig. 1, consisting of wideband optical source (WBS), unbalanced Mach–Zehnder interferometer (UMZI), optical sensing fiber (OSF) with a Faraday rotation mirror (FRM) at the end, multiple bi-directional amplifiers (BAs) in the sensing fiber link, and signal processing unit (SPU). With the reflection of FRM, the sensing fiber transports the forward and reverse signal simultaneously to form a Sagnac loop, and then the MZI-SI structure is established in this system [23]. Light output from the WBS is launched into the OSF through the UMZI and then reflected by FRM and goes back to the UMZI, resulting in bidirectional transmission in the OSF. Finally, the interference signals out from UMZI are detected and processed by SPU composed of two photodetectors (PD), data acquisition card (DAQ) and personal computer (PC). When intrusion occurs on the OSF, the phase of the light transmitting through the OSF will change due to the elasto-optical effect. Although there are four light routes in the MZI-SI structure, only two of them with the identical fiber length can interfere with each other, and the other two routes should
be considered as the direct current light. Since the frequency spectrum of the phase change is periodic and the interval of null-frequencies is proportional to the position of intrusion, the intrusion can be easily located by the 2-FFT algorithm [23].

Specifically, to realize ultra-long distance distributed intrusion detection, a series of BAs are inserted in OSF to amplify the sensing signal and sensitivity-enhanced fiber package is developed to improve SNR. Besides, modified 2-FFT algorithm is studied to improve the locating accuracy for the ultra-long distance sensing system.

2.1 Bi-Directional Amplification

To compensate the transmission loss of the sensing link and extend the sensing distance, the optical amplifiers are introduced. The configuration of the BA employed in this system is shown in Fig. 2. As the gain medium, a coil of erbium doped fiber (EDF, 6 m M-12) is adopted to amplify the weak wideband optical signal with the pump of a 975 nm semiconductor laser. Compared with the standard erbium doped fiber amplifier (EDFA), the isolators are removed in the BA to achieve bi-directional optical signal amplification in the long-distance sensing link. Especially, two band-pass filters (BPFs) are placed to filter amplified spontaneous emission (ASE) noise in two directions to realize linear amplification, which can further extend the sensing distance. To simplify the structure and lower the cost, BA is designed with only single end pump. Although there is slight difference in gain and noise between forward and backward amplification, both of them are still worked in the linear amplification region, and therefore has no impact on intrusion detecting. Additionally, the cascaded BAs are utilized to realize multi-stage relay amplification and further extend the sensing distance.

In order to achieve linear amplification of the analog sensing signal, the operating bandwidth should be optimized. By using Waveshaper (WS-AA-4000S-ZZ-H) as the BPF to adjust the bandwidth, the gain curves at different bandwidths are obtained as depicted in Fig. 3. It can be seen that the gain flatness increases with the bandwidth getting narrower. On the other hand, broader bandwidth i.e. shorter coherent length of the light source is better for the Sagnac interference (SI) due to the reduced backscattering noise [26]. Therefore, there is a trade-off in the bandwidth requirement between the linear amplification and SI. Here, the bandwidth of the BPFs is chosen as
6.5 nm (from 1545.75 to 1552.25 nm) under our laboratory condition. In addition, to compensate the loss of 100 km relay distance of the sensing link, the gain of the BA is designed as 20 dB.

2.2 Sensitivity-Enhanced Fiber Package

In our ultra-long distance intrusion detecting system, signal-to-noise ratio (SNR) is decreased due to the effect of noise accumulation. To improve SNR for high sensitive detection as well as the robust, special package of the bare fiber is studied by using organic silicone polymer, of which the elasticity modulus and poisson ratio are 25 Mpa and the 0.48, respectively.

The packaging process is described as follows. 1) Three 20 cm long hollow customized brass moulds with different inner diameters are designed. 2) Put a plastic tube into the inner hole of the mould and traverse the sensing bare fiber through it. With the help of two fiber fixtures at two ends, the bare fiber can be kept straight and maintained in the center of the tube. 3) Fill the plastic tube with mixture of liquid organic silicone and curing agent with the proportion of 5:1. 4) After curing reaction for 24 h, put the packaged fiber at room temperature with another week to stabilize the material. Finally, special packaged fiber with bare fiber in the middle, polymer sensitivity-enhanced layer and plastic tube based protection layer at the external surface is obtained.

With this polymer package, when there is an intrusion acting on the sensing fiber, the polymer is squeezed into the axial direction and strains the fiber to get an obvious phase change, thereby increasing SNR and sensitivity [27]. Meanwhile, the plastic tube can provide protection to the polymer package from pointed damages.

2.3 The Modified 2-FFT Algorithm

In our previous work, we have reported 2-FFT algorithm for distributed intrusion sensing system to achieve higher locating accuracy and multi-location [23]. However, the downtrend fitting parameters are not suitable for the ultra-long distance sensing system, owing to more serious noise. Therefore, a modified 2-FFT algorithm is applied, which employs higher order of the downtrend fitting function from 3 to 8 and longer feature fragment from 5000 points to 64k points before the second FFT procedure. The higher order function can expand the bandwidth of low-pass filter to thoroughly eliminate the downtrend curve and improve the locating accuracy. Meanwhile, the longer feature fragment can improve spectral resolution of FFT to obtain an exact peak-seeking result. Meanwhile, for the sustained vibration induced by intrusion, the original data of phase change from certain position are divided into severall fragments and each fragment is demodulated separately, and then the average of the multiple locating results is served as the measurement value, to further reduce the location error. In our experiments, the phase change data is divided into eight segments. As described in Fig. 4, the modified 2-FFT algorithm includes the following steps. 1) Collect 512k interference data from DAQ and then upload it to PC. 2) Demodulate phase change data by differential and integral algorithm [28], [29] and divide it into 8 segments. 3) Apply the first FFT to every data fragment and obtain the frequency spectrum curve $H_0(f)$. 4) Fit with high order downtrend
fitting function at the order of 8 and acquire its contour curve $H_1(f)$. 5) Subtract $H_1(f)$ from $H_0(f)$ to remove useless low frequency and obtain the normalized curve. 6) Expand the effective feature fragment extracting from the normalized curve with the method of zero-padding from 5000 points to 64k points and defined it as $H_2(f)$. 7) By applying the second FFT to $H_2(f)$, the interval of null-frequencies is obtained and the position of intrusion can be located. 8) From the distribution of the locating results of the eight segments, we select the dense section as the effective data and set the central value of the effective data as the median. To increase the locating reliability, the locating result, the deviation from which to the median is over than the threshold such as 100 m, are discarded as useless datum, and the average of the remanent results is served as the measurement value.
3. Experimental Results and Discussion

To demonstrate the proposed sensing scheme, a proof-of-concept experiment with dual-stage amplification is conducted. Filtering the optical signal from an ASE optical source with a predetermined BPF, WBS is achieved with optical intensity of 9.672 dBm, and polarization degree less than 1% which can be treated as an unpolarized optical source to eliminate the polarization effect. The acquisition of sensing data is accomplished at the sampling rate of 1 M/s by PCI4712 installed in PC. The voltage slightly higher than the background noise level is set as the threshold to identify the intrusions.

The total sensing distance is up to 226.337 km, consisting of six fiber spools with the lengths of 50 500, 50 496, 50 819, 24 041, 26 440 and 24 041 m, respectively. The fiber length between 3 dB coupler and the first BA is 74.522 km, which is determined by initial optical intensity injected into sensing fiber and linear gain region of BA. The fiber length between the first BA and the second BA is set as 100.996 km, which introduces the optical attenuation of around 20 dB, corresponding to the gain compensation of 20 dB provided by the BA. Since the optical signal is transported from the second BA and then goes back to it through the reflection of FRM, the length between the second BA and FRM is about 50.5 km which is half of the length between the two BAs. Meanwhile, defining the position of FRM in this system as the starting point, five positions at the distances of 50 500, 100 996, 151 815, 175 856, and 202 296 m from FRM are selected as the test points. The wideband vibration generator is adopted to simulate the intrusion at each test point.

When there is intrusion acting on the sensing fiber at the time of 10 ms, the voltage jump can be obviously seen as shown in the insets of Fig. 5(a)–(d). With signal processing on the interference data, the 2-FFT curves of different test positions at 50 500, 100 996, 151 815, and 202 296 m are separately displayed in Fig. 5(a)–(d), of which the x axis is distance proportional to frequency.
spectrum. By means of peak seeking, the locating measurement results are 50 544, 100 985, 151 734, and 202 686 m, respectively, which is close to the actual positions. It should be noted that by inserting multiple BAs into the sensing link, the sensing distance can be further extended in theory. However, the intensity and phase noise of the optical signal will become steadily worse at the same time, resulting in the deterioration of locating accuracy or even locating failure.

To compare the denoising effect with different downtrend fitting orders, the experiments are performed under the same condition for different orders, and the processed data at order of 3 and 8 are shown in Fig. 6. It is obvious that with the high order of 8, the downtrend curve can be thoroughly eliminated, acquiring a high locating accuracy.

In order to test the reliability of this sensing system, 50 times single intrusion events are continuously applied on each test point. The locating error of all the samples for the five test points are recorded in Fig. 7, of which the maximum value is less than ±400 m while the minimum value is only 11 m. Meanwhile, the average of the 50 samples for each test point is calculated and depicted in Fig. 8. It can be seen that with the method of multiple averaging, the locating error is further decreased to less than −150 m. In addition, the locating error increases with sensing distance due to weak interference signals which lower the SNR.

The absolute value distribution of locating error in multiple intrusions experiments is also shown in Fig. 9. It demonstrates that modified 2-FFT algorithm can still locate the multiple intrusions, but the locating error is larger than only single intrusion on account of the crosstalk among the different frequency components, and the locating error of two point intrusions is less than 600 m, while the locating error of three point intrusions is within 950 m. Although the locating error is relatively high for multiple intrusions at present, it can be further improved in future work by optimizing the locating algorithm and system SNR.

Moreover, to testify the sensitivity enhancement effect of polymer fiber package, 20 cm length packaged fibers with the diameters of 3, 4, and 5 mm are fabricated separately and then compared.
with bare fiber and indoor fiber cable with the same length under the same experimental condition with piezoelectric transducer (PZT) as vibration generator. The SNRs at three typical vibration frequencies of 100, 150 and 200 Hz are respectively tested, as exhibited in Fig. 10. It is obvious that the bare fiber without any protection has the highest sensitivity with SNR from 8.3 to 9.5 dB. Due to the silk interlayer of the indoor fiber cable, the intrusion detecting capacity is too weak with the SNR less than 2 dB. While, the polymer packaged fiber can not only provide a protection for the sensing fiber, but also improve the SNR at certain extent. And larger packaging diameter is, higher SNR as well as higher sensitivity is. For 5 mm diameter packaged fiber, the SNRs at different vibration frequencies are within the range from 6 to 8 dB, which improve over 4 dB than the indoor fiber cable. Specifically, the maximum SNR of 8 dB is achieved at the vibration frequency of 150 Hz.
It should be noted that the SNRs at different vibration frequencies are some different for the same fiber, which is caused by the resonant frequency of PZT.

4. Conclusion
The ultra-long distance distributed intrusion detecting system is proposed and proof-of-concept demonstrated. Particularly, the sensing distance is extended to 226.337 km due to the utilization of multiple BAs. By introducing the special packaging technique of the sensing fiber, the sensitivity is considerably enhanced. Assisted by the modified 2-FFT algorithm, the intrusion locating is realized with a high accuracy and reliability. Although the performance still needs to be improved, it is of broad application prospects, which can be applied not only in the near-distance cases such as the district alarm, but also in the long-distance situations such as the border patrol and submarine communication link security defense, etc.

References


