Fiber fault location utilizing traffic signal in optical network

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Abstract: We propose and experimentally demonstrate a method for fault location in optical communication network. This method utilizes the traffic signal transmitted across the network as probe signal, and then locates the fault by correlation technique. Compared with conventional techniques, our method has a simple structure and low operation expenditure, because no additional device is used, such as light source, modulator and signal generator. The correlation detection in this method overcomes the tradeoff between spatial resolution and measurement range in pulse ranging technique. Moreover, signal extraction process can improve the location result considerably. Experimental results show that we achieve a spatial resolution of 8 cm and detection range of over 23 km with −8-dBm mean launched power in optical network based on synchronous digital hierarchy protocols.

OCIS codes: (060.2300) Fiber measurements; (120.4825) Optical time domain reflectometry; (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems.

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1. Introduction

For the high-speed, large-capacity communication networks at present, instantaneous faults in transmission line will lead to service interruption and mass data loss. The troubleshooting in optical networks has attracted extensive attentions [1–3]. Conventional method uses optical time-domain reflectometer (OTDR) to detect faults. An OTDR usually excites an optical pulse at a fixed wavelength as probe light, which is only suitable for locating the fault in single transmission line. Some wavelength-tunable OTDR has been proposed recently for wavelength-division-multiplexing passive optical network (WDM-PON) [4–8]. Considering the wide constructed optical access networks like fiber-to-the-home/building, the fault location requires a large number of OTDRs which will incur great maintaining cost.

Recently, in order to reduce the operation expenditure (OPEX), some researchers proposed to integrate the OTDR function into communication equipment, utilizing the light source of the transmitter as probe light source. For example, Lim *et al.* [9] applied this method in WDM-PON to avoid the trouble of the probe wavelength adjustment on each dedicated path. In their configuration, a switch was integrated in the transmitter module to switch between communication data path and probe pulse path. Schmuck *et al.* [10] developed the method through embedding a photo detector into the transmitter module to receive the reflected probe signal. However, the pulse generator of OTDR is still a burden for the OPEX and the communication needs to be halted during the fault location in this kind of method. Moreover, there exists a crucial drawback in OTDR of the tradeoff between spatial resolution and measurable range due to its principle of the pulse ranging technique.

We note that correlation detection with random signal [11] or chaotic signal [12] could break the tradeoff. Biain *et al.* [13] and Takushima *et al.* [14] assumed that the traffic signal in transmission line vibrate in random form. And then they utilized a pseudo-random code generator to modulate the transmitter and simulated the correlation detection with this pseudo-random signal. But the real traffic signal is not in random form and different optical networks have their own signal forms. For example, in time-domain-multiplexing (TDM) optical network the downstream signal broadcasts in continuous form and the upstream converges in burst form. Mulder *et al.* [15] utilized this burst data as probe signal to realize the fault location. They implemented the instrument in user's unit at customer side, so the measurement results could not be reported to control office. Moreover, cross-talk may exist between each instrument reflection which will seriously disturb the location, when the fault occurs in the feeder fiber.

In this paper, we propose a method of fault location which uses real traffic signal as probe signal in optical communication network. Specifically, we demonstrate its feasibility experimentally on downstream fiber of optical network which is based on synchronous digital hierarchy (SDH) protocols. To improve the visibility of the range result we develop a signal extraction method. Our results demonstrate that the elimination of probe instrument significantly reduces the OPEX and correlation detection overcomes the tradeoff between the spatial resolution and measurable range existing in pulse-OTDR technique. Furthermore, we can monitor the fiber fault without the communication interference and acquire the result in control office directly.

2. Experimental setup and principle

Figure 1 shows our experimental setup in a SDH optical network. An optical line terminal (OLT) in the control office and a switch situated near the users are connected by two fibers, which transmit downstream and upstream signals, respectively. The detection unit is inserted close to the OLT in downstream fiber as plotted in blue area. It consists of a fiber coupler (FC), an optical circulator (OC), two avalanche photo detectors (APD) and a monitoring module. The module acquires the reference and probe signal data, correlates them, analyses the correlation trace and reports the fault information. In principle, the downstream signal is used as probe signal which is launched from a transmitter embedded in the OLT. Its echo from fiber breakpoint is received by the circulator and APD. The coupler extracts 1% of the downstream signal power as reference. The fault location in the fiber link is read by the peak position in correlation trace, which is calculated by the reference and echo signals.

In our experiment, the traffic signal is launched by an OLT (H3C S7510E) and the transceiver module has −8-dBm mean launched power with 1000-Mbps data rate. The reference and probe light are detected by APDs (Newport, APD 1647) with gain of 14000 V/W, and recorded by a real-time oscilloscope (Lecory, SDA806Zi-A, 6 GHz bandwidth). The correlation calculation between these two signals is performed by a computer.

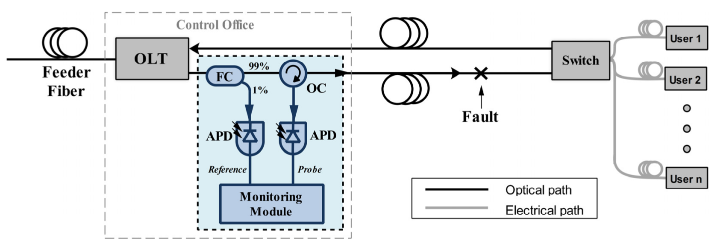

Fig. 1. Experiment setup. OLT: optical line terminal; FC: fiber coupler; OC: optical circulator; APD: avalanche photo detector.

3. Experiment results and analysis

Figures 2(a) and 2(b) demonstrate a time series of reference signal and a detection result of a breakpoint at distance of about 9.8 km. Many correlation peaks are shown in Fig. 2(b) and the highest of them correspond to the fault position. This indicates the feasibility of our method in this optical network.

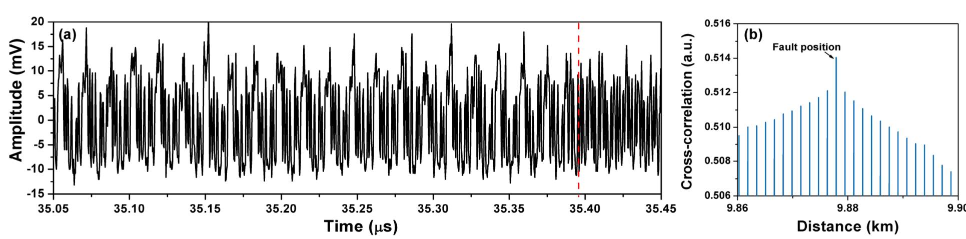

Fig. 2. Time series of reference signal (a) and its cross-correlation curve with echoed probe signal of fiber fault at the distance of about 9.8 km (b).

It should be pointed out that many peaks exist in correlation trace, which will induce the misjudging of the fault and reduce the signal-to-noise ratio (SNR). These regularly arranged peaks indicate periodic signal exists in the traffic signal shown in the front of Fig. 2(a). This

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periodic pattern results from the protocol of SDH including overhead, management, timing and synchronization to maintain the communication reliably and secretly. Fortunately, there is a section vibrating with random form in the traffic signal except for the periodic portion. If we extract the random portion, it will eliminate the misjudgment of the fault caused by the periodic portion and improve the SNR.

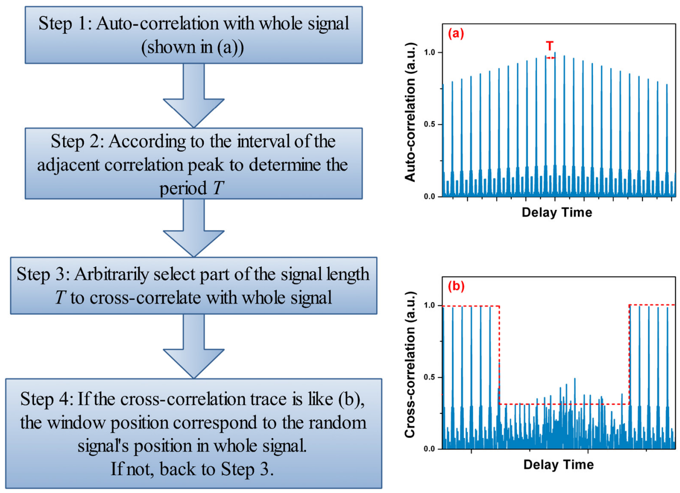

Fig. 3. The flow chart of random signal extraction with the diagrammatic sketches of step 1 (a) and step 3 (b).

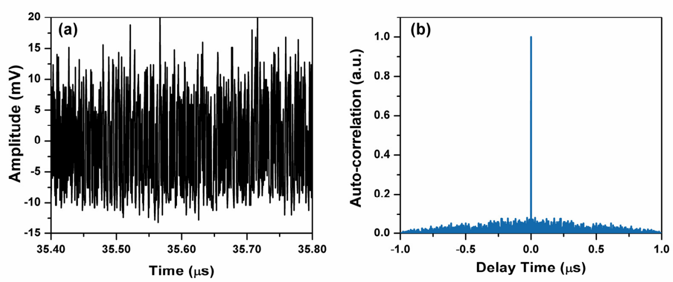

Fig. 4. The time series (a) and auto-correlation trace (b) of the extracted random signal.

Now, we introduce a method based on the principle of the correlation function to extract the random vibration portion from the traffic signal. The left side of Fig. 3 shows the flowchart of the extraction process and the right side shows the diagrammatic sketches of two key steps (step 1 and 3) for better understanding. The first step is to calculate the auto-correlation of the whole acquired traffic signal, which can obtain a comb-like curve as illustrated in Fig. 3(a). In the second step, we get the period T of the traffic signal from the correlation trace by calculating the space between two adjacent peaks. In step 3, we arbitrarily copy a segment with a length of T from the whole acquired signal and then correlate this segment with the whole. If the segment is copied from the periodic part (e.g. on the left side of the dash line in Fig. 2(a)), one can obtain a typical correlation trace shown in Fig. 3(b). A "window" appears in the correlation trace. The reason is that the selected segment is not correlative with the random portion and thus the correlation coefficient decrease rapidly at the random vibration position. The position of the window in the trace reflects the position of the random part in the whole acquired traffic signal. It should be mentioned that if the selected segment is copied from the random portion of the traffic signal, the correlation trace will be quite different with Fig. 3(b). There will be only one correlation peak at the selected position. In this situation, we cannot find the position of the entire random portion except this selected segment. However, the correlation length T is not enough to acquire an observable peak in the following calculation. Therefore the step 3 should be repeated again by selecting another segment until the correlation trace like Fig. 3(b) appears.

Note that, in the above-mentioned process, the cross-correlation trace in Fig. 3(b) sometimes has multiple windows, owing to the fact that the random component probably distributes to several sections in the whole signal. According to these windows' position, we can locate and extract all random portions from the acquired signal. In fact, it needs only calculate once to obtain the windows for the extraction of the random portion, because the period portion is the majority of the traffic signal when the malfunction occurs. Figure 4 shows the time series and auto-correlation trace of the extracted random portion from reference signal shown in Fig. 2(a) at the right side of the dashed line.

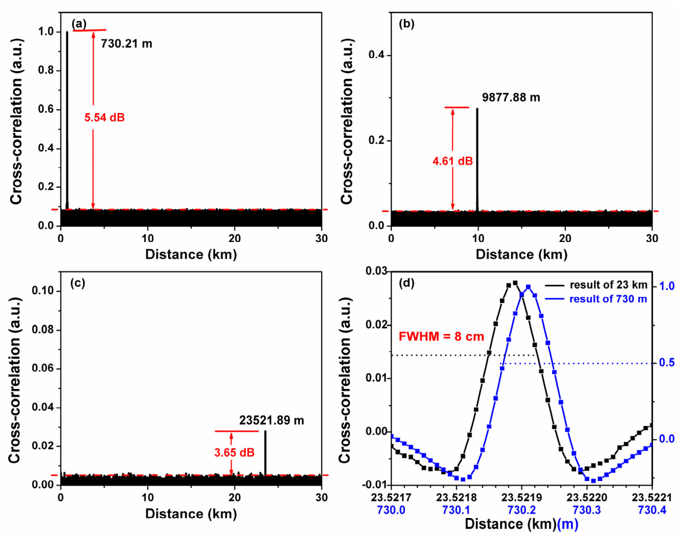

Fig. 5. (a)-(c) Experimental detection results of faults at 730.21, 9877.88 and 23521.89 m, (d) the magnified correlation peaks in (a) and (c).

Furthermore, we utilize the mentioned extraction process to deal with the reference signal and then calculate cross-correlation with echoed probe signal to realize fault location. We connect fibers of different lengths at the OC launch port and acquire a 300-μs time series (corresponding to 30 km) with 10-GS/s sampling rate for the location. The results are shown in Figs. 5(a)-5(c), respectively, where clear peaks are located at the different distance of 730.21, 9877.88 and 23521.89 m in each cross-correlation traces. We normalize each result by the peak value at 730.21 m. The level of each peak degrades with the increasing distance because of the fiber loss. According to the principle of the correlation function, the spatial resolution is determined by the full-width-at-half-maximum (FWHM) of the correlation peak. It does not change with the fault position in the correlation detectable range, which is the main advantage over the pulse ranging technique. As shown in Fig. 5(d), the FWHMs of 730-m and 23-km results both are 8 cm.

When there is more than one fault exists in the transmission line, they can also be detected by our method. We take the dual-fault events detection for example to explain this situation. Figure 6 shows the results of two faults detection with and without the extraction process. We connect an optical coupler (50:50, 1-m fiber lead) to split the optical path at the end of 10-km fiber we detected before, and add an additional 1-m fiber patch cable in one path. The cross-correlation result without random portion extraction process is shown in Fig. 6(a). We can find two arranged peak clusters with same rule which are marked by blue and red dots. In

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each cluster, the fault position peak is higher than other peaks similar with Fig. 2(b). Therefore, the two fault positions can be found with much more efforts. However, if we process the signal by random portion extraction before cross-correlation, the fault position peaks will be found easily shown in Fig. 6(b) and the entire view of the result is shown in the inset. This indicates the correlation process is also applicable for multiple faults detection.

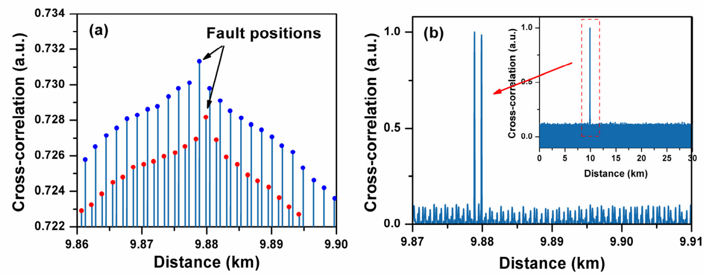

Fig. 6. The results of dual-fault events exist in the fiber line without (a) and with (b) the extraction process.

Finally, we examine the dynamic range of our method according to the peak noise level (PNL) which is defined as the ratio of the peak to the noise floor with 5-log calculation criterion. Compared with the trace in Fig. 2(b), the 4.61-dB PNL in Fig. 5(b) indicates that the correlation peak is easier to be distinguished and thus the proposed method could be readily achieved in practice. Meanwhile, the PNLs in Figs. 5(a)-5(c) are 5.54, 4.61 and 3.65 dB, respectively, which has a decreasing trend with the increasing distance. We evaluate this tendency shown in Fig. 7 in order to estimate the boundary of the ranging distance in our experiment. By 3-dB criterion, the tendency predicts that the method can detect a fault at 26-km distance. This is limited by the sensitivity of the receiver, and much long distance fault will be detected with higher sensitive receiver. However, according to ITU-T G.957 [16] on the mean launched power of transmitter for different optical interfaces, the power between −15 and −8 dBm is prepared for 15-km communication. In our experiment, we achieved the 23-km fault location in −8-dBm launched power, meaning that the detection method employing the traffic signal can cover the communication distance.

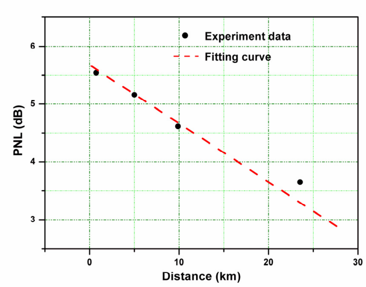

Fig. 7. The peak noise level (PNL) of the cross-correlation as a function of the ranging distance.

4. Discussions and conclusion

For the future optical network maintenance, the identification of the fiber fault event is more and more important to operator's priority consideration, such as the event with cut, disconnected, misalignment, and dirty contact. In these situations, we could define a criterion for each event according to their reflection level beforehand, which requires a large number of experiments. In the principle of correlation function, the peak level of the cross-correlation is only related to the echoed signal's strength while fix the other correlation condition (such as

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the strength of the reference signal and the correlation length of the signal). Therefore, we could identify the type of the reflective event and optimize the monitoring function. Here, we achieve the detection of dirty connector's weak reflection shown in Fig. 8, and the experiment for the criterion will be developed in our further research. Unfortunately, we cannot measure the fiber loss or non-reflected fault in this technique due to the weakness launched power. This challenge remains to be further studied. It should be pointed out that the proposed method is suitable for every optical communication network because the random vibration portion exists in every traffic signal. Recently, single fiber with bi-directional communication system is applied extensively due to the conservation of the material usage. In this condition, we just need to add another FC and OC in the traffic line to divide the signals into two directions.

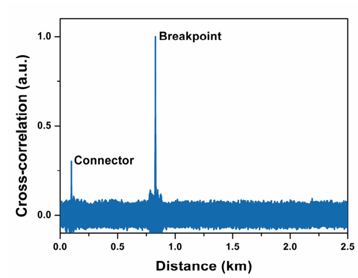

Fig. 8. The result of dirty connector and breakpoint detection.

In summary, we present a method using the real traffic signal as probe to locate the fiber fault in communication network. It is simple and cost effective due to the elimination of the dedicated probe instrument in common location techniques. The utilization of the correlation function overcomes the tradeoff in pulse ranging between spatial resolution and measurement range. Moreover, the correlation result improves significantly with the help of the random portion extraction. Experimental results demonstrate that we achieve a spatial resolution of 8 cm and detection range of above 23 km with the output power of −8 dBm. We believed that the proposed method has a promising future of wide application due to its ease of integration.

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