Long-range and high-resolution correlation optical time-domain reflectometry utilizing an all optical chaotic source

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ABSTRACT

A high resolution optical time domain reflectometry (OTDR) based on an all-fiber chaotic source is demonstrated. We analyze the key factors limiting the operational range of such an OTDR, e.g., integral Rayleigh backscattering and the fiber loss, which degrade the optical signal to noise ratio at the receiver side, and then the guideline for counter-act such signal fading is discussed. The experimentally demonstrated correlation OTDR presents ability of 100km sensing range and 8.2cm spatial resolution (1.2 million resolved points), as a verification of the theoretical analysis. To the best of our knowledge, this is the first time that correlation OTDR measurement is performed over such a long distance with such high precision.

Keywords: Fiber measurements, Optical time domain reflectometry, Rayleigh scattering.

1. INTRODUCTION

Chaotic sources have attracted much attention due to its unique characteristics and the huge potential for various applications including physical random bit generation [1], secure communication [2], chaotic lidar [3] and so on. As an example of the applications of electrical driven chaotic source, in 2007, a cross-correlation OTDR [4] was proposed utilizing a pseudo-random pulse sequence as the signal. However, its measurement accuracy is still limited by the bottleneck of the pseudo-random modulation bandwidth, and it is difficult and costly to generate broadband electrical random codes. For the above reasons, electronic chaotic sources are hard to compete with optical chaotic sources which have advantages of wider bandwidth and faster chaotic dynamics.

Later on, Y. Wang et al. demonstrated a 6cm spatial correlation OTDR based on a multi-GHz optical chaotic source utilizing LD laser [5]. This is the first proof-of-concept experiment of correlation OTDR by utilizing the optical chaotic source. However, that work only presented a 140m detection ranging. There is always tradeoff between the spatial resolution and detection range.

In this work, we propose a long-range, high-precision correlation OTDR based on an all-fiber chaotic source. The setup for the source is same as our previous work [6]. The characteristics of the chaotic source were fully investigated in ref [6], and it shows potential to achieve millimeter-scale resolution OTDR. Here we further analyze the limiting factors for realizing long-range correlation OTDR, such as integral effect of weak Rayleigh backscattering and the fiber loss. The potential methods to overcome the bottleneck of operation range are proposed and analyzed. Specifically, the effects of distributed amplification on the enhancement of signal quality are analyzed. As a result, we experimentally demonstrate a correlation OTDR which has 100 kilometers fiber fault location range with 8.2cm spatial resolution (1.2 million resolved points), with only 2ms data acquisition time. To the best of our knowledge, this is the longest fiber fault location system based on the correlation OTDR technique.

2. DISCUSSIONS FOR PERFORMANCE ENHANCEMENT OF CORRELATION OTDR

As the major properties of the proposed source were studied, here we directly discuss for performance enhancement of correlation OTDR besides the method mentioned in ref [6], i.e., increasing sampling time. With the increase of sensing

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range, OSNR of the detected signal would decrease thus it will be difficult to recognize the peaks among correlation trace. To extend the detection range of correlation OTDR, the signal quality must be improved.

Rayleigh scattering is the essential factor in this regime. At the receiver side, Rayleigh scattering components are an integral result. In another word, the fiber can be seen as a point-mirror with the integral Rayleigh scattering. When the fiber length is long enough, the Rayleigh scattering power will be significant [7], though the Rayleigh coefficient is very small (ε =4.3 × 10^{-8}/m @ 1550nm). We calculate the ratio of fiber-fault-reflected signal power to the Rayleigh-backscattered noise, which could be expressed as : $OSNR = P_{in} \cdot R \cdot e^{-2\alpha_s L} \Big/ P_{in} \cdot \int_0^L \varepsilon \cdot e^{-2\alpha_s l} dl$ where R stands for the reflectivity of the fiber fault, α_S represents the loss coefficient of signal (measured as 0.18dB/km), L is the fiber length. The green solid curve in Fig. 1 shows the accumulated reflectivity taking both Rayleigh-backscattering and round-trip loss into account. In our model, we assume a 4% Fresnel reflection to simulate the fiber fault. As shown in the insert of Fig. 1, the OSNR exponentially decreases with increased fiber length. From this calculation we see that if fiber length is 100km, the components of fiber-fault-reflected signal accounts very little (-17.2dB) of the total power received by the detector.

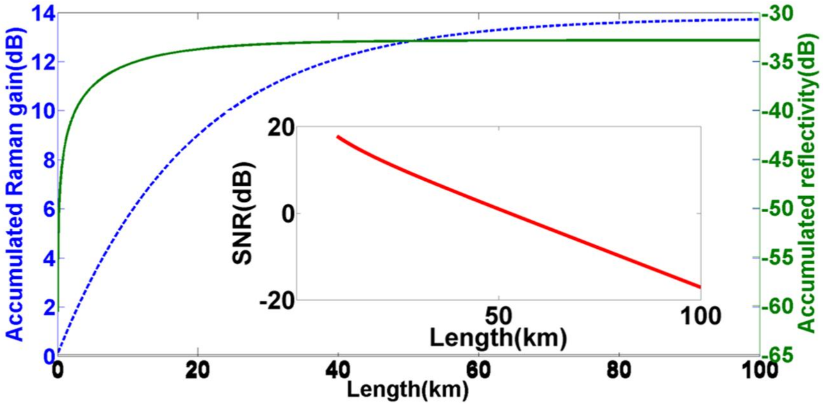

Fig. 1. Accumulated Raman gain over length and equivalent distribution reflectivity (insert: ratio of end-reflected signal power to Rayleigh-backscattered power along fiber without Raman amplification.

Here we show that the distributed amplification will perform much better than a pre-amplifier in front of the detector. A pre-amplifier such as an EDFA will boost the total optical power, but the OSNR would not enhance since the signal is actually buried in the in-band noise. On the other hand, when a distributed Raman amplifier is used, the intensity evolution of the chaotic probe light launched into the fiber can be calculated by the balanced steady equations [8]. By solving the equations, we calculate the ratio of fiber-fault-reflected signal power to the Rayleigh-backscattered power under Raman amplification as $OSNR_{Raman}$: $OSNR_{Raman} = R\cdot I_c(Z_{\max})\cdot g(Z_{\max})\cdot e^{-\alpha_c Z_{\max}} \Big/ \int_0^{Z_{\max}} I_c(z)\cdot g(z)\cdot \varepsilon \cdot e^{-\alpha_c z} dz$, where Ip represents the Raman pump intensity, Ic represents the chaotic probe light. g(z) stands for accumulated Raman gain distribution along fiber. We could obtain that OSNR will increase to -6.6dB under typical system parameters (Ip=26dBm and Ic=-5.5dBm), which means a 10.6dB enhancement compared with the case without Raman amplification (-17.2dB). According to the above analysis, it can be concluded that Raman amplification is able to enhance the OSNR and therefore extend the sensing range of correlation OTDR significantly.

3. EXPERIMENTAL DEMONSTRATION WITH CORRELATION OTDR

Finally, we establish an experimental system following the schematic setup in ref [6]. The combination of 1550nm fiber Bragg grating (FBG) and a circulator (CIR1) is act as a narrow bandwidth filter. The 3dB bandwidth of the filter is 0.26nm. After port3 of the CIR1, a 1:99 optical coupler is used to split the filtered light into two branches. One branch (1%) is used as the reference light detected by a 1GHz photo-detector, while the other branch (99%) transmission light acts as the chaotic probe light of OTDR. A Raman amplifier (RA) is used to enhance the signal quality. The fiber under test is 100km standard single mode fiber (SMF) with 0.18dB/km loss at 1550nm. Because the reflected signal is very weak, we use a 1GHz avalanche photo-detector (APD) for signal detection. A 50cm FC/PC jumper attached to the end of the 100km SMF with FC/APC connector, both ends of which are used to emulate fiber-faults.

We adjust all the parameters according to above analysis. The pump power of SC is 31.6dBm, the power of 1% branch of the filtered chaotic light is -25.5dBm, while the 99% branch launched into RA is -5.5dBm. The RA power is set to 26dBm. The total reflected light power detected by the APD is -22.1dBm. The signals of the two detectors are simultaneously recorded for 2ms by a multi-channel oscilloscope with 5GHz sampling rate. The recorded data is processed with cross correlation algorithm and the fiber fault could be located by the correlation trace. Fig. 2(a) shows the normalized correlation OTDR trace. The position of the peak (100.34080km) is corresponding to the open end of the FC/PC jumper. The SNR of our experiment result is 16.34dB which is an excellent result considering the fiber length, suggesting that even longer range is achievable without any modification of the setup.

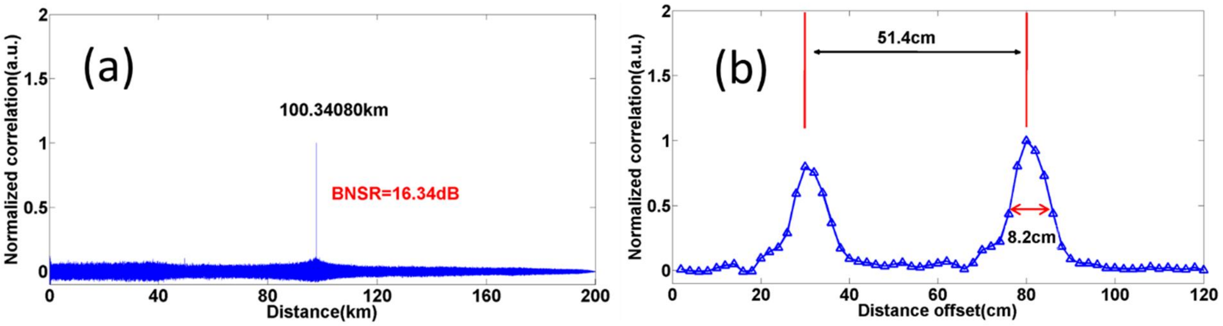

Fig. 2 (a) Experimental result of fault at 100.34080km; (b) magnified peaks of the correlation trace.

Fig. 2(b) shows the magnified correlation peaks. Because the FC/PC jumper has two flat- ends, the magnified correlation trace actually has two peaks. The two peaks are separated by 51.4cm which represents the jumper length and the result is reasonably accurate. From the magnified trace, we also identify the spatial resolution of the system as 8.2cm.

4. CONCLUSION

In summary, a long-range and high-resolution correlation OTDR based on all-fiber chaotic source is proposed. The time domain properties and other correlation characteristics of such source studied in our previous work show the potential ability in high precision correlation OTDR. The key factors limiting the sensing range of correlation OTDR are analyzed, including integral effect of weak Rayleigh backscattering and the fiber loss. Based on the analysis, an instruction about how to achieve a long range correlation OTDR is presented. The key to extend sensing range is improving OSNR of the received signal, and we demonstrated that distributed amplification is a favorable approach. Finally, we realize cm-level spatial resolution and 100km sensing range with 2ms data acquisition time, which is a significant improvement compare to the conventional OTDR.

5. ACKNOWLEDGMENTS

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