

# High resolution optical time-domain reflectometry based on correlation utilizing an all-fiber chaotic source

M. Q. Fan<sup>a</sup>, Z. N. Wang<sup>a,\*</sup>, H. Wu<sup>a</sup>, D. V. Churkin<sup>b,c,d</sup>, Y. Li<sup>a</sup>, L. Zhang<sup>a</sup>, X. Y. Qian<sup>a</sup> and Y. J. Rao<sup>a,\*</sup>

<sup>a</sup>Key Lab of Optical Fiber Sensing & Communications, University of Electronic Science & Technology of China, Chengdu, Sichuan, China 611731

<sup>b</sup>Institute of Automation and Electrometry SB RAS, Novosibirsk 630090, Russia

<sup>c</sup>Novosibirsk State University, Novosibirsk 630090, Russia

<sup>d</sup>Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK

## ABSTRACT

We propose a high-resolution optical time domain reflectometry (OTDR) based on an all-fiber supercontinuum source. The source simply consists of a laser with moderate power and a section of fiber which has a zero dispersion wavelength near the laser's central wavelength. Spectrum and time domain properties of the source are investigated, showing that the source has great capability in nonlinear optics, such as correlation OTDR. We analyze one of the key factors limiting the operational range of such an OTDR, i.e., sampling time. Finally, we experimentally demonstrate a correlation OTDR with 25km sensing range and 5.3cm spatial resolution, as a verification of theoretical analysis.

**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.

Followed this work, 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 high-resolution correlation OTDR based on an all fiber supercontinuum (SC) source. The fluctuation and auto-correlation properties of such SC sources are investigated for the first time. It is demonstrated that the SC source is a powerful tool to generate ultra-wideband fluctuation in time domain, which is an ideal source for correlation OTDR, and its potential to achieve millimeter-scale resolution is shown. On the other hand, one of the limiting factors for realizing long-range correlation OTDR is analyzed, i.e. sampling time. We analyze the potential methods to overcome the bottleneck of operation range. As a result, we experimentally demonstrate a correlation OTDR which has 25 kilometers fiber fault location range with 5.3cm spatial resolution, with only 400us data acquisition time.

## 2. CHARACTERISTICS OF THE SUPERCONTINUUM SOURCE

The schematic setup of the proposed system is shown in Fig. 1. The proposed correlation OTDR system mainly consists of two parts (i.e. SC and OTDR). As the box diagram in Fig. 1 shows, the SC simply consists of a 1455nm quasi-CW Raman fiber laser and 16km TrueWave (TW) fiber.

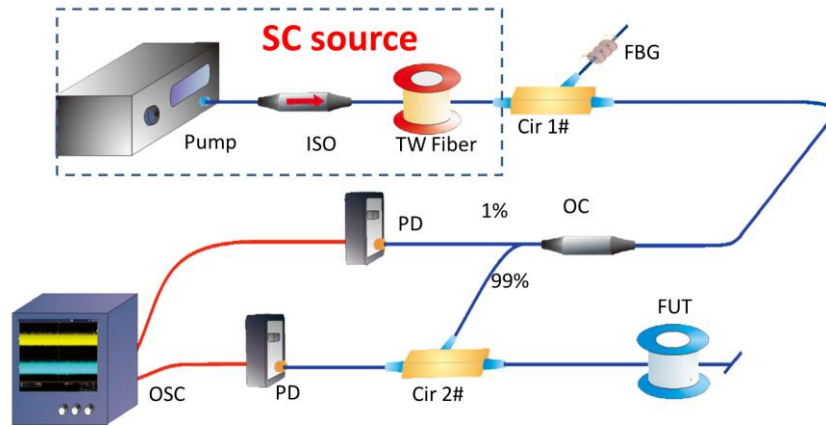


Fig. 1. Schematic setup (ISO: isolator; TW Fiber: TrueWave Fiber; SC source: supercontinuum source; Cir: circulator; FBG: fiber Bragg grating; OC: optical coupler; PD: photo-detector; FUT: fiber under test; OSC: oscilloscope).

The SC spectra recorded at the end of the TW fiber are shown in Fig. 2. It should be noted that, when pump power reaches to 0.95W, spectral components extended to 1550nm region are generated. If the pump power is increased to 1.48W, the generated SC has the widest bandwidth, i.e., 141nm within 10dB range. By further increasing pump power, the bandwidth of generated SC would be reduced. The reason is that more powerful pump stimulates higher-order Stokes waves and enhances total pump-Stokes conversion efficiency, thus shorter wavelength photons are significantly depleted.

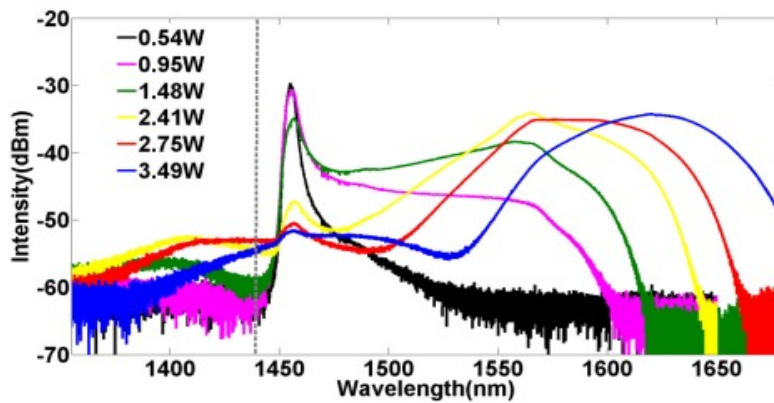


Fig. 2. Spectrum evolution with pump power (the vertical dotted line corresponds to the zero-dispersion wavelength of the TW fiber).

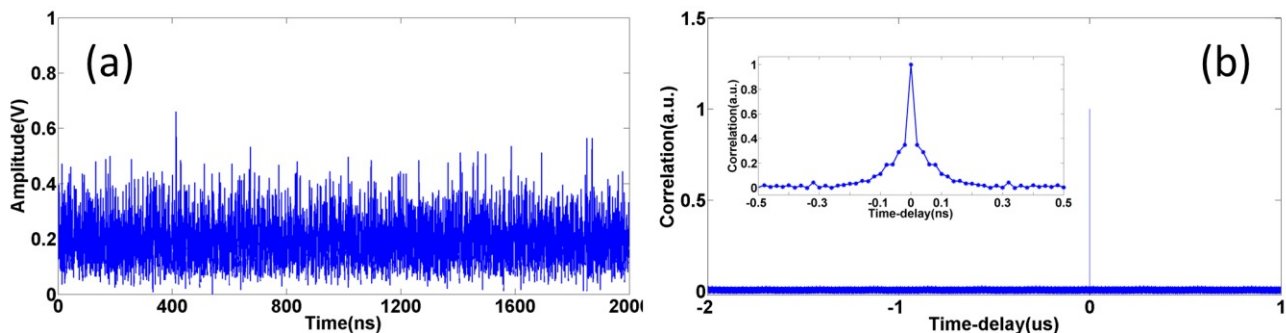


Fig. 3. (a) Time series of generated SC (with 1.48W pump power); (b) ACF of SC, insert: magnified peak of ACF.

We investigate the source in time domain (filtered with 0.26nm FBG). A 45GHz PD and an oscilloscope with 25GHz bandwidth and 50Gs/s sampling rate are used. The time series are shown in Fig. 3(a). It shows that the SC has time dynamics with high-contrast fluctuations which is a favorable condition for correlation analysis. We calculate the auto-correlation function (ACF) with DC removed, as shown in Fig. 3(b). Narrow-width ACF peak ( $\sim 20$ ps, corresponding to

~2mm spatial resolution for OTDR) could result in the ultra-fine resolution for correlation OTDR, up to the limit of the bandwidth of the PD and the oscilloscope (ignoring the signal distortion in fiber). Overall, the demonstrated SC source could be an important member in the family of chaotic sources because of its stochastic temporal properties.

### 3. DISCUSSIONS FOR PERFORMANCE ENHANCEMENT OF CORRELATION OTDR

With the increase of sensing range, optical signal to noise ratio (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.

Increasing sampling time is a direct way to enhance system performance. In correlation OTDR, the cross-correlation procedure is essentially matched filtering. Assuming  $x(t)$  is the signal, the maximum achievable SNR can be expressed as [6]

$$SNR = \frac{\int_{-\infty}^{+\infty} |x(t)|^2 dt}{N_0} \quad (1)$$

where  $N_0$  is power spectral density of white noise. On the other hand, the energy of signal  $x(t)$  is as  $E = \int_{-\infty}^{+\infty} |x(t)|^2 dt$ . Finally, we could obtain that the maximum achievable  $SNR = E/N_0$ . It depends only on the energy of the waveform. Thus, if the sampling time is increased, SNR of correlation OTDR would be increased linearly. As the verification, we demonstrate a 1km sensing range experiment without any amplification. Fig. 4 shows SNR varies with different sampling times. Basically, the experiment result is qualitatively in accordance with the theoretical analysis.

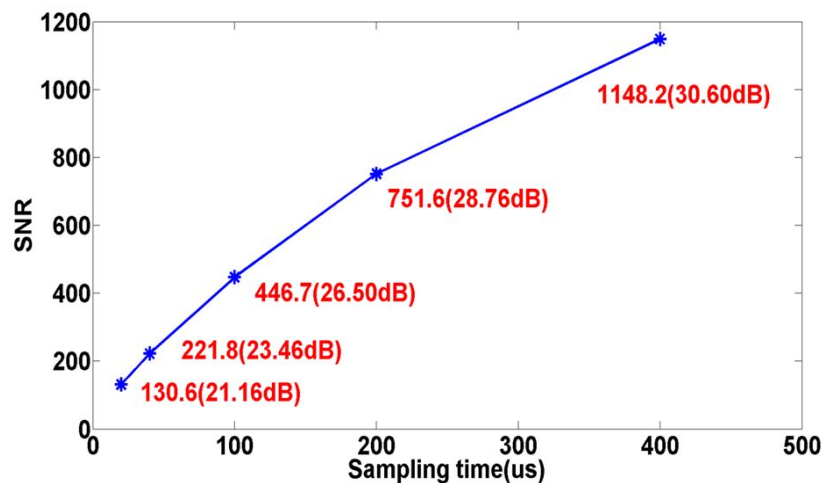


Fig. 4 Calculated SNR versus sampling time

### 4. EXPERIMENTAL DEMONSTRATION WITH CORRELATION OTDR

Finally, we establish an experimental system following Fig. 1. 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 0.6nm. 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. The fiber under test is about 25km standard single mode fiber (SMF) with 0.18dB/km loss at 1550nm. The reflected signal is detected by a 1GHz photo-detector which is similar to the detector placed in 1% branch. A FC/APC connector connects to the fiber end port thus the connector is used to emulate fiber-fault.

The pump power of SC is 31.6dBm, the power of 1% branch of the filtered chaotic light is -17dBm, while the 99% branch power is 0.82dBm. The total reflected light power detected by the detector is -25dBm. The signals of the two detectors are simultaneously recorded for 400us by a multi-channel oscilloscope with 25GHz sampling rate. The recorded data is processed with cross correlation algorithm and the fiber fault could be located by the correlation trace. Fig. 5 shows the normalized correlation OTDR trace. The position of the peak (25447.541m) is corresponding to the open end of the FC/PC connector. The inset of fig. 5 shows the magnified correlation peaks. From the magnified trace, we also identify the spatial resolution of the system as 5.3 cm.

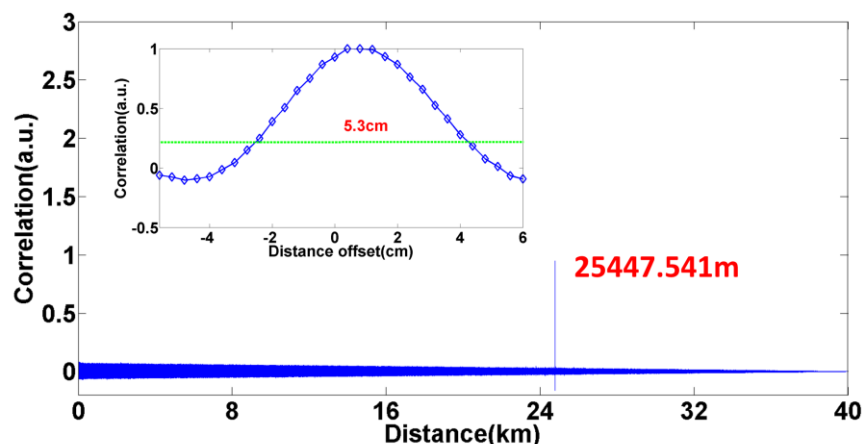


Fig. 5 Experimental result of fault at 25447.541m; inset: magnified peaks of the correlation trace.

## 5. CONCLUSION

In summary, a high-resolution correlation OTDR based on all-fiber SC source is proposed. The temporal properties of SC are investigated, showing that the SC is a promising source of chaotic radiation for applications such as correlation OTDR. The sampling time as the key factor limiting the sensing range of correlation OTDR is analyzed. The result shows that increasing sampling time is an effective way to enhance the SNR of correlation trace. Finally, we realize a centimeter level spatial resolution and 25km sensing range OTDR measurement, which is a significant improvement compare to the conventional OTDR.

## 6. ACKNOWLEDGMENTS

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