Optical pulse compression reflectometry with high spatial resolution and long range

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Abstract: In this talk, we introduce the novel reflectometry with high spatial resolution and long range, which is nominated optical pulse compression reflectometry (OPCR). The working principle, numerical simulation, and state-of-the-art experimental achievements of the OPCR are demonstrated.

OCIS codes: (060.2370) Fiber optics sensors; (060.2630) Frequency modulation; (120.4825) Optical time domain reflectometry.

1. Introduction

Reflectometry is an important instrument to monitor intrinsic or external disturbance in optical fiber sensing and optical fiber transmission (OFC) system [1]. Up to date, different types of reflectometry have been demonstrated [2-5]. The first type of optical time domain reflectometry (OTDR) dates back to 1970s [2], which has been widely used in the nowadays OFC system due to long-length interrogation ability. Referred to the frequency modulation continuous wave (FWCW) Radar, optical frequency domain (OFDR) [3] was extensively developed to overcome the limited spatial resolution of OTDR. However, the measurement range of OFDR is physically limited by the half of coherence length of the laser source.

In this talk, we introduce a new reflectometry inspired by pulse-compression radar [4], called pulse-compression OTDR or optical pulse compression reflectometry (OPCR) [5-7], which is able to overwhelm the tradeoff between the spatial resolution and measurement range in OTDR and OFDR. A long optical pulse with the linear frequency modulation (LFM) is launched into an optical fiber and the backscattered light is coherently detected and matched filtered so as to significantly compress the original pulse and achieve high spatial resolution. The working principle, numerical simulation and state-of-the-art experimental achievements are presented.

2. Principle

The backscattered curve in the OPCR is expressed by [5]

$$y(t) = A(t) * C(t), \tag{1}$$

where A(t) determines the backscattered light attributed to Rayleigh scatter occurring anywhere in the fiber, splicing loss at particular points, and end reflection due to Fresnel reflection. C(t) stands for the impulse response (i.e. pulse compression) of the pulsed LFM given by

$$C(t) = \left[rect\left(\frac{t}{2T}\right) + \eta \right] \cdot T \cdot \frac{\sin\left[\pi K\left(T - |t|\right)(t)\right]}{\pi KT(t)}, \tag{2}$$

where K is the slope of the LFM, T is the pulse width, $rect(\cdot)$ denotes the rectangular function, $B=KT$ is the LFM sweeping range, and η is the reciprocal of the extinction ratio of the LFM pulse (such as $\eta = 0.001$ corresponds to 30-dB extinction ratio). The spatial resolution of the OPCR is decided by

$$\Delta z = \frac{c}{2nB}, \tag{3}$$

where c is the light speed in vacuum and n the refractive index of the fiber under test (FUT).

Two different schemes generating an optical LFM pulse for the OPCR with different η are compared in Fig. 1(a) and 1(b). An arbitrary waveform generator (AWG) is used to generate two synchronous electric waveforms of rectangular pulse and sawtooth. The period of the sawtooth is equal to the width of the rectangular pulse. In the original scheme (see Fig. 1(a)) [5], the sawtooth is connected with a VCO that drives a single sideband modulator (SSBM) to generate a LFM light; the electric pulse is launched to a Mach-Zender modulator (MZM) so as to achieve an optical LFM pulse. As shown in Fig. 1(b), both electric waveforms in the new scheme are connected simultaneously with the VCO so as to generate an electric pulsed LFM, which drives the SSBM to obtain an optical pulsed LFM or an optical LFM pulse [6]. As long as the rectangular pulse served as supply voltage switches from high-level voltage to zero voltage, the VCO changes from normal status (high power) to shut-down status (zero power), generating an electric pulsed LFM with infinite extinction ratio. Correspondingly, an optical LFM pulse with infinite extinction ratio (i.e. $\eta_{new} = 0$) is formed. In comparison, the optical LFM pulse generated by the commercial MZM (see Fig. 1(a)) has finite and unstable extinction ratio (typically, 20-30 dB), leading to $\eta_{old} = 0.001–0.01$. Besides, the complexity of the new scheme is significantly reduced since only one polarization controller (PC) and SSBM are sufficient in the optical unit. The experimental setup of a typical OPCR is depicted in Fig. 1(c). The electric unit to generate the electric pulsed LFM is comprised of an AWG (Agilent 81150A), a VCO (Mini-Circuits ZX95-5400+), and an electric amplifier (EA1, Mini-Circuits ZX60-542LN+). The VCO provides an LFM scanned from ~4.4 GHz to ~5.4 GHz (i.e. B = ~1 GHz), corresponding to a nominal spatial resolution of Δz = 10 cm according to Eq. (3) and n = 1.446 in the SMF.

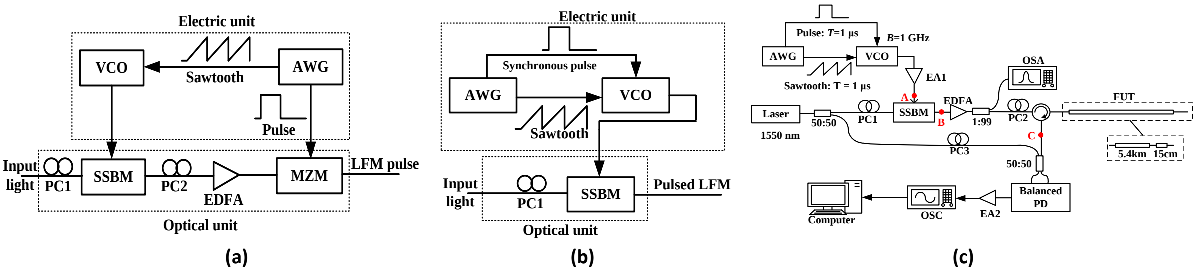


Fig. 1. Two different schemes (a-b) to generate an optical LFM pulse. VCO: voltage controlled oscillator; AWG: arbitrary waveform generator; SSBM: single-sideband modulator; MZM: Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; PCs: polarization controllers. (c) Experimental setup of the OPCR. DFB-LD: distributed feedback laser diode; EAs: electric amplifiers; OSA: optical spectrum analyzer; OSC: real-time oscilloscope; PD: photo-diode; FUT: fiber under test.

3. Experimental results

First, a 1550 nm distributed feedback laser diode (DFB-LD, NEL NLK1C6DAAA) with ~100 kHz linewidth is used as a laser source [6]. An FUT is prepared by tightly connecting a 5.4-km standard single mode fiber (SMF) spool with the circulator and loosely connecting a 15 cm jumper with the far end of the SMF spool. The backscattered light of the FUT through the circulator is measured by the heterodyne detection (see Fig. 1(c)). The time-domain trace of the backscattered light recorded by the OSC is digitally I/Q converted to the complex signal. The digital matched-filtering process is implemented by use of the characterized optical LFM pulse. Figure 2(a) depicts the autocorrelation of the optical LFM pulse. The full width at half maximum (FWHM) of ~1 ns agrees with B = 1 GHz. The measured curve of the backscattered light in the FUT is illustrated in Fig. 2(b). The transmission loss of ~1 dB and/or Rayleigh scatter can be clearly identified. One can also see the high reflection peak due to Fresnel reflection at the far end. The inset of Fig. 2(b) shows the magnified view of the far end, where two distinguishable peaks with an interval of 15 cm are interrogated. It also verifies that the measurement range is equal to 5.4 km, which is beyond the 2-km coherence length of the DFB-LD. Note that the time varying amplitude of the optical LFM pulse influences to some extent the sidelobes (see Fig. 2(a)); besides, the sidelobes of the OPCR due to the nature of LFM pulse compression still exist in the backscattered curve (see Fig. 2(b)). These factors can be possibly reduced somehow by use of proper windowing (i.e. apodization).

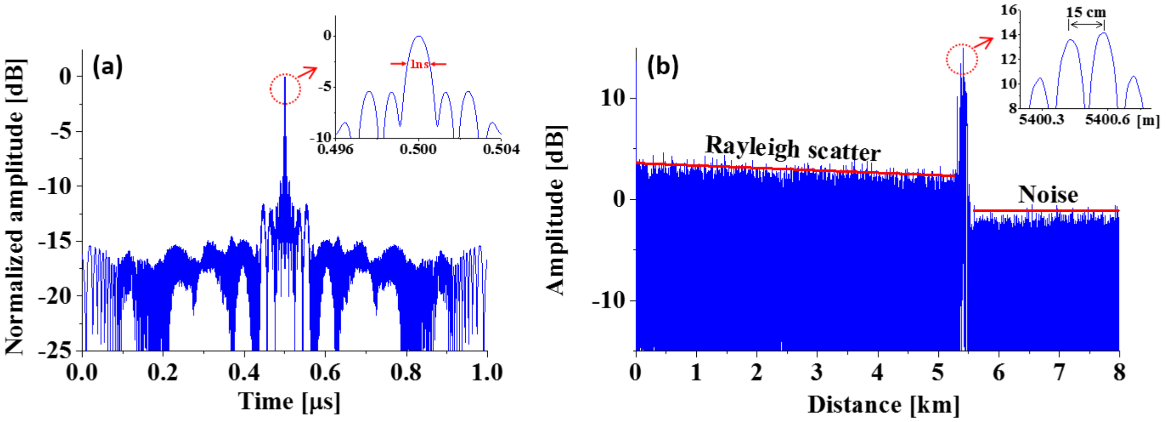
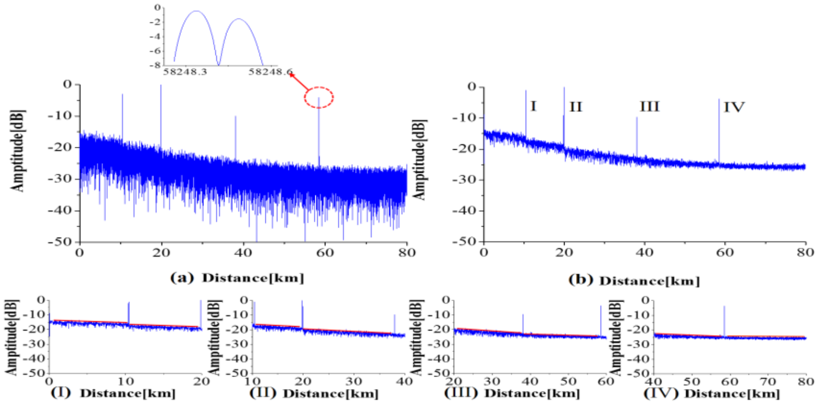


Fig. 2. (a) Autocorrelation of the characterized optical LFM pulse. The inset denotes the magnified view around the central peak. (b) Measured curve of the Backscattered light in the 5.4-km FUT. The inset corresponds to the magnified view around the far end of the FUT.

Second, a 1550-nm narrow linewidth laser with 3 kHz linewidth is used as the laser source [7]. Figure 3(a) and 3(b) show the original and smoothed overall envelop of the back scattering in a 60-km FUT. The Fresnel reflection at the far end of the 60-km FUT can be clearly observed. Two separate peaks with 15 cm interval are identified as well. Different zoomed-in views around four connectors are depicted in Fig. 3(c). Fiber attenuation between any two connectors is linear. It means that OPCR reaches a high spatial resolution of 10 cm and a long range of 60 km.



(c)

Fig. 3. Experimental result of OPCR trace with 60 km FUT. (a) Overall back scattering curve and (b) smoothed overall envelope. The inset in (a) shows the magnified curve around the two reflection peaks at the FUT's far end with 15-cm interval. (c) Magnified veiws around four different locations (I) ~ (IV).

Acknowledgement

This work was partially supported by National Natural Science Foundation of China (61571292, 61535006, and 61127016), SRFDP of MOE (Grant No. 20130073130005), and the State Key Lab Project of Shanghai Jiao Tong University (GKZD030033).

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Biography

Weiwen Zou received his B.S. degree in physics and M.S. degree in optics from Shanghai Jiao Tong University, China, in 2002 and 2005, respectively, and Ph.D. degree in optoelectronics from the University of Tokyo, Japan, in 2008. Since 2005, he had been working on Brillouin-scattering-based discriminative sensing of strain and temperature for his doctoral research in electronic engineering, the University of Tokyo, Japan. From 2008 to 2009, he was a Postdoctoral Research Fellow at the University of Tokyo. In 2009, he became a Project Assistant Professor of the University of Tokyo. In 2010, he joined Shanghai Jiao Tong University as an Associate Professor. Dr. Zou has published more than 100 peer-reviewed journal and international conference articles.

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