Optical pulse compression reflectometry with 10 cm spatial resolution based on pulsed linear frequency modulation

Weiwen Zou,* Shuo Yang, Xin Long, and Jianping Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks,
Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
**E-mail: wzou@sjtu.edu.cn*

Abstract: A new scheme based on pulsed linear frequency modulation is proposed to improve the stability and spatial resolution of optical pulse compression reflectometry. 10 cm spatial resolution over 5.4 km measurement range is experimentally 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 comparison, optical coherence domain reflectometry (OCDR) [4] and optical low coherence reflectometry (OLCR) [5] can also provide competitive spatial resolution but the measurement range is confined as well. Most recently, a new reflectometry inspired by pulse-compression radar [6], called pulse-compression OTDR or optical pulse compression reflectometry (OPCR) [7], was proposed to overwhelm the tradeoff between the spatial resolution and measurement range. 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.

In this work, we demonstrate a new scheme to improve the spatial resolution of the OPCR by use of only one electro-optic modulator and pulsed VCO with 1 GHz instantaneous bandwidth. Compared with the previous scheme based on two modulators [7], the new scheme can generate the electric pulsed LFM and optical LMF pulse with less complexity, broader bandwidth and larger extinction ratio. We successfully achieve 10 cm spatial resolution over 5.4 km measurement range using a laser source with coherence length of 2 km.

2. Principle

The backscattered curve in the OPCR is expressed by [7]

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

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).

Figure 1 compares two schemes generating an optical LFM pulse for the OPCR with different η. In both cases, 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)) [7], 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. 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.

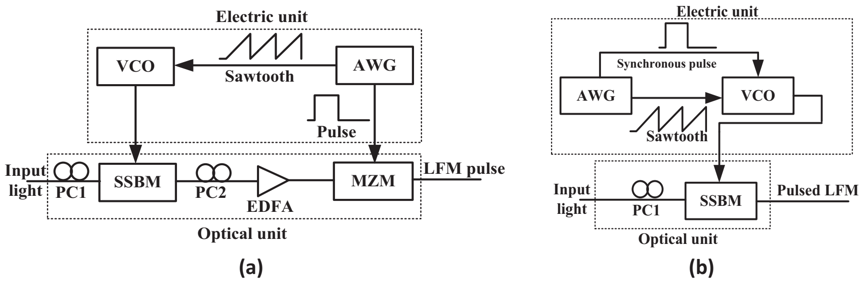

Fig. 1. Two different schemes to generate an optical LFM pulse. (a) The old scheme [7] and (b) the new scheme in this work. VCO: voltage controlled oscillator; AWG: arbitrary waveform generator; SSBM: single-sideband modulator; MZM: Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; PCs: polarization controllers.

3. Experimental details

The experimental setup of the modified OPCR is depicted in Fig. 2(a). 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+). Figure 2(b) demonstrates the measured electric spectrum at the port of "A" in Fig. 2(a), providing the LFM scanned from ~4.4 GHz to ~5.4 GHz (i.e. B = ~1 GHz). Figure 2(c) illustrates the measured time-domain profile with regular amplitude and $T = 1$ μs.

A 1550 nm distributed feedback laser diode (DFB-LD, NEL NLK1C6DAAA) with ~100 kHz linewidth and ~10 dBm power is split into two equal beams. One beam is launched into an SSBM (Photline MXIQ-LN-40) driven by the electric pulsed LFM. As shown in the optical spectrum (see Fig. 2(d)) measured by an OSA laid after an EDFA, proper bias control of SSBM results in a single sideband generation with more than 15 dB suppression of other sideband and 20 dB suppression of the optical carrier. Its frequency difference from the optical carrier is equal to the LFM. The ports of "B" and "C" in Fig. 6(a) are connected together for characterization of the time-domain profile of the optical LFM pulse by heterodyne detection as explained below. First, the optical beating between the local optical oscillator (i.e. the other beam of the DFB-LD, ~7 dBm) and the optical LFM pulse at a 50:50 coupler is optimized by a PC3 and detected by a balanced PD (Discovery DSC720, 16 GHz bandwidth). Second, the electronic signal after the balanced PD is amplified by EA2 and recorded by 25-GSa/s real-time oscilloscope (OSC, Tektronix DSA70804). As illustrated in Fig. 2(e), the profile has a time varying amplitude with the same $T = 1$ μs.

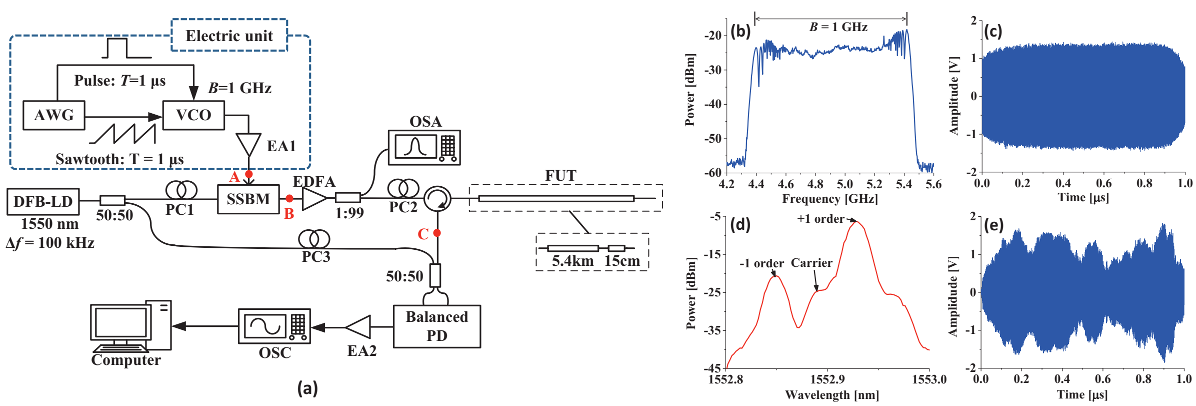

Fig. 2. (a) Experimental setup of the modified OPCR. DFB-LD: distributed feedback laser diode; EAs: electric amplifiers; OSA: optical spectrum analyzer; OSC: real-time oscilloscope; PD: photo-diode; FUT: fiber under test. Measured electric spectrum (b) and time-domain profile (c) of the electric pulsed LFM. Measured optical spectrum (d) and time-domain profile (e) of the optical LFM pulse.

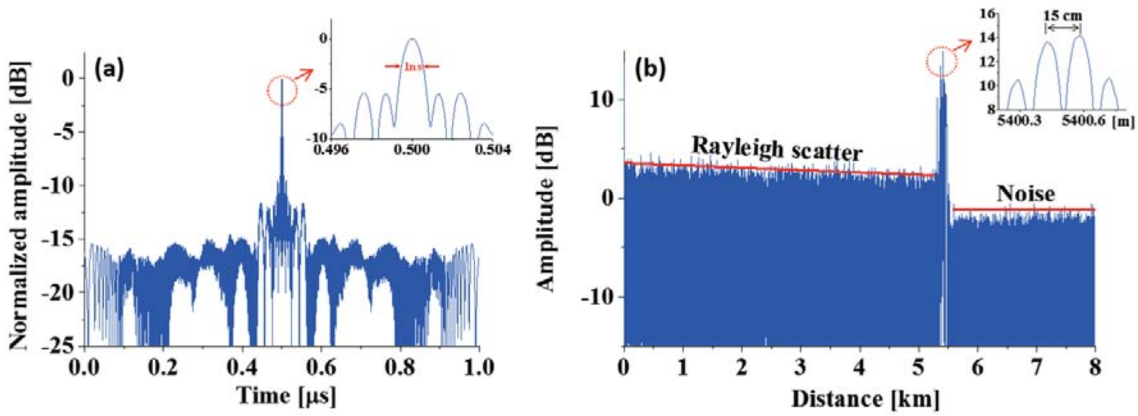

Fig. 3. (a) Autocorrelation of the characterized optical LFM pulse. The inset denotes the magnified view around the central peak. (b) Measured curve of the Backscattered light in the FUT. The inset corresponds to the magnified view around the far end of the FUT.

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. 2(a)), which is the same as the characterization of the time-domain profile of the optical LFM pulse as explained above. 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 (see Fig. 2(e)) rather than the electric LFM pulse itself presented in [7]. Figure 3(a) depicts the autocorrelation of the optical LFM pulse. As clearly shown in the inset of Fig. 3(a), the full width at half maximum (FWHM) of ~1 ns agrees with B = 1 GHz. Since n = 1.446 in the SMF, the nominal spatial resolution is Δz = 10 cm. The measured curve of the backscattered light in the FUT is illustrated in Fig. 3(b). The transmission loss of ~1 dB and/or Rayleigh scatter can be clearly identified, which was not successfully observed in [7]. One can also see the high reflection peak due to Fresnel reflection at the far end. The inset of Fig. 3(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. 3(a)); besides, the sidelobes of the OPCR due to the nature of LFM pulse compression still exist in the backscattered curve (see Fig. 3(b). These factors can be possibly reduced somehow by use of proper windowing (i.e. apodization) [6], which is now under investigation.

4. Conclusion

We have demonstrated a modified OPCR based on the new generation of the optical LFM pulse by directly switching the VCO. The properties of the electric pulsed LFM and the optical LFM pulse are experimentally characterized. The experimental results verify that the modified OPCR has better performance than [7], such as less complexity, more robust stability, and higher spatial resolution (10 cm). If a new technology of generating broader sweeping bandwidth by recirculating the SSBM [8] is adopted into the OPCR, the spatial resolution is expected to be further improved.

This work was partially supported by National Natural Science Foundation of China (61007052 and 61127016), Shanghai Pujiang Program (12PJ1405600), SRFDP of MOE (Grant No. 20130073130005), and the State Key Lab Project of Shanghai Jiao Tong University (GKZD030033).

References

[1] X. Bao and L. Chen, "Recent progress in distributed fiber optic sensors," *Sensors* **12**, 8601-8639 (2012).

[2] M. K. Barnoski, M. D. Rourke, S. M. Jensen, and R.T. Melville, "Optical time domain reflectometer," *Appl. Opt.* **16,** 2375–2379 (1977).

[3] B. Soller, D. Gifford, M. Wolfe, and M. Froggatt, "High resolution optical frequency domain reflectometry for characterization of components and assemblies," *Opt. Express* **13**, 666-674 (2005).

[4] M. Kashiwagi and K. Hotate, "Long range and high resolution reflectometry by synthesis of optical coherence function at region beyond the coherence length," *IEICE Electron. Exp.* 6(8), 497-503 (2009).

[5] S. Li, X. Li, W. Zou, and J. Chen, "Rangeability extension of fiber-optic low-coherence measurement based on cascaded multistage fiber delay line," *Appl. Optics*, **51**, 771-775 (2012).

[6] M. A. Richards, Fundamentals of radar signal processing, McGraw-Hill Education, (2005).

[7] S. Yang, W. Zou, X. Long, and J. Chen, "Pulse-compression optical time domain reflectometer," in the 23rd International Conference on Optical Fiber Sensors, *Proc. of SPIE*, Vol. 9157, 915736, Jun. 2014.

[8] W. Li and J. Yao, "Generation of linearly chirped microwave waveform with an increased time-bandwidth product based on a tunable optoelectronic sscillator and a recirculating phase modulation loop," *J. Lightwave Technol.* **32**, 3573-3579 (2014).