Range enlargement of optical pulse compression reflectometry based on amplified heterodyne detection

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Abstract: A new scheme of optical pulse compression reflectometry based on amplified heterodyne detection is proposed to enlarge the measurement range. 58 km measurement range with 10 cm spatial resolution is experimentally demonstrated.

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

1. Introduction

Optical time domain reflectometry (OTDR) [1] and optical frequency domain reflectometry (OFDR) [2-4] have been widely studied. Though their performance is predecessor, limitations still exist. The spatial resolution of OTDR is directly related to the pulse width. Higher spatial resolution needs narrower pulse width, but a narrow pulse width decreases the power of detecting light and limits the dynamic range [1]. OFDR can alleviate the tradeoff via employing a continuous linear frequency modulated light as the source, which makes the spatial resolution determined by sweeping bandwidth. Its measurement range, however, is limited by the half of the laser source's coherent length [4]. To break the above limitations, a novel reflectometry technology based on a linear frequency modulation (LFM) pulse, called optical pulse compression reflectometry (OPCR) [5, 6], was proposed. The matching filter compresses the backscattered frequency-modulated pulse based on the pulse compression technology. The spatial resolution is determined by the compressed pulse width since the backscatter is measured in time domain, which breaks the limitation between spatial resolution and dynamic range. Also, the pulse compression technology has higher resistance to the phase noise than OFDR [5], so OPCR can detect a fiber comparable to or even longer than the coherent length of light source. To date, OPCR can achieve 10 cm spatial resolution over 5.4 km measurement range using a laser source with a coherent length of 2 km and instantaneous bandwidth of 1 GHz [6].

In this work, we demonstrate a new scheme of amplified heterodyne detection to enlarge the measurement range of the OPCR. Either a single-sideband modulator (SSBM) or double-sideband modulator (DSBM) is verified to work equally for generation of the linearly frequency-modulated (LFM) pulse and measurement ability of the OPCR. In the experiment, 58 km measurement range with 10 cm spatial resolution is achieved.

2. Principle

The basic configuration of OPCR [5] requires a laser source to be split into two branches: one is modulated with an LFM pulse and the other serves as the local reference light. When a continuous light is launched into an intensity modulator, it is reasonable to assume that only the first-order modulated sidebands are considerable. So the detecting modulated pulse E_p can be expressed by

$$E_p(t) = \mathrm{rect}\left(\frac{t}{T}\right)\left\{\begin{array}{l}\exp\left(j\omega_c t + j\omega_0 t + j\pi K t^2\right)\\ +\exp\left(j\omega_c t - j\omega_0 t - j\pi K t^2\right)\end{array}\right\} \tag{1}$$

where rect(·) denotes the rectangular function, T is the pulse width, ω_c is the center angular frequency of optical carrier (laser), ω_0 is the start angular frequency of LFM, and K is the LFM slope. The modulated pulse is launched into the fiber under test (FUT) and generates backscattered light. The backscatter is coherently detected with the local reference light. The electrical signal converted by a photodetector (PD) is I/Q demodulated in digital domain. Later, the I/Q demodulated signal goes through a matching filter to recover the backscatter of Rayleigh scattering and/or end reflection in an FUT. The recovered backscatter can be expressed by

$$y(t) = A(t) * \left\{ rect\left(\frac{t}{2T}\right)\frac{T\sin\left[\pi K\left(T-|t|\right)(t)\right]}{\pi KT(t)}\right\} \tag{2}$$

where the symbol of "*" denotes the convolution operation and A(t) corresponds to the backscatter of Rayleigh scattering occurring anywhere in the fiber, splicing loss at particular points, and end reflection due to Fresnel

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reflection. In the SSBM- or DSBM-based OPCR system, $A(t)$ can be respectively expressed by

$$\begin{aligned} A_S(t) &= \Re \cdot r(t)\exp(-j\omega_c t) \\ A_D(t) &= \Re \cdot r(t)\cos(\omega_c t) \end{aligned} \tag{3}$$

where R corresponds to the total response of PD, the amplitude of modulated pulse and local reference light. $r(t)$ is the amplitude function determined by Rayleigh scattering and loss in the fiber. t denotes different time delays, corresponding to the position (z) along the FUT.

Eq. (2) and Eq. (3) show that DSBM doesn't change the main lobe width of the compressed pulse. In contrast, in the SSBM-based OPCR, there is only one sideband in Eq. (1). After coherent detection and I/Q demodulation, the phase change at different time delay remains an exponential form of [exp(−jωct)]. In the DSBM-based OPCR, two sidebands in Eq. (1) are coherently detected with the same reference signal. Two beat signals with opposite values of carrier's phase change are generated and thus there are some particular positions where the amplitude of AD is small or null. Thus, it might be an error in the reflection measurement. However, the above theory only considers a monochromatic carrier. In fact, the laser source always has its linewidth and phase noise [7].

Figure 1 depicts the numerical simulation of the influence of phase noise on the DSBM-based OPCR. The width of modulated pulse is 2 μs and the sweeping bandwidth is 1 GHz. The FUT is a ~2.7 km fiber spool connected with another ~2.7 km fiber spool. There are two reflection peaks caused by Fresnel reflection. As shown in Fig. 1(a), only one peak is detectable if the carrier frequency is monochromatic. This is because the time delay corresponding to the position of 2.7 km makes the phase close to $m\pi$ (m is an integer). According to Eq. (3), the reflection amplitude at 2.7 km is null. In contrast, if the linewidth of laser source is considered, the suppressed peak appears [see Fig. 1(b)], which indicates that the refection suppression is weakened.

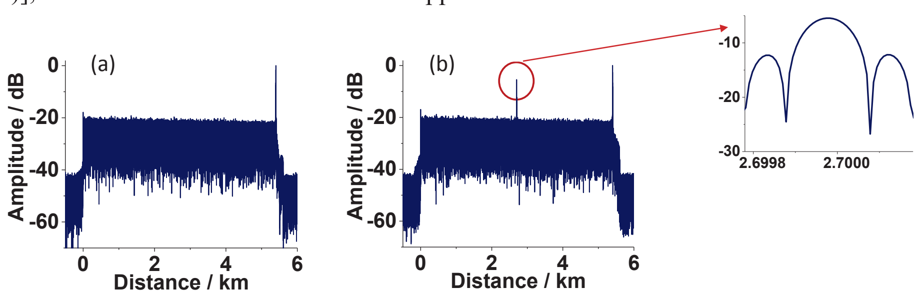

Fig. 1. Numerical simulation of DSBM based OPCR. (a) Backscattering curve with the monochromatic laser source. (b) Backscattering curve considering the linewidth of laser source. The inset is the magnified peak at 2.7km.

3. Experimental details

The experimental setup of the modified OPCR is depicted in Fig. 2. A laser with ~3 kHz linewidth (FM Photonics Ltd.) is used as the optical source. A VCO (Mini-Circuits Ltd.) with 1-GHz sweeping range after an electrical amplifier (AMF) is driven by a sawtooth wave to generate LFM microwave pulse. It modulates a dual-parallel Mach-Zehnder modulator (DP-MZM, Photline MXIQ-LN-40) to generate DSBM or SSBM under proper dc bias. The polarization state before and after DP-MZM is properly adjusted and its output is monitored by an optical spectrum analyzer (OSA, Yokogawa Ltd.). An erbium-doped fiber amplifier (EDFA) lays behind MZM to compensate its loss.

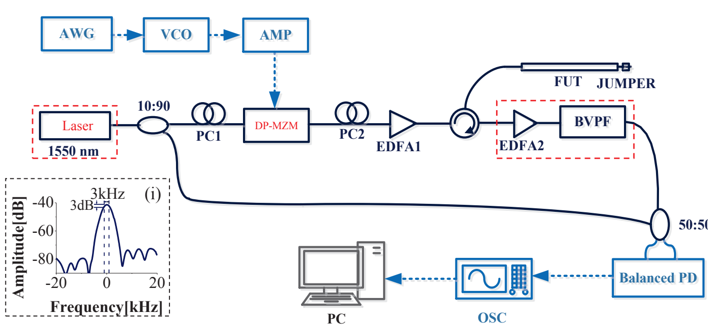

Fig. 2. Experimental setup of the modified OPCR. AWG: arbitrary waveform generator, VCO: voltage control oscillator, g: electrical amplifier, PC: polarization controller, EDFA: Erbium-doped fiber amplifier, OSA: optical spectrum analyzer, BPF: bandpass filter, DP-MZM: dual-parallel Mach-Zehnder modulator, OSC: oscilloscope.

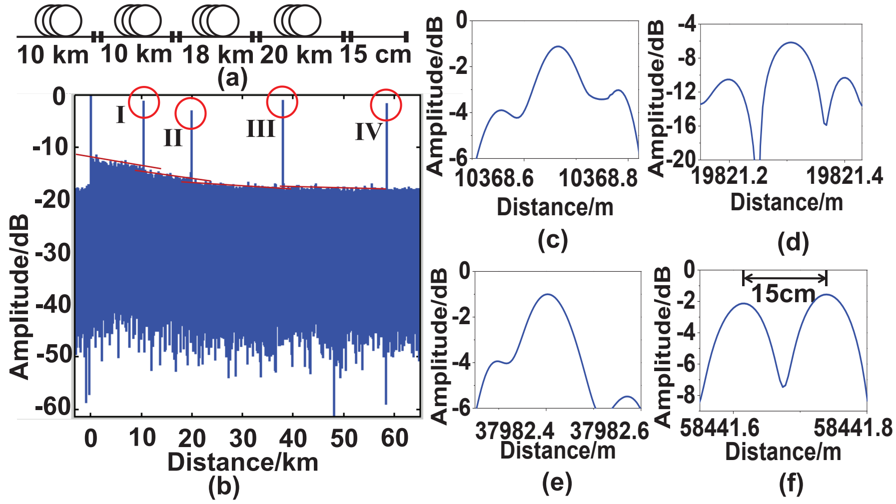

Fig. 3. (a) Configuration of 58 km FUT. (b) Overall backscattering curve. (c) Magnified curve at "I" position of (b). (d) Magnified curve at "II" position of (b). (e) Magnified curve at "III" position of (b). (f) Magnified curve at "IV" position of (b).

The backscatter is coherently detected with the local reference light and then converted into the electrical signal by a balanced PD (Discovery DSC720) with 16-GHz bandwidth. The digitalization is employed by an oscilloscope (Tektronix DSA 70804), and the I/Q demodulation and matching filter are digitally fulfilled by a computer. When the FUT is sufficiently long, the backscatter contains less reflection of the LFM pulse due to fiber loss. In order to overcome this problem, another EDFA and an optical bandpass filter (BPF) are laid before the PD so as to amplify the heterodyne detected signal power.

The measurement results in the 58-km FUT comprising four fiber spools and the 15-cm jumper are summarized in Fig. 3. The connection is not strictly tight so that both ends of the jumper generate Fresnel reflection, creating two reflection peaks with an interval of 15 cm. Note that the measurement results are approximately the same when the modulator works as SSBM or DSBM. It verifies the measurement ability of 58-km measurement range [see Fig. 3(b)] and 10-cm spatial resolution since the fiber connectors [see Fig. 3(c)-(e)] and fiber jumper [see Fig. 3(f)] can be well interrogated. Figure 3(b) shows that the rear part of backscatter has very gentle slope, this is because the longer the fiber increases, the lower ratio of Rayleigh scattering in total backscatter signal, which makes the Rayleigh scattering buried in noise. To overcome this, more times averaging can be used as in [5].

4. Conclusion

We have demonstrated a modified OPCR by use of a narrow linewidth laser, optical amplifiers, and optical filter. The experimental results verify that the modified OPCR has enlarged the measurement range from 5.4 km in [6] to 58 km with the same spatial resolution. The measurement range of the OPCR is expected to be further improved by more times averaging and/or with a pulse duty ratio of the LFM pulse.

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