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Pulse-Compression Optical Time Domain Reflectometer

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ABSTRACT

This paper introduces a novel pulse-compression optical time domain reflectometer (OTDR) by utilizing linear frequency modulation (LFM) pulse-compression technology. The working principle of the pulse-compression OTDR is demonstrated. The spatial resolution is determined by the sweeping range of the pulsed LFM instead of the pulse width, which solves the dilemma of spatial resolution and measurement range in the conventional OTDR. A preliminary experiment of the pulse-compression OTDR is performed, providing 55 cm spatial resolution and 5.4 km measurement range under 2 μs pulse, 221 MHz LFM sweeping range, and 100 kHz linewidth laser diode. It is expectable to achieve a spatial resolution of less than 1 cm and dozens-kilometer measurement range by tens of GHz LFM sweeping ranges via microwave photonics.

Keywords: Optical Time Domain Reflectometer, Pulse Compression, Linear Frequency Modulation

1. INTRODUCTION

Optical time domain reflectometer (OTDR) was developed to detect disturbance to optical fibers decades ago [1]. The spatial resolution of a conventional OTDR is determined by pulse width. For higher spatial resolution, narrower pulse width is needed. Because of the limitation of output power, narrow pulse leads to small energy which decreases the dynamic range and the measurement range. In order to break this limitation, optical frequency domain reflectometry (OFDR) was proposed [2, 3]. OFDR uses periodical linear frequency modulation (LFM) light as the detecting signal and analyzes the back scattering light in frequency domain. The spatial resolution of OFDR is determined by the sweeping range rather than the pulse width, which solve to a certain extent the dilemma of spatial resolution and dynamic range. However, its measurement range is limited by the laser source's coherent length [3]. Laser source with narrow linewidth is required to achieve long measurement range. Referred to radar system, the principle of conventional OTDR is similar to single pulse radar and that of OFDR to frequency modulation continuous wave (FMCW) radar [4]. There is another kind of radar called pulse-compression radar whose spatial resolution is comparable to FMCW radar while measurement range is comparable to single pulse radar.

This paper presents a novel OTDR based on pulsed LFM technology, called pulse-compression OTDR, which is inspired by the principle of pulse-compression radar so as to break the limitation of both conventional OTDR and OFDR. In section 2, we will provide the principle of the novel OTDR and the theoretical analysis on the spatial resolution. In section 3, preliminary experiment will be demonstrated to verify the spatial resolution and to prove that the measurement range can be easily beyond the laser source's coherent length. In section 4, a concluding remark will be given.

2. PRINCIPLE AND THEORETICAL ANALYSIS

There are several kinds of pulse compression methods and in this paper the simple but easy one, the pulsed LFM, is taken as an example [4]. Figure 1 depicts the working principle of the pulse-compression OTDR with the pulsed LFM. An optical source is split into two branches. One of them is modulated with a pulsed LFM signal as the detection light towards a long-length optical fiber under test (FUT); the other one is the local reference light. Then the back scattering light of the FUT is coherently detected with the local reference light. The electrical signal converted by a photodetecter (PD) is I/Q demodulated and goes through a match filter to obtain the back scattering curve.

The back scattering light E_s and the local reference light E_{local} can be described as follows.

$$\begin{aligned} E_s(t) &= \int_0^{T_s} A_1(\tau)\, rect\left(\frac{t-\tau}{T}\right) \exp\left[-j2\pi f_c(t-\tau) - j\pi K(t-\tau)^2 - j\phi(t-\tau)\right] d\tau \\ E_{local}(t) &= A_2 \exp\left[j2\pi f_c t + j\phi(t)\right], \end{aligned} \tag{1}$$

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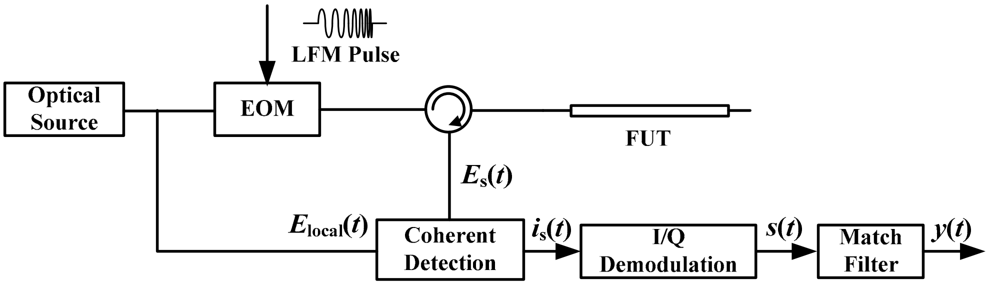

Fig. 1. The structure of OTDR with LFM pulse compression technology. EOM: electro-optic modulator, FUT: fiber under test.

where rect(t) means rectangular function, $A_1(t)$ is the amplitude function determined by Rayleigh scattering and loss in the fiber, T is the pulse width, T_s is the total propagation duration for a light going forth and back in the fiber, τ is the time delay related to the position in fiber, A_2 is the amplitude of the local reference light, f_c is the frequency of carrier light, K is the LFM slope, and $\phi(t)$ is the phase noise of the optical source.

After coherent detection, the photocurrent from the PD is given by

$$i_s(t) \propto 2\mathfrak{R}\,\mathrm{Re}\left\{E_s E_{local}^*\right\} = 2\mathfrak{R}A_2\int_0^{T_s} A_1(\tau)\exp\left(-\frac{\tau}{2\tau_c}\right) rect\left(\frac{t-\tau}{T}\right)\cos\left[\pi K(t-\tau)^2 - 2\pi f_c\tau\right]d\tau, \tag{2}$$

where $\mathfrak{R}$ is the PD's response and τ_c is the source's coherent time. The term of $\exp(-\tau/2\tau_c)$ is the time-domain average of $\phi(t)$-$\phi(t$-$\tau)$ under the condition that $\phi(t)$ is a stochastic process satisfying Gauss distribution [3].

Using I/Q demodulation to convert a real signal to complex one for processing [4], one obtains

$$\begin{gathered} s(t) = \int_0^{T_s} A(\tau)\, rect\left(\frac{t-\tau}{T}\right)\exp\left[j\pi K(t-\tau)^2\right]d\tau \\ A(\tau) = 2\mathfrak{R}A_2A_1(\tau)\exp\left(\frac{-\tau}{2\tau_c}\right)\exp\left(-j2\pi f_c\tau\right). \end{gathered} \tag{3}$$

The impulse response of the match filter is given by [4]

$$h(t) = rect\left(-\frac{t}{T}\right)\exp\left(-j\pi K t^2\right). \tag{4}$$

Then, the signal after match filtering can be expressed as

$$y(t) = s(t) * h(t) = \int_0^{T_s} A(\tau)\, rect\left(\frac{t-\tau}{2T}\right)\frac{T\sin\left[\pi KT\left(1-\frac{|t-\tau|}{T}\right)(t-\tau)\right]}{\pi KT(t-\tau)}d\tau. \tag{5}$$

Equations (3)-(5) are the basis of the pulse-compression process. Figure 2 depicts a numerical simulation of the qualitative process for a single pulse when τ is zero. The original LFM pulse (see Fig. 2(a)) becomes a narrow sinc-like pulse (see Fig. 2(b)) through this process. As shown in Fig. 2(b), the full width at half magnitude (FWHM or 3 dB width) of main lobe is 1/KT. In theory, spatial resolution is defined as the propagation distance within one FWHM of the pulse. Thus, the spatial resolution of pulse-compression OTDR is given by

$$R = \frac{c}{2nKT} = \frac{c}{2nB}, \tag{6}$$

where c is the light speed in vacuum, n is the refractive index, and $B=KT$ is the LFM sweeping range. Equation (6) shows that the spatial resolution of the pulse-compression OTDR is now determined by B instead of the pulse width, which physically breaks the restriction between spatial resolution and measurement range.

According to equation (3), if τ is far larger than τ_c, the term of $\exp(-\tau/2\tau_c)$ becomes dominated and $A(\tau)$ is too weak to be detected from noise, which is the main reason why the measurement range of OFDR is no farther than the double of the source's coherent length [3]. Fortunately, match filter makes the output signal have higher signal-to-noise ratio (SNR) and the power of compressed pulse increase about B times due to the pulse compression [4]. Hence, the measurement range in the pulse-compression OTDR can physically exceed the limitation of OFDR, which will also be experimentally verified.

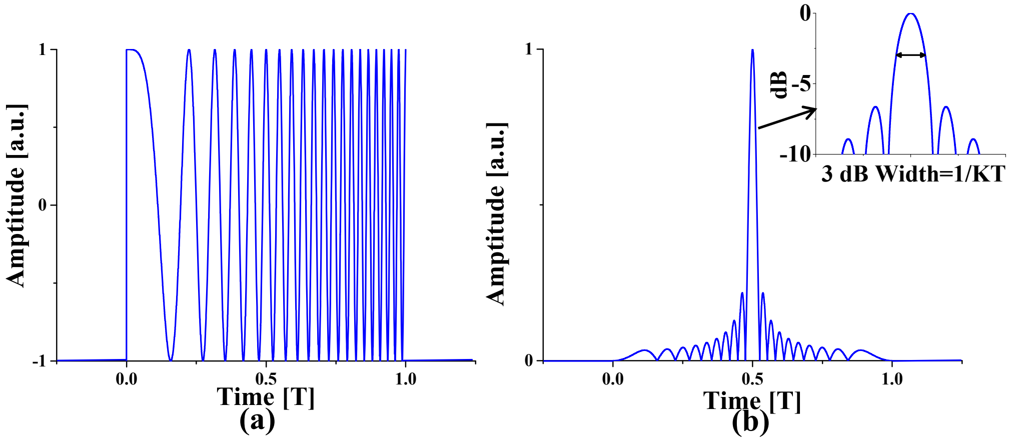

Fig. 2. Qualitative description of pulse-compression process. (a) time-domain shape of LFM pulse (b) the compressed pulse with a 3 dB width of 1/KT.

3. EXPERIMENTAL DEMOSTRATION

The experimental setup of the pulse-compression OTDR system is depicted in Fig. 3. A 1550 nm distributed feedback laser diode (DFB-LD, NEL NLK1C6DAAA) with 100 kHz linewidth is used as the optical source. A VCO with 221 MHz sweeping range (Minicircuits ZX95-2536C, 2.315–2.536 GHz) is driven by a sawtooth wave with 2 μs period to generate periodical LFM signal, which is connected to a single sideband modulator (SSBM). The SSBM modulates one beam of the DFB-LD to get either the upshifted or downshifted sideband that is in frequency away from the carrier. In consequence, the frequency change of the VCO leads to the same change of the modulated sideband and thus a periodical LFM light is generated. This light is further modulated by a MZM with a square pulse with the same width as the period of LFM signal so as to turn the periodical LFM light to a pulsed LFM light. The sawtooth wave and square pulse are strictly synchronous since both are generated by the same arbitrary waveform generator (AWG, Agilent 81150A). Two EDFAs are set to compensate the loss of SSBM and MZM. The back scattering light is coherently detected with the local reference light (the other part of the DFB-LD) and an oscilloscope is used to collect the electrical signal from the PD (Discovery DSC720, 16 GHz bandwidth). I/Q demodulation and match filter are fulfilled by computer software. For verifying the spatial resolution, a 55 cm jumper is connected at the end of 5.4 km test fiber. This connection is not totally tight so both the end of test fiber and jumper will generate strong Fresnel reflection, which should lead to two reflection peaks with 55 cm interval in back scattering curve.

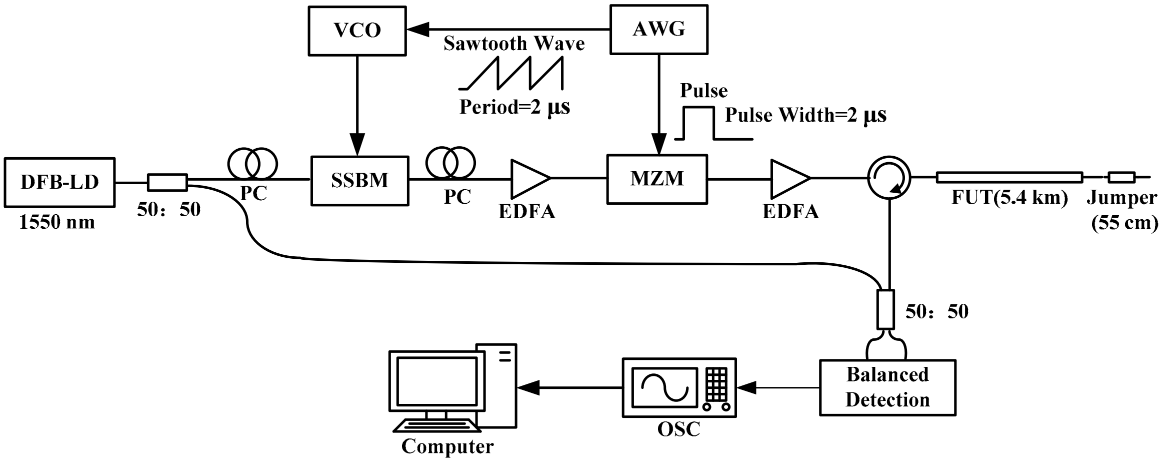

Fig. 3. Experimental setup of the pulse-compression OTDR system. DFB-LD: distributed feedback laser diode, SSBM: single sideband modulator, VCO: voltage control oscillator, AWG: arbitrary waveform generator, MZM: Mach-Zehnder modulator, PC: polarization control, EDFA: Erbium-doped fiber amplifier, FUT: fiber under test, OSC: oscilloscope.

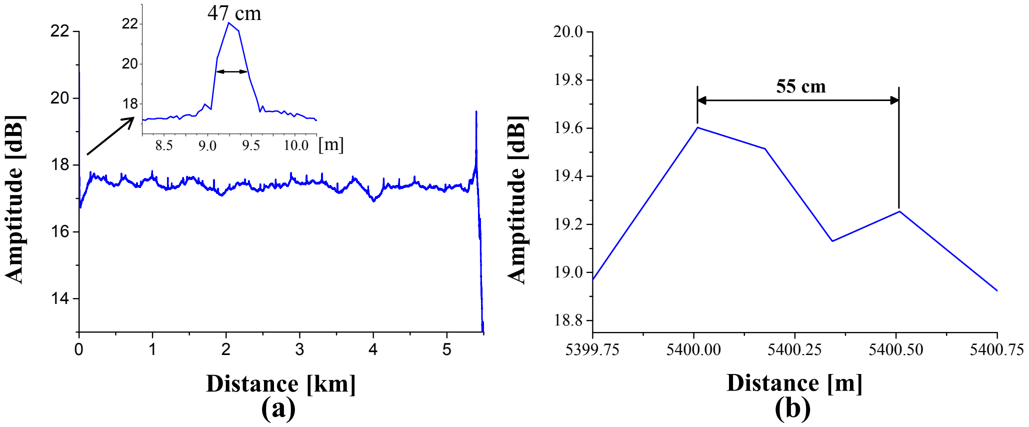

Fig. 4. Experimental results. (a) Overall back scattering curve. The inset shows the 3dB width (47 cm) at the FUT's near end. (b) Magnified curve around the two reflection peaks of the jumper at the FUT's far end with 55-cm interval.

Figure 4 depicts the measured back scattering curve. Figure 4(a) demonstrates that the OTDR can successfully detect the reflection at 5.4 km far end, which is 5.4 times larger than the source's coherent length (1 km). The amplitude fluctuation and periodical small peaks are mainly caused by the insufficient suppression ratio of MZM and the instability of SSBM driven by the LFM, which can be improved by changing the method of generating pulsed LFM in future. Because of the 221 MHz sweeping range, the theoretical value of spatial resolution is estimated to be 45 cm according to Eq. (6), which is obviously verified by the 3dB width at the FUT's near end (see the inset of Fig. 4(a)) or the clearly interrogated two peaks of the 55 cm jumper at the FUT's far end (see Fig. 4(b)).

4. CONCLUSION

We presented a pulse-compression OTDR with pulsed LFM as an example. The working principle and the theoretical analysis shows that the spatial resolution is only determined by the LFM sweeping range instead of the pulse width, suffering no dilemma between spatial resolution and measurement range of the conventional OTDR. The experimental confirmation verifies that the spatial resolution can easily reach 55 cm in 5.4 km measurement range with 221 MHz sweeping range and the measurement range can be far beyond the source's coherent length. Furthermore, because the spatial resolution of pulse-compression OTDR is irrelevant to the measurement range, by replacing VCO with OEO whose tunable frequency range can be tens of GHz [5], its resolution can reach 1 cm or less with long measurement range.

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