Influence of Phase Noise on Measurement Range in Optical Pulse Compression Reflectometry

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***Abstract*—Optical pulse compression reflectometry (OPCR) has been proposed to utilize the frequency modulation pulse-compression technology so as to overcome the tradeoff between the spatial resolution and measurement range. In this paper we theoretically analyze and simulate the influence of phase noise on OPCR. The phase noise determining the coherent length of the light source is closely linked to the measurement range.**

***Keywords*—phase noise; coherent length; linear frequency modulation; spatial resolution; pulse width**

I. INTRODUCTION

It is well known that the spatial resolution of conventional optical time domain reflectometry (OTDR) is directly determined by the width of optical pulse although the measurement range can be long [1, 2]. In contrast, optical frequency domain reflectometry (OFDR) uses periodic linear frequency modulation light and the spatial resolution is decided by the frequency sweeping range of LFM [3, 4]. However, their measurement ranges are in tradeoff relation with the spatial resolution. Optical pulse compression reflectometry (OPCR) [5, 6] was inspired by the pulse-compression concept in radar [7]. It can break through the limitation of conventional OTDR and OFDR with simpler optical equipment. The proof-of-concept experiment of the OPCR verified 47-cm spatial resolution of with 221 MHz frequency sweeping range and 2 μs pulse duration and 5.4 km measurement range which is beyond the source's coherent length by 2.7 times [5]. Most recently, 15 cm spatial resolution with 1 GHz frequency sweeping range at the same measurement range was successfully achieved [6].

In this paper, we theoretically analyze the working principle of OPCR and simulate the influence of phase noise on its measurement range. We verify that the measurement range is limited by the coherent length of the laser source. Additionally, theoretical and numerical analysis shows that time averaging process is a useful way to get a smooth backscattered curve with 100 km measurement range when the coherent length is set to be 2 km, 40 km, 100 km, and infinity.

II. PRINCIPLE AND THEORY

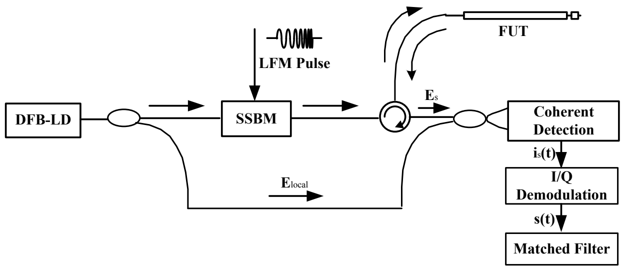

Fig. 1. Schematic configuration of OPCR based on pulse compression technology. DFB-LD: distributed feedback laser diode; SSBM: single sideband modulator; FUT: fiber under test.

Figure 1 illustrates the schematic configuration of OPCR based on LFM pulse compression technology [6]. The optical source is split into two branches: one is modulated by a LFM pulse that is served as the detection light towards a long-length optical fiber under test (FUT); the other one is used as the local reference light. The backscattered light of the FUT is coherently detected with the local reference light. The electrical signal converted by a photodetector (PD) is I/Q demodulated and goes through a matched filter to obtain the backscattered curve.

The output of light source with phase noise can be expressed by [8]:

$$E_{LD}(t) = \exp\left[j2\pi f_c t + j\phi(t)\right] \tag{1}$$

where f_c is the center frequency of the output light and $\phi(t)$ represents its phase noise. Assume the phase change of distributed feedback laser diode (DFB-LD) is stochastic process with zero-mean so that the phase in different time t is statistically independent:

$$\sigma_\phi^2(t) = 2\pi t \Delta\nu \tag{2}$$

where $\Delta\nu$ is the linewidth of the laser source that determines the coherence of the laser source as $l_c = \frac{c}{n} \cdot \frac{1}{\Delta f}$.

Assuming a Lorentzian source is used, the distribution of random phase $\Delta\phi(\tau)$ satisfies Gauss distribution with deviation $\sigma^2(\tau) = 2\pi|\tau|\Delta\nu = 2\tau/\tau_c$, where τ_c is the coherent time of the source [9]. Obviously, the phase noise differs in different distances. The way that we always assume the phase deviation to be a certain value so as to simulate the backscattered light will result in neglecting the influence of phase noise in different distances.

More details of phase noise is obtained if we take the distance influence into consideration [5]:

$$E_s(t)=\int_0^{T_S} A_1(\tau) rcet\left(\frac{t-\tau}{D}\right)\exp\left[j2\pi\left(\int_{-D/2}^{t-\tau}\left(K(s+D/2)+f_0+f_c\right)ds\right)+j\phi_\tau(t)\right]d\tau \; ,$$
$$E_{lacal}(t)=A_2\exp\left[j2\pi f_c t+j\phi(t)\right] \tag{3}$$

where $A_1(t)$ is the amplitude function of the backscattered light and A_2 is the amplitude function of the local light.

The signal after I/Q demodulation at a delay of τ turns to:

$$s(t)=\int_0^{T_s} A(\tau)s_\tau(t)d\tau \tag{4}$$

$$s_\tau(t)=rect\left(\frac{t-\tau}{T}\right)\exp\left[j2\pi\left(\int_{-D/2}^{t-\tau}\left(K(s+D/2)+f_0+f_c\right)ds\right)\right]\exp\left[j2\tau/\tau_c\right] \; ,$$

where $A(\tau)$ is defined as the normalized amplitude of different instants of time.

After the matched filtering process:

$$y(t)=s(t)*rect\left(-\frac{t}{T}\right)\exp\left[-j2\pi\left(\int_{-D/2}^{-t}\left(K(s+D/2)+f_0+f_c\right)ds\right)\right] \tag{5}$$

According to the law of large numbers in statistics, we will get the expectation of random numbers when the average time N is large enough [9]. Consequently, $s_\tau(t)$ is expressed by:

$$s_{\tau,ave}(t)|_{N\to\omega}=\left\langle rect\left(\frac{t-\tau}{T}\right)\exp\left[j2\pi\left(\int_{-D/2}^{t-\tau}\left(K(s+D/2)+f_0+f_c\right)ds\right)\right]\exp\left[j\Delta\phi_k(\tau)\right]\right\rangle \tag{6}$$
$$=rect\left(\frac{t-\tau}{T}\right)\exp\left[j2\pi\left(\int_{-D/2}^{t-\tau}\left(K(s+D/2)+f_0+f_c\right)ds\right)\right]\exp\left[j2\tau/\tau_c\right]$$

where $\langle . \rangle$ represents expectation and $\Delta\phi_k(t)$ denotes the k-th phase change. Thus it can be seen that the waveform distortion is correspondingly eliminated when the average time N is large enough the phase noise tends to be constant.

III. Simulation

On the basis of Eq. (5), the curve of 100 km distance with a 15 cm jumper connecting at the end of 100 km FUT is simulated when the coherent length is set to be 2 km, 40 km, 100 km, and infinity, respectively. The attenuation slop is set as 0.2 dB/km. Numerical simulations are shown in Figs. 2-5, respectively. It is noted that there is no any averaging process undertaken in the simulation although it is possibly effective to reduce the influence of the phase noise according to Eq. (6).

In Figs. 2-5, the part (a) shows the original curve while the part (b) depicts its envelope so as to expect the measurement range. TABLE I summarizes the linear attenuation range and measurement range for different coherent lengths. The linear attenuation range is expected by the attenuation slope while the measurement range is estimated by the maximum measurable range. It is found that the linear attenuation range is less affected by the phase noise but the measurement range is, more affected by phase noise. The measurement range extends along with the extension of coherent length, but the increasing trend gradually decreases. The phase noise determining the coherent length of the light source is closely linked to the measurement range. This is because the accumulation of the phase noise becomes large along with the extension of coherent length, which results in the decreasing of measurement range.

TABLE I. LINEAR ATTENUATION RANGE AND MEASUREMENT RANGE FOR DIFFERENT COHERENCE LENGTH

Coherence Length(km)	Linear Attenuation Range(km)	Measurement Range(km)
2	18.75	30
40	40	80
100	80	160
Infinite	Infinite	Infinite

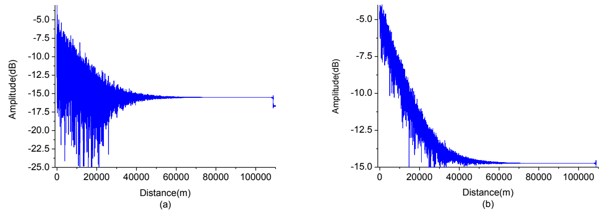

Fig. 2. Numerical simulation of OPCR trace under 2 km coherence length. (a) Original curve and (b) its envelope.

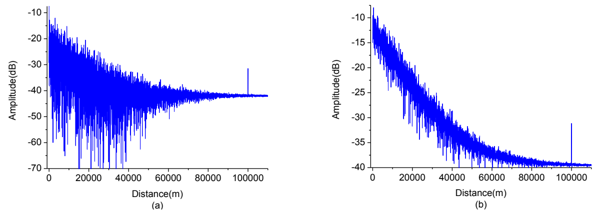

Fig. 3. Numerical simulation of OPCR trace under 40 km coherence length. (a) Original curve and (b) its envelope.

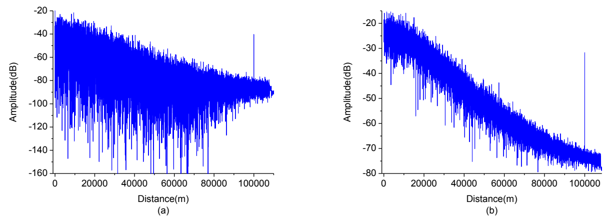

Fig. 4. Numerical simulation of OPCR trace under 100 km coherence length. (a) Original curve and (b) its envelope.

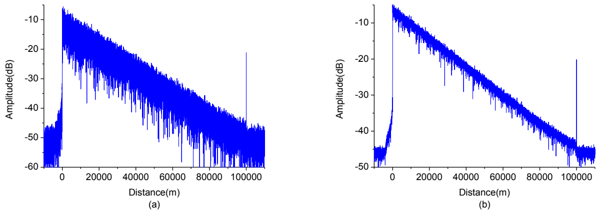

Fig. 5. Numerical simulation of OPCR trace under infinite coherence length. (a) Original curve and (b) its envelope.

IV. Conclusion

This study demonstrates that the influence of phase noise on the OPCR is closely linked to the coherence length of light source. Examples of the measurement length of 100 km for the coherent lengths of 2 km, 40 km, 100 km, and infinity are numerically simulated and compared. When the influence caused by phase noise exceed the fiber's attenuation, the measurement range will be influenced accordingly.

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