Simulation Result for Dynamic Range Extension in Coherent Optical Frequency Domain Reflectometry

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***Abstract* – A coherent OFDR model that enables to extend the dynamic range is proposed. π/2 phase shifting technique is involved in the proposed system in order to obtain complex interference signal. The obtained complex signal is processed to remove DC and mirror peaks in the frequency domain. The simulated results show the enhancement of dynamic range.**

I. Introduction

Optical frequency domain reflectometry (OFDR) has been widely studied for inspecting distributed internal and/or external perturbations along the fiber line [1-4]. There have been various applications reported to measure physical parameters such as temperature, strain, and vibration as well as to test optical properties of components such as birefringence, mode delay, gain, and tuning linearity [2]. Among several types of OFDR systems, a coherent detection scheme has an outstanding advantage of high spatial resolution up to micrometer scale. One of the biggest issues for coherent OFDR systems is to extend a dynamic range for a long distance interrogation. However, the dynamic range of the system is strongly limited by the coherence length of laser utilized. Since the extension of dynamic range can be achieved in general by using highly coherent input laser sources, most of the researches have focused on narrowing laser linewidth for the OFDR systems. To our knowledge, the longest dynamic range of 100 km was implemented by adopting 1 kHz fiber laser [3].

In more practical point of view, the use of quite expensive narrow linewidth laser can make the system to be bulky and not cost-effective. Recently, a method to extend the dynamic range beyond the laser coherence length has been demonstrated but its spatial resolution is not enough for practical applications (hundreds of meter) [4]. In this paper, a novel modelling of the coherent OFDR is proposed and simulated to extend the dynamic range. The proposed system is based on a little system modification that adopts phase shifting interferometry and simple signal processing algorism whose complex output signal is analyzed in a frequency domain by Fourier transform. Simulated results verifies 2 times of enhancement in the dynamic range of the system.

II. Proposed System and Operation

A schematic of the proposed coherent OFDR system is illustrated in Fig. 1. A tunable laser source (TLS) where

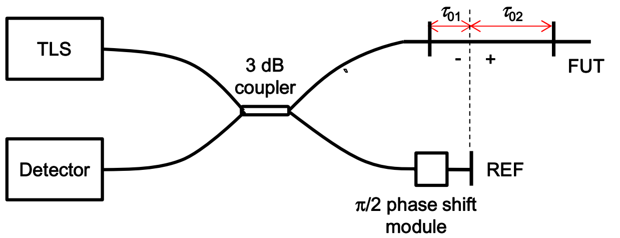

Fig. 1. Schematics of the proposed coherent OFDR system. π/2 phase shift module is installed in the reference path. Two local reflectors are assumed to be located at both sides of reference position. TLS: tunable laser source, FUT: fiber under test

optical frequency is linearly swept in time is launched into the fiber and divided into two paths: one is for probing fiber under test (FUT) and the other is for reference signal. Back-reflected light arising from local reflectors at FUT interferes with reference signal depending on the time delay between them. The resulting signal is measured at a time-sampled photo detector and processed by fast Fourier transform (FFT) in order to obtain frequency response of the interfering signal. Finally, resolved beat frequencies are converted into the locations of internal/external perturbation involved.

The signal obtained from the photo detector is expressed by [5]

$$\begin{aligned} &\text{for } |t| \le \tau_0 \\ &I(t) = (1+R)^2 + 2R\exp(-2|t|/\tau_c)\cos(2\pi\gamma\tau_0 t) \\ &\text{and for } |t| \ge \tau_0 \\ &I(t) = (1+R)^2 + 2R\exp(-2\tau_0/\tau_c)\cos(2\pi\gamma\tau_0 t) \end{aligned} \tag{1}$$

where τ_0 is time delay caused by optical path difference (OPD) between the reference and reflecting position, R is reflectivity at the local reflecting position of FUT, and γ is sweep rate of the source. τ_c is coherence time of the input laser source, which is determined by the coherence length L_c as nL_c/c where n is refractive index of fiber and c is speed of light in vacuum.

In most cases of coherent OFDR systems, the dynamic range is determined by half of laser coherence length because beat frequency is resolved by FFT as symmetric mirror peaks from DC component. If the local reflectors exist in both plus and minus directions from reference locations, significant confusion in reading the corresponding beat frequency is caused due to the mirror peaks. Therefore, time delay between two signals has been processed in every case. In order to solve this problem, the proposed system is designed to remove DC and mirror peaks by employing a phase shift unit at the reference path in Fig. 1. Signal processing algorism reported in [6] is adopted. This method involves two measurements of original signal $R(t)$ and $\pi/2$ phase shifted signal $I(t, \Delta\phi = \pi/2)$ to produce a complex signal $\tilde{I}(t) = I(t) + iI(t, \Delta\phi = \pi/2)$ and $\tilde{I}(t)^* = I(t) - iI(t, \Delta\phi = \pi/2)$. Then, these signals are transformed to the frequency domain by FFT and their difference is calculated to be

$$\Delta = \left|FT\{\tilde{I}(t)\}\right| - \left|FT\{\tilde{I}(t)^*\}\right|. \qquad (2)$$

With this procedure, DC component is eliminated and the mirror peak appears to have a minus value in intensity. Thus, after filtering minus intensity values we can successfully obtain only beat frequency without DC and mirror peaks. It means both sides of reflecting points from reference position can be used for frequency analysis. Eventually, the dynamic range of the system can improved up to maximum 2 times without scarifying spatial resolution if the reference mirror is located at half position of FUT length.

III. Results and Discussions

For the verification of the proposed method, we simulated the OFDR signal obtained from Eq. (1) and its phase shifted signal, assuming n = 1.45, R = 0.04, γ = 5 GHz/s, and τ_c = 66.7 μs (15 kHz linewidth laser). Also, it was assumed that two local reflectors exist at -500 m and +1 km from reference position. So, the time delay of two reflecting position τ_{01} and τ_{02} is calculated as -2.417 μs and 4.833 μs, respectively. Figure 2(a) shows the resulting signal with above assumptions $I(t)$ (black curve) and its phase shifted signal $I(t, \Delta\phi = \pi/2)$ (red curve). Due to the superposition of two beat frequencies, signal looks a little complicated. The FFT signal of I(t) is plotted in Fig. 2(b) with black curve. The beat frequencies $\gamma\tau_{01}$ and $\gamma\tau_{02}$ were resolved in the transformed domain but it cannot distinguish the wanted frequency due to the mirror peaks. On the other hand, the signal Δ clearly shows that DC peak is completely removed and mirror peaks are inverted toward minus intensity direction as shown in Fig. 2(b) with red curve. With this method, therefore, both sides of reflecting points from reference position are fully available, which means the dynamic range of the system can reach to the laser coherence length.

IV. Conclusion

In this paper, we proposed the extended dynamic range in the coherent OFDR system. By applying the phase shifting unit at the reference path to obtain complex signal and then by taking signal processing algorism to eliminate DC and mirror peak in frequency domain, we could simply implement two times enhancement in the dynamic range of the system. It is expected that the proposed method can be effectively used for a long distance distributed sensing tool without using expensive narrow linewidth laser source.

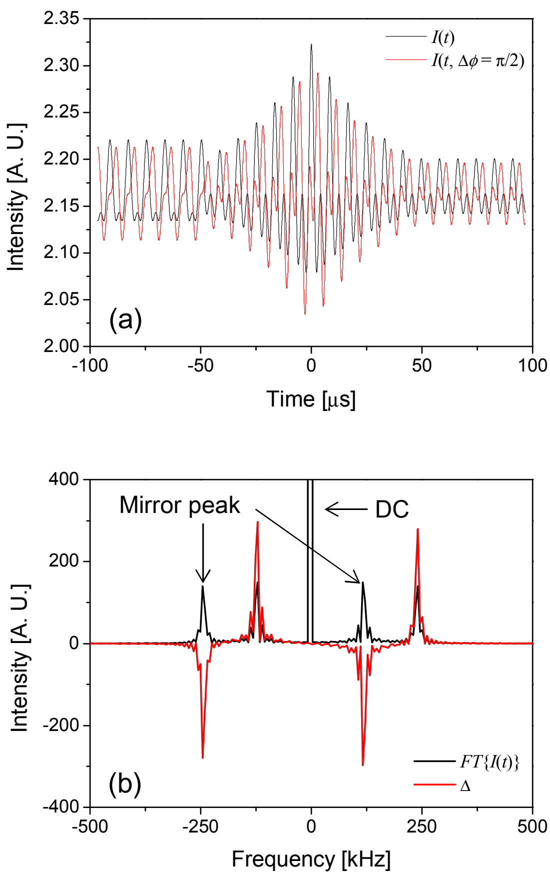

Fig. 2. (a) The original and phase-shifted signal at time-sampled photo detector obtained from the model of Fig. 1 and (b) the FFT signal with and without applying signal processing algorism. After processing, it was obviously shown that the DC and mirror peak are eliminated.

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References

[1] K. Shimizu and T. Horiguchi, "Measurement of Rayleigh backscattering in single-mode fibers based on coherent OFDR employing a DFB laser diode," *IEEE Photon. Tech. Lett.* 3(11), 1039-1041 (1991).

[2] K. Yuksel, M. Wuilpart, V. Moeyaert, and P. Megret, "Optical frequency domain reflectometry: A review," *ICTON 2009, Tu.C2.5*, 1-5 (2009).

[3] J. Geng, C. Spiegelberg, and S. Jiang, "Narrow linewidth fiber laser for 100-km optical frequency domain reflectometry," *IEEE Photon. Tech. Lett.* 17(9), 1827-1829 (2005).

[4] Z. Ding, X. S. Yao, T. Liu, Y. Du, K. Liu, Q. Han, Z. Meng, J. Jiang, and H. Chen, "Long measurement range OFDR beyond laser coherence length," *IEEE Photon. Technol. Lett.* 25(2), 202-204 (2013).

[5] S. Venkatesh and W. V. Sorin, "Phase noise considerations in coherent optical FMCW reflectometry," *J. Lightwave Technol.* 11(10), 1694-1700 (1993).

[6] E. Götzinger, M. Pircher, R. A. Leitgeb and C. K. Hitzenberger, "High speed full range complex spectral domain optical coherence tomography," *Opt. Express* 13(2), 583-594 (2005).