Single-shot hybrid CP- φOTDR/CP-BOTDA system for simultaneous distributed temperature/strain sensing

Yuan Wang[1,*], **Xiaoyi Bao**[1,2,#]
1School of Electrical Engineering and Computer Science, University of Ottawa, Ontario K1N 6N5, Canada;
2Department of Physics, University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada;
*Author e-mail address: * ywang681@uottawa.ca; # xiaoyi.bao@uottawa.ca;*

Abstract: A real time simultaneous temperature and strain measurement based on hybrid chirped pulsed ϕ-OTDR and BOTDA is demonstrated for the first time. The high accuracy of 4.3 με for strain and 0.32℃ for temperature is achieved over 5 km non-uniform fiber.

1. Introduction

In the traditional BOTDA system, the frequency sweeping process takes usually several seconds to several minutes, which lowers the acquisition rate of the system, leading to a limited measurable frequency range of dynamic strain. Recently, many ultra-fast BOTDA systems have been studied to save the sweeping time for high frequency dynamic strain measurement, such as optical frequency comb (OFC) scheme [1], slope-assisted scheme [2], and fast-frequency sweeping scheme [3]. However, these proposed schemes have disadvantage on low spatial resolution, small measurement range and complicated post-data process. In [4], the frequency-sweep pulse is used to achieve fast dynamic measurement in a 10 km fiber by converting the temperature or strain-induced Brillouin frequency shift into local time delays . However, the entire distribution acquisition rate is limited by the number of measurement points along a fiber, due to it needs repeated pulse launching until the whole completed distribution is obtained.

However, most of there proposed methods could only used for one parameter measurement. In this paper, a real time and simultaneous temperature and strain sensing system is proposed by combining the chirped pulse Brillouin optical time-domain analysis (CP-BOTDA) technique and chirped pulse φ-OTDR technique. The proposed system is an good candidate for dynamic sensing and the acquisition rate is only limited by fiber length and averaging time. In the proof-of-principle experiment, 4.5m spatial resolution with strain uncertainty of 4.3 με and temperature uncertainty of 0.32℃ is achieved in a 5 km non-uniform fiber.

2. Experiment setup and principle

In Fig.1, a frequency chirped pulse ($\upsilon_p=\upsilon_0+(\Delta\upsilon/W)*T$) with pulse width of W=40ns and frequency chirping range of Δυ=575MHz is utilized as pump signal, and another single frequency Stokes lights (υ_s) is counter-propagating along the fiber. When the frequency deviation range between chirped pump pulses and probe signals covers the local Brillouin gain spectrum (BGS), the amplified Stokes lights could be calculated the integral of the amplified Stokes light within the effective width corresponding to the local Brillouin gain spectrum convoluted with chirped pulse spectrum. And the power of Stokes light $P_{cw}(t)$ at given time t could be expressed as:

$$P_{cw}(t) \propto P_{dc} + P_p(0,\upsilon_p)\cdot\exp(-\alpha_p\cdot tC/2)\cdot P_{dc}\cdot\frac{Cg_p}{2A}\int_{t-2Z_{eff}/C}^{t-(2Z_{eff}/C-W\cdot\frac{\Delta\upsilon_B}{\Delta\upsilon})}\frac{(\Delta\upsilon_B/2)^2}{(\upsilon_0+\frac{\Delta\upsilon}{W}t-\upsilon_s-\upsilon_B)^2+(\Delta\upsilon_B/2)^2}dt \quad (1)$$

where υ_B is the local Brillouin frequency shift of the fiber, g_p is the peak value of the Brillouin gain coefficient occurring at υ_p-υ_s=υ_B, and $\Delta\upsilon_B$ is the Brillouin gain bandwidth. $P_{dc}=P_{cw}(L)\exp(-\alpha_{cw}L)$ representing CW Stokes light that arrives at $Z=0$ without interacting with the pulse and $P_p(0,\upsilon_p)$ is the power of pump pulse with frequency of υ_p at time t=0. C is the speed of the lights in the fiber. α_p is the attenuation coefficient for a chirped pulse and A is the effective cross section of the fiber. Z_{eff} represents the distance between the input end and the front end of the interaction range.

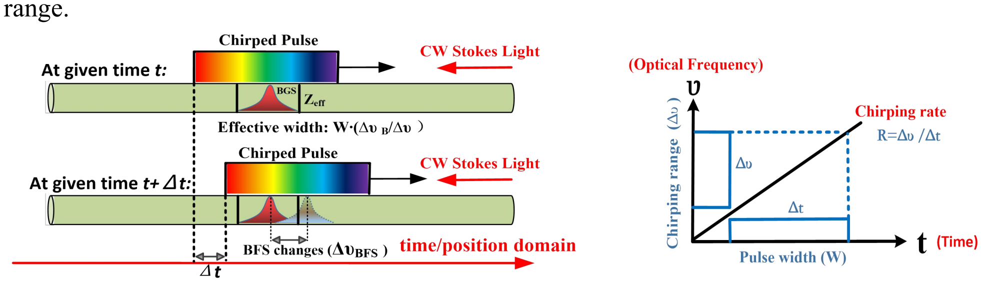

Fig.1 Principle of Chirped pulse BOTDA.

For two measurements with and without strain/temperature applied, the same interested fiber section (within in effect width) is corresponding to different parts of the chirped pulse, since a BGS shift is introduced by local strain variation. The different parts of a chirped pulse (covers BGS range) have different arrival time, t_0 and $t_0+\Delta t$, thus the strain variation induced-BGS shifts is translated into local time delays when a frequency chirped pulse is used. The value of the time delays is determined by the chirping rate of the pulse and the local BFS changes as shown in right figure in Fig.1. Since the local BFS changes are measured from the local time delays within a selected time window from Brillouin traces, the intensity of the Brillouin signal within selected time window includes convolution of the chirped spectrum and Brillouin spectrum, and we measure the delay pulse envelope, which has little sensitivity to the polarization matching required pump and probe signal for maximum Brillouin gain, and thus the time delays measurement is immune to the polarization fading problems. On the other hand, the principle of chirped pulse φ-OTDR by using Rayleigh traces for temperature/strain measurement could be found in references [5].

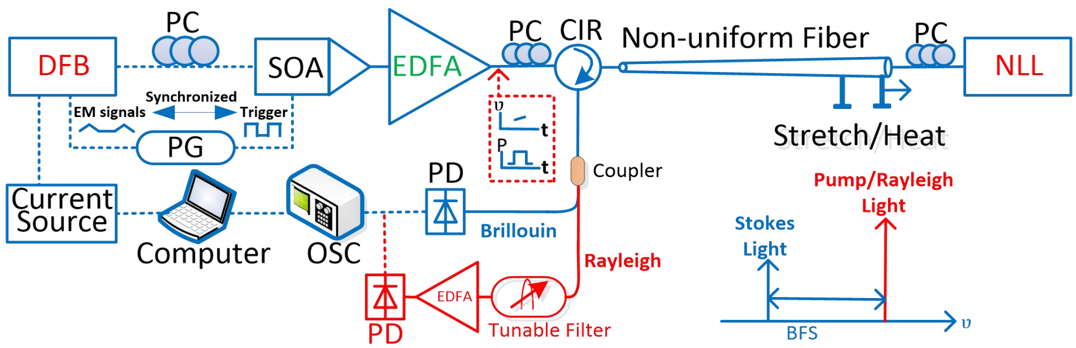

Fig.2 The proposed hybrid system for simultaneous temperature and dynamic strain measurement

The setup of our proposed system is shown in Fig.1. A DFB laser diode (CQF938/500, JDS Uniphase) is driven by an linearly modulated current source to generated a frequency chirped output optical signal, which is further reshaped by the semiconductor optical amplifier (SOA) into a rectangular chirped optical pulse signal. After being boosted by Erbium doped fiber amplifier (EDFA), the chirped pulse signal (pump) is launched into a non-uniform fiber, while probe lights operated at Stokes frequency is sent into the fiber from another end. The reflected optical signal includes amplified Stokes lights from SBS effect and Rayleigh signals from Rayleigh scattering, which are accompanied with frequency deviation about 10 GHz, determined by the local Brillouin frequency shifts. Due to the intense amplified Stokes lights in the mixed signals, Rayleigh signal should be filtered out by a optical tunable band-pass filter before sending it to EDFA to avoid the gain competition. After that, the amplified Stokes lights, namely Brillouin traces, and Rayleigh traces could be detected by photodetector and then displayed on the Oscillatorscope (OSC).

3. Demodulation method and experimental results

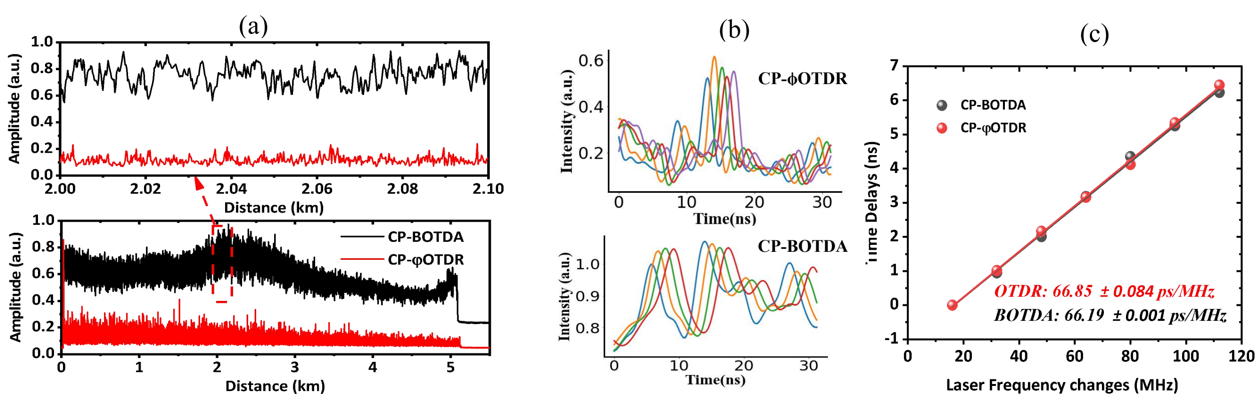

Fig. 3. (a) Time domain traces from stimulated Brillouin scattering (SBS) effect and Rayleigh scattering effect; (b) Time shifts of Brillouin traces and Rayleigh traces when the frequency deviation between pump and probe lights is changed with step of 16 MHz (blue traces is corresponding to frequency deviation of 10 GHz); (c) Relationship between relative frequency deviation changes and time delays.

The time domain Brillouin and Rayleigh traces are shown in Fig.3 (a). The high accuracy time delay measurement requires that the Brillouin traces have steep peaks in the intensity variation profile, which allows small change in BFS changes being measured due to small temperature or strain change. Based on Fig.3, a non-uniform fiber with steep peaks could give various sharp fluctuations, which is a good candidate for small strain or temperature measurement. The simulation results between time delays in Brillouin traces/Rayleigh traces and frequency deviation changes are shown in Fig.3 (b). It clearly shows that the time domain traces experience longitudinal temporal shifts when the frequency deviation between pump and probe is changing by tuning the initial frequency v_0 of the chirped pulse. The relationship between time delays and frequency deviation changes in Brillouin traces and Rayleigh traces are plotted in Fig.3 (c), and they have almost the same coefficient since it is only determined by the chirping rate of the chirped pulse signal.

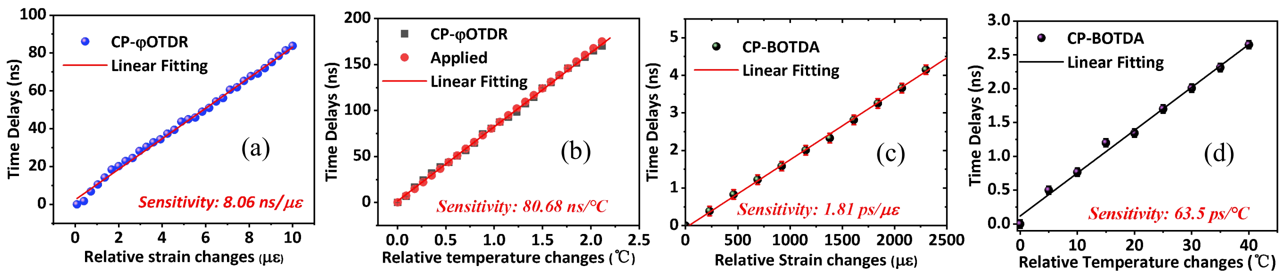

Fig. 4 Time delays-strain coefficient (a) (c) and time delays-temperature coefficient (b) (d) in CP-φOTDR and CP-BOTDA respectively.

In order to obtained the time delays related temperature and strain coefficient for dynamic distributed temperature and strain measurement , static strain and temperature measurement with acquisition rate of 10 kHz is carried out at the end of the fiber. Four different coefficients are obtained as shown in Fig.4. The temperature and strain could be then demodulated separately by linear equation with two unknowns as following:

$$\begin{bmatrix}\Delta t_{CP-\varphi OTDR}\\ \Delta t_{CP-BOTDA}\end{bmatrix} = \begin{bmatrix}C_{\varepsilon-OTDR} & C_{T-OTDR}\\ C_{\varepsilon-BOTDA} & C_{T-BOTDA}\end{bmatrix}\begin{bmatrix}\Delta\varepsilon\\ \Delta T\end{bmatrix} \tag{2}$$

where $C_{\varepsilon\text{-}OTDR}$ and $C_{T\text{-}OTDR}$ are respectively the strain-time delays coefficient (Fig.4 (a)) and temperature-time delays coefficient (Fig.4 (b)) on the Rayleigh traces. $C_{\varepsilon\text{-}BOTDA}$ and $C_{T\text{-}BOTDA}$ are the strain-time delays coefficient (Fig.4 (c)) and temperature-time delays coefficient (Fig.4 (d)) on the Brillouin traces, respectively. Then the measurement uncertainties of the temperature and strain are respectively

$$\delta T = \frac{\sqrt{(C_{\varepsilon-OTDR}\cdot\delta t_{CP-BOTDA})^2+(C_{\varepsilon-BOTDA}\cdot\delta t_{CP-\varphi OTDR})^2}}{|C_{\varepsilon-OTDR}C_{T-BOTDA}-C_{\varepsilon-BOTDA}C_{T-OTDR}|} = 0.32°\text{C} \quad \text{and} \quad \delta\varepsilon = \frac{\sqrt{(C_{T-OTDR}\cdot\delta t_{CP-BOTDA})^2+(C_{T-BOTDA}\cdot\delta t_{CP-\varphi OTDR})^2}}{|C_{\varepsilon-OTDR}C_{T-BOTDA}-C_{\varepsilon-BOTDA}C_{T-OTDR}|} = 4.3\ \mu\varepsilon.$$

Note that large difference between strain and temperature coefficient in Brillouin and Rayleigh signals would give a much smaller measurement uncertainties.

3. Conclusion

The distributed temperature and strain measurement could be achieved simultaneously in our proposed system, providing a method to solve cross sensitive problems with high accuracy. This proposed system with compact configuration and simple data processing could become an good tool for distributed temperature/ strain sensing.

4. References

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