Forward-transmission based distributed fiber sensing compatible with C+L unidirectional communication systems

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Abstract: We propose forward-transmission based distributed fiber sensing that is compatible with C+L unidirectional communication systems and relaxes the requirement of remote timing synchrony. We demonstrate detection and accurate localization of polarization perturbation utilizing telecom transceivers. © 2024 The Author(s)

1. Introduction

Incorporating the capability of distributed fiber sensing (DFS) into optical transmission systems has drawn growing attention since it enables new applications such as environmental monitoring and early disaster warning using the deployed optical fiber network [1]. Recent work has demonstrated optical transmission systems that can simultaneously perform various types of optical time domain reflection (OTDR), such as phase-OTDR [2-3], polarization-OTDR [4], and Brillouin scattering-based OTDR [5]. However, backscatter-based OTDR technology has a limited sensing range due to limited detection sensitivity and has low compatibility with the deployed fiber network having amplifier modules equipped with isolators at the outputs. In comparison, forward-transmission based sensing scheme offers a significantly longer sensing range and overcomes the compatibility issue based on the retrieval of physical parameters such as phase or state-of-polarization (SOP) from two counter-propagating carriers or optical signals [6-8]. Nevertheless, this type of scheme requires precise timing synchrony achieved between the two remote receiving ends of a fiber sensing system, which could be challenging for cases where long fiber lengths, e.g. at transoceanic distances, are considered.

In this paper, we propose a forward-transmission based fiber sensing scheme with a relaxed requirement of remote timing synchrony. The proposed scheme is compatible with C+L *unidirectional* optical transmission system, and enables disturbance localization based on the group velocity difference of two telecom signals traveling at different wavelengths in the C- and L-band, respectively. We demonstrate detection and accurate localization (standard deviation less than 25 m) of polarization disturbances applied at different positions of 50.5 km of single-mode fiber. Since the extraction of SOP changes is realized based on the equalization of telecom signals, the sensing and communication capability of our system are simultaneously achieved utilizing the same transceivers. Our scheme provides a cost-effective and highly compatible approach to integrating distributed sensing capability into multiband transmission systems.

2. Operating principle of the proposed distributed sensing scheme

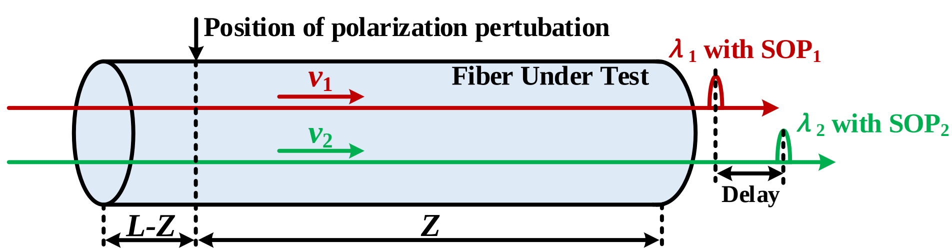

Fig. 1. Schematic diagram of the forward-transmission based unidirectional distributed fiber sensing scheme.

Fig. 1 shows the schematic diagram of our proposed scheme. In a C+L WDM transmission system, two optical signals at different wavelengths of λ_1 and λ_2 have distinct group indexes and thus propagate at different group velocities. When an external disturbance, e.g. birefringence perturbation is applied at a specific position L-Z of a fiber under test of length L, the SOPs of the two polarization division multiplexed (PDM) signals are simultaneously modulated. After demodulating the SOP fluctuations encoded in these two PDM signals traveling over a length Z, a delay Δt between the SOP fluctuations, i.e. SOP1 and SOP2 can be obtained by means of cross-correlation. Note that Δt is uniquely associated with length Z because of chromatic dispersion (CD) and Z is proportional to Δt as expressed by the following equation:

$$Z = \frac{\Delta t + n}{\int_{\lambda_1}^{\lambda_2} \Delta CD(\lambda) \cdot d\lambda} \tag{1}$$

where $\Delta CD(\lambda)$ (ps/nm/km) is the relative chromatic dispersion between the two wavelengths λ_1 and λ_2, n is the noise that degrades the accuracy of the obtained time delay. Thus, a wider separation between λ_1 and λ_2 leads to a greater term of $\int_{\lambda_1}^{\lambda_2} \Delta CD(\lambda) \cdot d\lambda$ and consequently lesser impact at a given level of noise, offering a higher localization resolution for the source of birefringence perturbation. The requirement of a wide wavelength spacing can be readily satisfied in C+L transmission systems and multiband systems with additional transmission band such as E and S.

The SOPs of signals at two wavelengths are demodulated by use of a constant modulus algorithm (CMA), which is commonly employed to compensate for polarization rotation and inter-symbol interference (ISI). By exploiting the finite impulse response (FIR) filter coefficients of a 2×2 CMA multiple-inputs multiple-output (MIMO) equalizer, we derive Stokes parameters {S_1, S_2, S_3} from the received telecom signal [9]. This approach enables simultaneously i) coherent detection of PDM signals for optical communications, and ii) distributed sensing of SOP fluctuations along the fiber link without requiring dedicated hardware for the detection of sensing signals. We also bring to your attention that the proposed distributed sensing scheme can be extended for other parameters of the telecom signal, such as phase which is more sensitive to vibration.

3. Experimental setup and results discussions

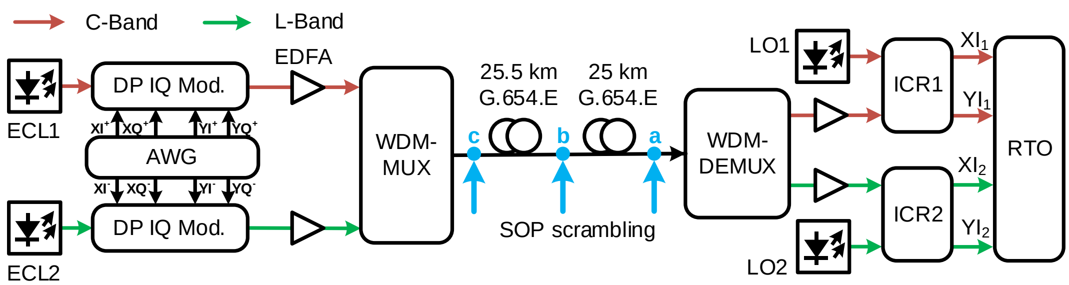

Fig. 2. Experimental setup of proposed integrated coherent transmission and distributed fiber sensing scheme.

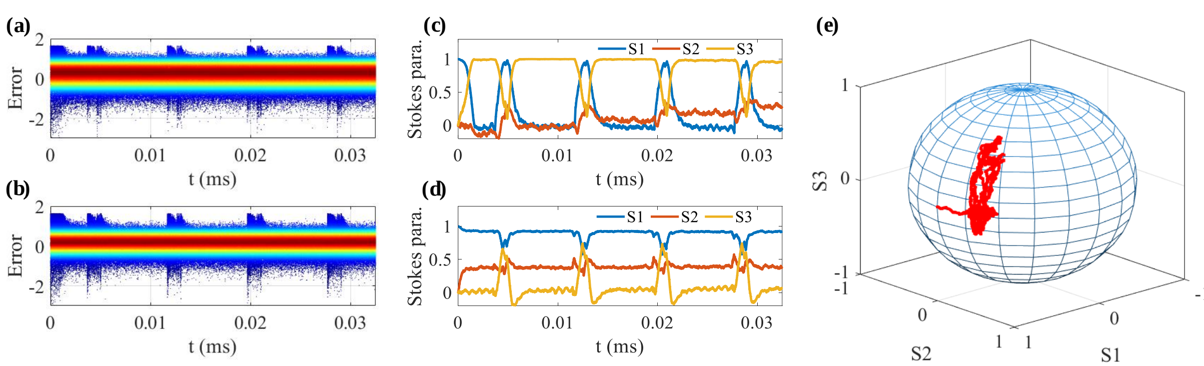

Fig. 3. Measured density diagrams of equalization error versus time of λ_1 (a) and λ_2 (b), and the retrieved Stokes parameters of λ_1 (a) and λ_2 (b). (e) The red curve on the Poincaré sphere shows the SOP corresponding to the Stokes parameter shown in (d).

Fig. 2 shows the experimental setup. A C-band and a L-band external cavity lasers (ECLs) provide the optical carriers for two dual-polarization (DP) IQ modulators with co-packaged driver amplifiers, respectively. The 8 differential outputs of a 4-channel 128 GSa/s arbitrary waveform generator (AWG, Keysight 8199A) are fed to two DP IQ modulators in order to emulate two 4-channel AWGs. We generate 15 Gbaud DP-QPSK signals in the C- and L-band, which are amplified, multiplexed, and subsequently launched into a single-mode fiber. The fiber used in experiments is ITU-T G.654.E compliant fiber, which has low attenuation (0.166-0.168 dB/km at 1550 nm), large effective area (125 μm^2 at 1550 nm) and high CD (~21 ps/nm/km at 1550 nm). The higher CD of this fiber is advantageous for increasing the group delay between the two wavelengths of λ_1 and λ_2 as required for improving the localization accuracy. At the testing points along the fiber (a, b and c), we introduce a sudden birefringence disturbance by use of a programmable polarization scrambler (Novoptel, EPS1000) in order to emulate abrupt changes of SOP that can be caused by lightening. At the receiver end, the signals are separated by a WDM demultiplexer and heterodyne detected by two integrated coherent receivers (ICRs). Finally, the output signals of ICRs are sampled by a 4-channel real-time oscilloscope (RTO, Keysight UXR0594AP) operating at 32 GSa/s for offline processing.

Fig. 3(a-b) shows the density diagrams of equalization error for the C- and L-band signals by using CMA-MIMO, respectively. We observe from the diagrams that the CMA effectively converges within the time interval between adjacent birefringence disturbances, resulting in near-zero equalization error. Nevertheless, a more significant equalization error is found at instants of sudden SOP scrambling, since the equalizer coefficients cannot perfectly compensate for abrupt SOP changes. Fig. 3(c-d) depicts the derived Stokes parameters of the C- and L-band optical signal, respectively. It is seen from the figures that our approach effectively detects the change of the polarization state, showing significant SOP changes at the instants of abrupt polarization scrambling. The periodic SOP scrambling can also be visualized by means of a Poincaré sphere as shown in Fig. 3(e).

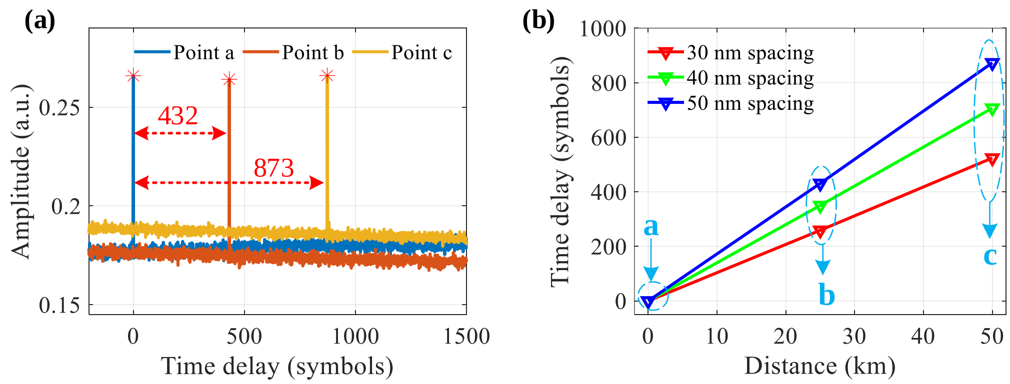

Fig. 4. (a) Cross-correlation peaks under different fiber length of with the wavelength interval of 50 nm. (b) Time delay versus transmission distance with different wavelength intervals of 30 nm (red), 40 nm (green) and 50 (nm) respectively.

Fig. 4(a) shows the cross-correlation between the SOP changes from C- and L-band optical signals, respectively, with the abrupt polarization perturbation applied at three different testing points along the fiber, i.e. a, b, c. As can be seen from this figure, the correlation peaks correspond to time delays Δt of 0 ns, 28.8 ns and 58.2 ns, respectively. Based on Eq. (1), we locate the positions of SOP change at 0, 25.044, 50.609 km, respectively, which well agree with the actual location of polarization perturbation considering the lengths of fibers in EDFAs and fiber patch cords. Furthermore, through 100 repeated measurements, we calculate a standard deviation of localization results of 22.04 m, indicating a high level of localization precision. Fig. 4(b) shows the change of time delay Δt when different wavelength spacing are set for the C- and L-band optical signals. It can be seen that Δt linearly decreases as the wavelength interval $\Delta\lambda = \lambda_2 - \lambda_1$ decreases from 50 nm to 30 nm. Thus, in order to improve the accuracy of localization, a wider wavelength spacing is more desirable because of stronger resilience against noise within the estimated time delay.

4. Conclusion

In this paper, we proposed a forward-transmission based distributed fiber sensing scheme that is compatible with the C+L unidirectional communication. We show effective disturbance localization by use of the time delay between two optical signals propagating at distinct group velocities due to a wide wavelength spacing allowed in C+L multiband systems. We demonstrate a high localization accuracy with a standard deviation below 25 m. The proposed scheme offers a cost-effective and highly accurate candidate for integrating distributed fiber sensing capability into the existing C+L WDM networks.

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5. References

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