Code length limit in phase-sensitive OTDR using ultralong (>1M bits) pulse sequences due to fading induced by fiber optical path drifts

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ABSTRACT

Recently, it has been demonstrated that by recovering the amplitude and phase of the backscattered optical signal, a ΦOTDR using pulse coding can be treated as a fully linear system in terms of trace coding/decoding, thus allowing for the use of tens of thousands of bits with a dramatic improvement of the system performance. In this communication, as a continuation of previous work by the same authors, a preliminary study aiming at characterizing the limits of the system in terms of maximum usable code length is presented. Using a code exceeding 1million bits over a duration of 0.26ms, it is observed that fiber optical path variations exceeding ≈π occurring over a time inferior to the pulse code length can lead to localized fading in the ΦOTDR trace. The occurrence, positions and form of the fading points along the ΦOTDR trace is observed to be strongly dependent on the type, frequency and amplitude of the perturbations applied to the fiber.

Keywords: Phase-sensitive OTDR, Pulse coding, Trace fading, I/Q detection, Dynamic strain sensing, Distributed vibration sensing, Phase-shift keying

1. INTRODUCTION

Distributed optical fiber sensors (DOFS) can monitor parameters such as temperature, strain, vibration or birefringence along tens of kilometers using a single interrogation unit, thus providing cost-effective solutions for the monitoring of large infrastructures or characterization of optical networks [1]. DOFS can make use of different physical principles (Raman, Brillouin, Rayleigh) and/or use different configurations, but the performance of the sensor (mainly sensing range, spatial resolution, resolution of the measured parameter) is generally dependent (and limited by) the sensor's signal-to-noise-ratio (SNR). The search for techniques to improve the SNR is therefore a constant presence in the literature of DFOS.

The use of pulse coding techniques allows to increase the power launched to the fiber without increasing the pulse peak power, and is therefore a powerful technique which allows to increase the SNR (particularly at the end of the trace) of DOFS measurements without increasing the nonlinearities of the system or measurement time. Pulse coding has been successfully demonstrated in several DOFS schemes, such as non-coherent Rayleigh-based optical time-domain reflectometry (OTDR) [2], Raman OTDR [3] and Brillouin optical time-domain analysis (BOTDA) [4]. Each scheme presents trade-offs due to different physical principles and, therefore, in-depth studies characterizing the limitations for different DOFS using pulse coding are of critical importance to better understand and maximize the performance of the sensor [4].

Until very recently, the implementation of pulse coding in phase-sensitive OTDR (ΦOTDR) had not been described in detail in the literature. The main problem being that the addition of intensities of the optical traces generated from each optical bit is not linear, due to the coherent interference between traces backscattered from neighboring bits [5]. In this case, if direct detection is used, distortions will be introduced in the decoding process. Therefore, using direct detection, the use of pulse coding in phase-sensitive OTDR is either not possible or imposes strong limitations in the system operation in terms of bit width and separation, laser coherence, and maximum SNR gain [5].

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However, it has been recently demonstrated that by recovering the amplitude and phase of the backscattered optical signal, a ΦOTDR using pulse coding can be treated as a fully linear system in terms of trace coding/decoding, thus allowing for a dramatic improvement of the system performance [6]. The dynamic and quantitative measurement of strain with high sensitivity was achieved with 2.5cm spatial resolution by decoding traces using 32767 (2^15-1) bits [6].

In this communication, as a continuation of previous work by the same authors [6], a study is presented characterizing the impact of fiber optical path drifts occurring during pulse code flight time in a ΦOTDR using long pulse codes with phase recovery. It is observed that fiber optical path variations of $\approx\pi$ occurring over a time inferior to the pulse code length lead to localized fading of the ΦOTDR trace. The occurrence, positions and form of fading along the fiber trace is observed to be strongly dependent on the type, frequency and amplitude of the perturbations applied to the fiber.

2. THEORETICAL BACKGROUND

2.1 ΦOTDR using pulse coding

In traditional ΦOTDR using single pulse operation, the frequency f with which optical pulses are launched into the fiber is limited by the fiber round-trip time (RTT) ($f\lesssim 1/\text{RTT}$), in order to avoid the superposition of traces generated from different pulses. With the use of pulse coding however, multiple bits can be launched into the fiber within a time <RTT, thus allowing to increase the power launched to the fiber and, correspondingly the SNR, without increasing the measurement time. Provided that the launched optical bits [described by an amplitude A_n and phase ϕ_n] are known or measured, and the Rayleigh backscattered signal [described by the vector $E(t_n)$] is fully (amplitude and phase) recovered, the fiber impulse (single-bit) response [$r(t_n)$] of the fiber can be calculated by solving the matrix eq.:

$$\begin{pmatrix} \mathrm{E}(t_0) \\ \cdots \\ \\ \mathrm{E}(t_N) \end{pmatrix} = \begin{pmatrix} A_0 e^{i\phi_0} & A_1 e^{i\phi_1} & \cdots & A_N e^{i\phi_N} \\ A_{-1} e^{i\phi_{-1}} & A_0 e^{i\phi_0} & \cdots & \cdots \\ \cdots & \cdots & \cdots & A_1 e^{i\phi_1} \\ A_{-N} e^{i\phi_{-N}} & \cdots & A_{-1} e^{i\phi_{-1}} & A_0 e^{i\phi_0} \end{pmatrix} \cdot \begin{pmatrix} r(t_0) \\ \cdots \\ \\ r(t_N) \end{pmatrix} \tag{1}$$

It should be noted that while the use of pulse coding has been demonstrated in other DOFS, the technique is particularly powerful in ΦOTDR. Other DOFS typically employ configurations using up to 511 bits [2,3,4], due to limitations imposed by different physical principles [4]. In ΦOTDR however, there is in principle no limitation as for the minimum optical bit size or separation. In fact, in previous work [6], the authors reported a configuration using non-return-to-zero (NRZ) phase-shift keying (PSK) modulation with tens of thousands of optical bits, which allowed to achieve the ultimate power input to the fiber: a continuous flat temporal power limited by the nonlinearities. For more information regarding ΦOTDR using pulse coding, an interested reader is invited to read [6], where a detailed theoretical model can be found.

2.2 The analyzed problem: Fading due to optical path drifts during pulse code flight time

While, in principle, there is no limitation for the minimum optical bit size or separation in ΦOTDR using pulse coding, eq. (1) can only be used if the fiber [$r(t_n)$] is assumed to be static during the duration of the pulse coding pattern [A_n]. However, this may not be a valid approximation when long fibers and long optical codes are used. Note that for a 20km SMF, a drift of the average fiber temperature $\Delta T\approx 4\mu K$ would result in a phase variation $\Delta\phi\approx 2\pi$ of the ΦOTDR signal backscattered from the end of a fiber [6]. If such ΔT were to occur in a time equal to the used bit pattern length (in the presented case ≈260µs, equivalent to the RTT of a 26km fiber), then, for a uniform ΔT drift over the fiber and time, this would mean that there would be on average a π shift between the ΦOTDR signal reflected at the end of the fiber by the bits of the first and second half of the optical pulse code. In this case, the fields reflected at the end of the fiber from bits from the first and second half of the pulse code which would add constructively if the fiber was unperturbed, will now be added destructively, and vice-versa. Therefore, in this case, a strong distortion in the decoded trace would be expected.

The requirement to operate in a regime where the fiber can assumed to be static during the duration of the pulse code will impose restrictions in the length of the pulse code and/or fiber length, which will critically dependent on the type and statistics of the perturbations which are applied to fiber. Preliminary trace simulations show that the fading effects are greatly reduced if the accumulated $\Delta\phi$ at the end of the fiber is limited to $\approx 2\pi/8$.

Lastly, note that while the ΦOTDR fading here described is visually similar to the fading arising due to modulation instability [7] (which leads to a periodic decrease of the coherence of the ΦOTDR pulse), the two effects are not related.

3. EXPERIMENTAL RESULTS

The experimental setup used (shown in Fig. 1) was the same as in the previous experiment [6] (where a more detailed description can be found), with exception for two changes: the used fiber was a 2000m fiber roll (previously 500m) and the used pulse modulation was a cyclic pseudorandom binary sequence (PRBS), modulated using binary PSK (BPSK) at 4 Gbaud and with 2^20-1 bits of period, i.e., 262.14375µs (previously 2^15-1 bits, i.e., 8.19175µs). In short, the CW output of an external cavity laser (ECL) [linewidth of ≈1 kHz] was modulated by a Mach-Zehnder modulator (MZM). The setup allowed to launch a continuous stream of optical bits into a 2000m SMF roll. The bit modulation was a cyclic PRBS using BPSK at 4 Gbaud and with 2^20-1 bit of period i.e., 262.14375µs. The complex backscattered field (phase, amplitude and polarization) was then measured with I/Q detection [using a dual-polarization integrated coherent receiver with 90 degree hybrid and 10% of the ECL CW as local oscillator (LO)] and then recorded by a high-speed digitizer.

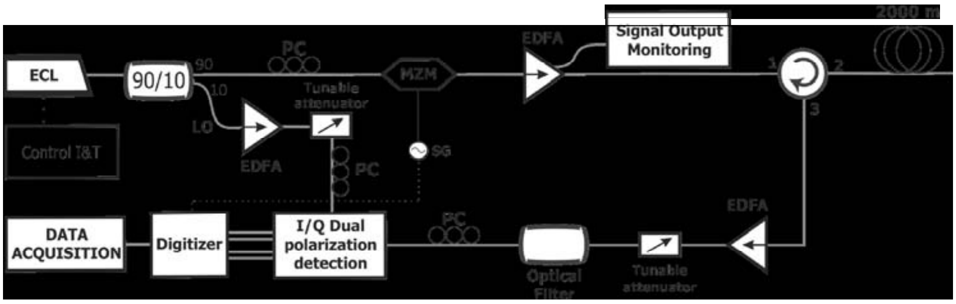

Figure 1 Experimental setup: Acronyms are explained in the text. A more detailed description can be found in ref. [6].

Perturbations were applied to the fiber optical path by placing the fiber roll under an air flow which was varied (provided by an air conditioner), thus changing the fiber temperature. In this way, relatively fast and uniform average temperature shifts were applied to an entire fiber roll, thus allowing for a better visualization of the fading phenomena, as demonstrated below. Note that the measurements only intend to present a qualitative description of the fading phenomenon, rather than precisely quantifying it. In fact, the temperature variations applied were not quantitatively measured and its precise control was not possible over millisecond times.

Fig. 2 shows the ΦOTDR decoded trace for varying perturbations applied to the fiber roll. Depending on the perturbation amplitude, the trace presented (a) no distortions, (b) visible decrease of its amplitude, or (c) complete fading of the trace towards the end of the fiber. In this case, the measurement time for each trace was 262.14375µs. Note that these measurements were performed with the same setup and only a few seconds apart.

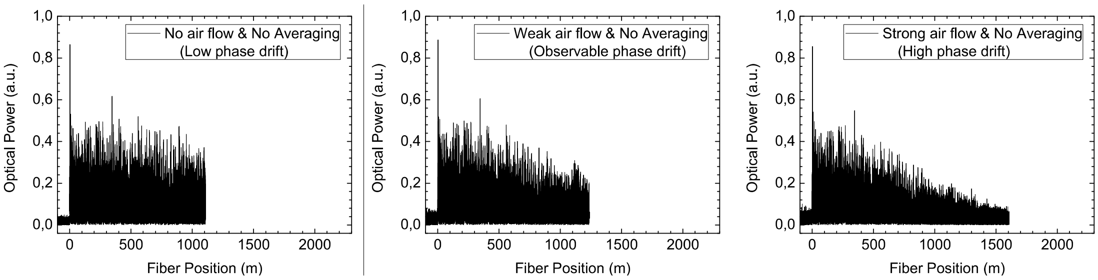

Figure 2. Decoded phase-sensitive OTDR using 2^20-1 bits and no averaging when fiber is subjected to a) No air flow (Low phase drift) b) Weak air flow (observable phase drift) c) Strong air flow (high phase drift).

Then, fig. 3 shows the ΦOTDR decoded traces using an averaging of 8 traces, thus increasing the measurement time for each trace to 8*262.14375µs=2097.15µs. As expected, for an increased measurement time the trace distortions are larger, and can occur at earlier positions of the fiber, as the phase drifts accumulated over the measurement time can be higher.

It should be point out that, while allowing for a good understanding of the problem, the fading characterization provided in this simple analysis may not be applicable for specific circumstances. For e.g., if the perturbations along the fiber (and along time) are random, then the expected $\Delta\phi$ (and resulting trace fading) will strongly depend on the statistics of the applied perturbations and, in general, $\Delta\phi$ will not vary linearly with the fiber size (and/or the measurement time). For fast locally applied strains, the trace fading may present fast variations, rather than a smooth variation along the fiber.

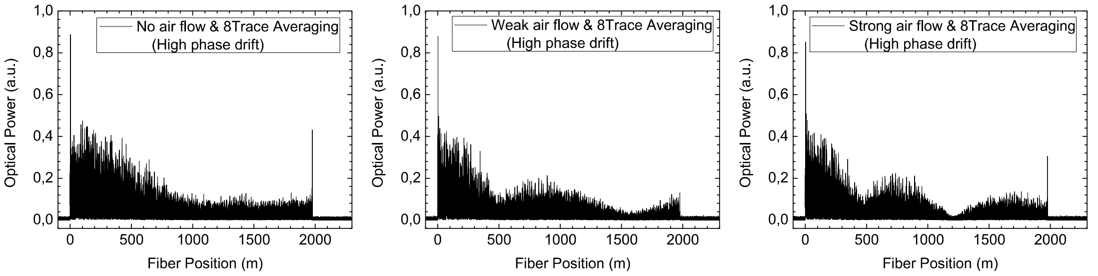

Figure 3. Decoded phase-sensitive OTDR using 2^20-1 bits and averaging of 8 traces when fiber is subjected to a) No air flow b) Weak air flow c) Strong air flow. In all cases strong fading is observed, but it is higher for stronger perturbations.

4. CONCLUSIONS

In this work the authors characterize the occurrence, and limitations imposed by, fading in a ΦOTDR using long pulse codes with phase recovery due to optical path variations of the fiber occurring during a time inferior to the pulse code length. By using relatively fast and uniform average temperature shifts of an entire fiber roll, smooth fading is observed along the fiber, thus providing a highly intuitive and visual description of the physical principle behind the fading.

It is observed that for a given setup, the existence and/or characteristics of trace fading is critically dependent on the statistics and amplitude of the perturbations applied to the fiber. Therefore, the parameters of a ΦOTDR using pulse coding (mainly, the fiber and pulse code length) should be designed considering the type of the perturbations which are expected to be measured. For e.g., note that for a 10km fiber experiencing average temperature drifts of 10 μK/ms, the use of a code of length 400 000 bits at 4Gbaud (2.5cm resolution) would result in an accumulated $\Delta\phi$ at the end of the fiber of ≈2π/8 during the fiber measurement time (0.1 ms) , thus keeping the fading effects bounded.

5. ACKNOWLEDGEMENTS

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