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Chirped-pulse phase-sensitive optical time-domain reflectometry

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Abstract: We review our recent work on chirped-pulse phase-sensitive optical time-domain reflectometry along optical fibers and its application in the measurement of true nanostrain variations in the kHz frequency range over lengths up to 20 km.

OCIS codes: (060.2370) Fiber optic sensors; (060.2430) Fibers, (290.5870) Scattering, Rayleigh.

1. Introduction

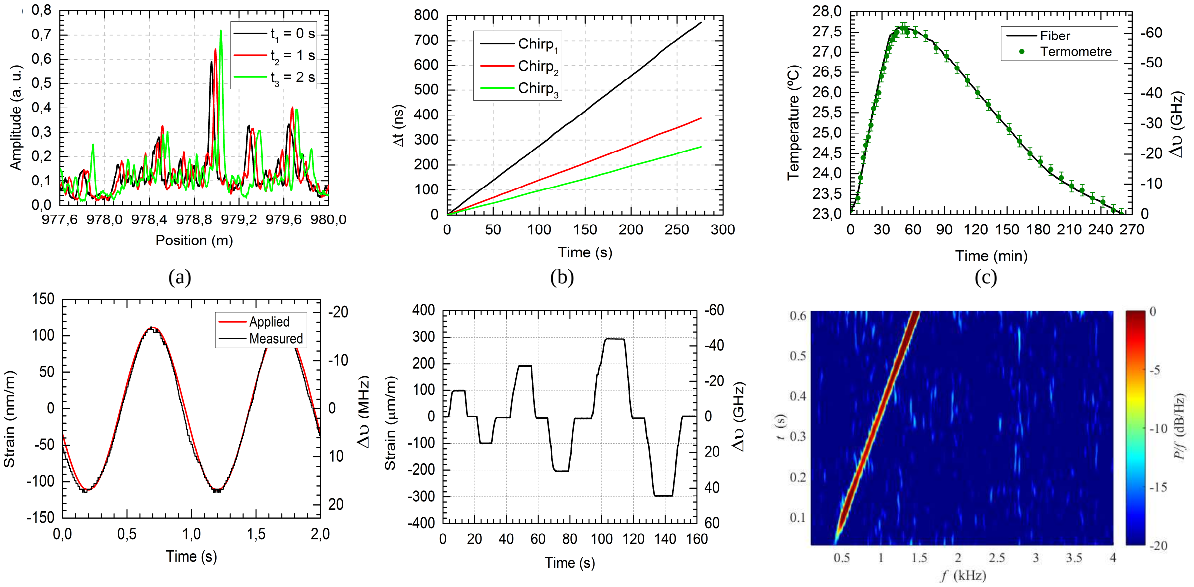
Distributed optical fiber sensing using phase sensitive optical time domain reflectometry (ϕOTDR) [1] is gaining increasing attention due to its potential application in pipeline surveillance and perimeter protection [2]. In ϕOTDR a pulse of highly coherent light is injected into a conventional single-mode fiber and the light reflected from different scattering centers interferes coherently to produce the detected optical power trace [1]. Traditional phase-sensitive ΦOTDR (single frequency, without phase recovery) allows for distributed vibration measurements with a high bandwidth, only limited by the fiber length, ranging from 10's of kHz for a few kilometers [1], to 100's of Hz for more than 100 km [8-12]. These measurements however, are based on intensity variations of the ΦOTDR signal, which do not show a linear variation with the applied perturbation. On the other hand, by precisely sweeping the frequency of the pulses, ΦOTDR has been shown to allow for very sensitive static measurements of refractive index variations, which can be used for very high-resolution temperature/strain [3] and birefringence [4] measurements. With these techniques, the demonstrated temperature resolutions of 0.01 ºC [3] are two orders of magnitude below the typical resolutions of ≈1 ºC provided by Brillouin or Raman sensors. However, due to the requirements of a frequency scan, in this case the measurement time and complexity of the system is increased. By recovering the phase of the ΦOTDR signal, the dynamic measurement of strain has also been demonstrated [5]. In this case, however, the system is more complex and laser coherences of at least the fiber size are required in order to avoid noise when beating the signal with the local oscillator. The long term-stability of such systems (i.e. after several minutes or hours) has not been clearly addressed either.

Here we review our recent work on chirped-pulse ΦOTDR systems [6]. These systems use linearly chirped pulses in a ΦOTDR to achieve a frequency-to-time mapping of the fiber response over long lengths and in a single-shot. The technique uses only intensity detection, and no frequency scan or local oscillator is needed. With the proposed method, it is possible to combine the best features of ΦOTDR which had been previously demonstrated by separate: fast measurements with a bandwidth only limited by the fiber size, and measurement of temperature/strain variations with resolutions which can be several orders of magnitude below those provided by e.g. Brillouin. Since the measurement is relative, the total range of temperature/strain variation is in principle not limited, being in practice determined only by how the cumulative errors are handled. The technique allows measurements at kHz rates, while maintaining reliability over several hours. The sensitivity can also be tuned by acting on the chirp of the pulses. Temperature/strain resolutions of mK/(4nε) have been readily demonstrated.

2. Working principle and results

The method proposed here for temperature/strain variation measurements originates from the principle described in [3] that a refractive index change Δn in the fiber can be compensated (in terms of the shape of the trace) by a frequency shift $\Delta\upsilon$ of the pulse sent into the fiber. This principle is typically implemented by performing a laser frequency sweep. In our case, instead of requiring a time-consuming frequency sweep to determine $\Delta\upsilon$ and calculate Δn, a single pulse which has linear chirp is used. Since different positions of the pulse have different frequencies, when a Δn is applied, the same trace pattern at a given position can be generated by a slightly temporally-shifted region of the pulse, leading essentially to a longitudinal shift Δt of the local ΦOTDR trace. It is then possible to calculate $\Delta\upsilon$ (and consequently Δn and the temperature/strain shift) from Δt, which is obtained directly from the time-domain trace measurements. A detailed explanation of this working principle, including a full theoretical model derived from the pulse propagation equations can be found in ref. [6].

Fig. 1(a) presents the evolution of the trace at a given position when there is a local temperature/strain change: at consecutive traces, the local trace shape shifts temporally, which is recovered by cross-correlation The amount of shift relates to the temperature/strain change. Fig 1(b) shows the accumulated shift suffered in the trace for different chirp values (Chirp$_1$ = 0.81 ± 0.02 GHz, Chirp$_2$ = 1.62 ± 0.04 GHz and Chirp$_3$ = 2.32 ± 0.05 GHz) and a total temperature change of 5ºC over 280 s. This shows two things: first, that the sensitivity scales with the inverse of the chirp and second, that temperature/strain variations well beyond the pulse spectral content can be measured, provided that the shift accumulation is computed correctly. From Fig 1(c) a similar conclusion can be derived, where a complete heating-cooling cycle was done over >4 hours, and a fiber-thermometer comparison was done. Fig 1(d) illustrates the good linearity an accuracy achieved by the system as a dynamic strain sensor, with nε resolution, while Fig 1(e) shows the feasibility of large static strain measurements using the same accumulation principle as used in Fig 1(b-c). Fig 1(f) shows again the system linearity: sinusoidal strain variations with a swept frequency (from 0.5 to 1.5 kHz) are applied at the end of a 11 km fiber, and recovered without harmonics and >20 dB SNR.



(a) (b) (c)

(d) (e) (f)

Fig. 1. (a) Trace shifts caused by a local temperature change around meter 978 of the fiber. (b) Accumulated shift obtained along the time for a total temperature change of 5ºC over 280 s. (c) Heating-cooling cycle performed in the same fiber position, comparing temperatures determined with the fiber and with an external thermometer. (d) Dynamic strain measured at a given position along time, compared with the input strain. (e) Large strain steps applied at a given position, recovered with the fiber, showing negligible error accumulation along the time. (f) Sinusoidal strain variations with a swept frequency applied at the end of a 11 km fiber, recovered with the proposed system.

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