Compensation of phase-noise in pulse-compression phase-sensitive OTDR sensors

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Abstract: We introduce a technique to compensate the performance impairments due to the laser phase noise in long-range pulse-compression DAS sensors. Experiments demonstrate the use of the longest duration pulse compression waveform to date.

1. Introduction

Distributed acoustic sensors (DAS) have been intensively researched in the last years. One area that has attracted considerable interest is long-range DAS setups in which extremely small vibrations are detected along tens of kilometers of fiber optic cables. These have application for the monitoring of pipelines, electric power cables, road traffic, or seismic sources.

The DAS sensors that have demonstrated the best capability to provide the longest possible range measurements in a purely passive link without additional distributed amplification are based on optical pulse compression (OPC) implemented in a coherent optical time-domain reflectometry (COTDR) setup [1, 2]. OPC is based on launching into the fiber signals with long duration (high energy) and high time-bandwidth product so that they can be processed upon reception with matched filters to produce narrow effective pulse widths. This greatly relaxes the trade-off between spatial resolution and range, providing an enhancement in the measurement signal-to-noise ratio (SNR) that is, in principle, proportional to the increased duration (energy) of the pulse. However, in practice, the phase-noise of the laser greatly degrades the sensor's performance when the pulse duration is increased, as we have recently studied in detail [3], making it necessary to deploy high-cost lasers with extremely low linewidth and phase-noise for long-distance measurements.

In this work, we introduce a technique to compensate for the effects of the phase-noise of the laser source so that OPC can demonstrate its potential for long-range measurements using lasers with less stringent phase-noise requirements. We experimentally demonstrate the concept in a 50-km OPC-COTDR sensor that uses a 500-µs pulse compression waveform to achieve 36.8 $\mathrm{p}\varepsilon/\sqrt{\mathrm{Hz}}$ of measurement sensitivity with 2-m spatial resolution. This setup uses a laser with a linewidth that is at least an order of magnitude larger than that used in other previous comparable long-range DAS demonstrations.

2. Fundamentals of the phase-noise compensation technique

In OPC-COTDR sensors, the optical signal that is launched into the fiber can be expressed as [3]:

$$E_{\mathrm{IN}}(t) = E(t)e^{j\phi(t)}e^{j\omega_0 t} \tag{1}$$

where $E(t)$ is the pulse compression waveform, which can be, for instance, a linear frequency modulated (LFM) pulse or a coded pulse sequence such as Golay [4] or perfect periodic autocorrelation (PPA) [5], ω_0 is the center radial optical frequency, and $\phi(t)$ represents the phase noise of the laser source. Then, the reflected signal backscattered from the fiber under test is detected in a coherent receiver and digitally cross-correlated with $E(t)$ to obtain the "compressed response", i.e., the measured complex backscatter profile of the sensing fiber, $\tilde{r}(\tau)$, where $\tau \equiv 2z/v$ denotes the roundtrip time to a position z in the fiber with v group velocity. This profile can be expressed as [3]:

$$\tilde{r}(\tau) = \int_0^{T_{rt}} r(\tau_{rt})e^{j\omega_0\tau_{rt}} \int_{-\infty}^{+\infty} E^*(t-\tau)E(t-\tau_{rt})e^{j[\phi(t-\tau_{rt})-\phi(t)]}dt d\tau_{rt} \tag{2}$$

where T_{rt} is the round-trip delay to the end of the fiber, and τ_{rt} is the roundtrip delay in the fiber to a Rayleigh backscattered reflection that has a $r(\tau_{rt})$ random local backscatter coefficient. The phase-noise induced term in

(2), $\psi_{\tau_{rt}}(t) \equiv \phi(t-\tau_{rt}) - \phi(t)$, leads to the deviation of the fiber's backscatter measurement from the nominal signal and the introduction of the main penalty to the SNR and sensitivity of OPC-COTDR sensors [3]. Now assume that we were able to measure $\psi_{\tau_{rt}}(t)$ for every τ_{rt}. In that case, it would be possible to modify the OPC processing and fully compensate the phase noise degradation simply by cross-correlating the detected signal with $E(t)e^{j[\phi(t-\tau_{rt})-\phi(t)]}$, instead of just with $E(t)$, so that the phase noise terms in (2) cancel out and $\tilde{r}(\tau)$ becomes:

$$\tilde{r}(\tau) = \int_0^{T_{rt}} r(\tau_{rt}) q(\tau - \tau_{rt}) d\tau_{rt} \tag{3}$$

where $q(t)$ describes the auto-correlation of the transmitted signal, i.e., the nominal compressed response. However, measuring $\psi_{\tau_{rt}}(t)$ for every τ_{rt} is not simple. What we propose in our technique is to measure $\psi_{\tau_{rt}}(t)$ for a particular τ_{rt} by using the experimental setup in Fig. 1, which is described in detail below. This uses a auxiliary interferometer with a delay imbalance, $\tau_{aux} = L_{aux}/v$ provided by a length of fiber L_{aux} so that in the receiver the phase difference $\psi_{\tau_{aux}}(t) \equiv \phi(t-\tau_{aux}) - \phi(t)$ can be measured. Therefore, by correlating the received signal in the measurement channel with $E(t)e^{j\psi_{\tau_{aux}}(t)}$, the phase noise effects for the reflections arriving from the position in the fiber under test $z_1 = L_{aux}/2$ can be compensated. Furthermore, it is possible to employ the concatenately generated phase (CGP) method, which has been used in the past in the compensation of phase-noise effects in optical frequency domain reflectometers [6], to obtain the compensation phase difference for any integer multiple i of τ_{aux}:

$$\psi_{i\tau_{aux}}(t) = \phi(t - i\tau_{aux}) - \phi(t) = \sum_{k=0}^{i-1} \psi_{\tau_{aux}}(t - k\tau_{aux}) \tag{4}$$

Therefore, with our technique and using a single simultaneous auxiliary interferometer measurement, we can compensate for the phase noise degradation for all positions in the fiber under test that are at multiples of the round-trip delay of the auxiliary interferometer.

3. Experiments and results

Fig. 1 depicts the experimental setup that we have used to demonstrate the technique. The upper branch is a conventional OPC-COTDR sensor setup [1–3] in which a Mach-Zehnder electrooptic modulator (MZ-EOM) is used to generate the pulse compression waveform. The optical source was a 2.2-kHz linewidth (RIO ORION) laser. Homodyne receivers are used in this implementation to enable the use of more complex codes, but for the LFM pulses that we used in our experiments, it would be possible to use heterodyne receivers instead and further simplify the setup. Furthermore, polarization diversity is not used in this proof-of-concept demonstration, but it is very simple to add. Vibration measurements are performed along a 50-km standard single-mode fiber length. At the end of this fiber, a 10-m piezoelectric fiber stretcher (PZT) is used to simulate excitation. The lower branch consists of the auxiliary interferometer in which a $L_{aux} = 5.4$-km fiber reel is used. In principle, this interferometer could work in baseband as depicted in the figure, but to avoid DC-drift issues we used a 100-MHz acousto-optic modulator to implement a frequency shifter that leads to bandpass demodulation of the interferometer phase. Finally, the complex field measurements in the upper and lower interferometers are digitized and processed in a computer.

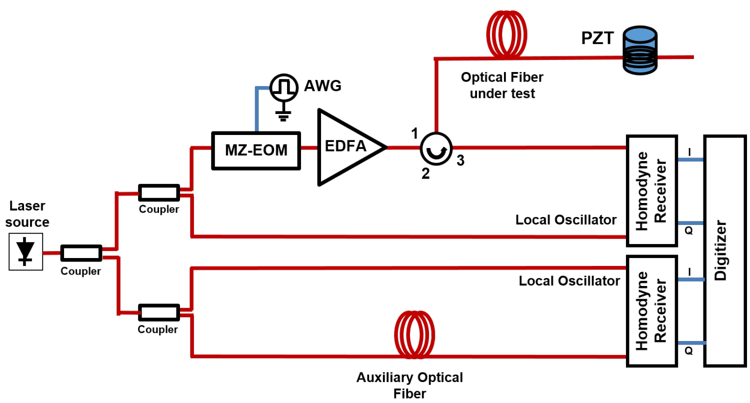

Fig. 1: Experimental setup.

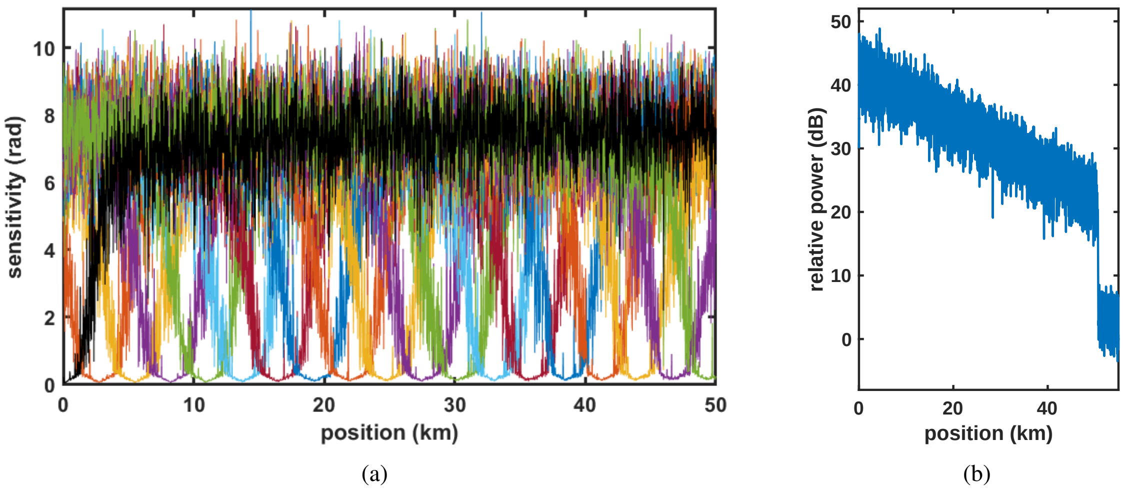

Fig. 2: (a) Sensitivity vs. position before compensation (black line) and after compensation for the different multiples of the auxiliary interferomenter delay (color lines). (b) Detected power after pulse compression.

Fig. 2(a) depict the measurement of the sensitivity, calculated as the standard deviation of the sensor self-noise for the full measurement bandwidth. LFM pulses with 500-μs duration and 50-MHz peak-to-peak frequency deviation centered at 50-MHz are used in these measurements, which provided a 2-m spatial resolution (compressed pulse) after matched filtering in reception. A 6-m moving average of the measured $\tilde{r}(\tau)$ was used to mitigate fading effects and the gauge length for the calculation of the phase difference between adjacent positions in the fiber was also 6 m. In addition, for these measurements, the fiber under test was enclosed in a vibration and sound isolation box, so that the measured noise is just due to the sensor. Notice that for the uncompensated measurement (black line) the sensitivity quickly degrades as the distance increases due to the effect of the phase noise term $\psi_{\tau_{rt}}(t)$. The different colored traces depict the compensation obtained cross-correlating the detected signal with $E(t)e^{j\psi_{i\tau_{aux}}(t)}$ calculated for each multiple of τ_{aux} from the measurement of phase in the auxiliary interferometer using (4). The compensation is very good at the specific $z_i = iL_{aux}/2$ locations, almost equal to the sensitivity at the start of the fiber for the uncompensated case. Furthermore, there is also a good compensation in the vicinity of these locations because $\psi_{i\tau_{aux}}(t)$ is still a good approximation to the phase noise that the signals backscattering from those locations experience. In the fully compensated sensor, the fiber under test is divided into equal-length segments around each z_i in which the optimized cross-correlation with $E(t)e^{j\psi_{i\tau_{aux}}(t)}$ is applied, hence high sensitivity is obtained throughout the full fiber length.

Fig. 2(b) depicts the relative power of the compressed backscattered profile where the enhancement in the detected SNR due to the use of a long LFM pulse is apparent. Notice that at the end of the 50-km length of fiber the signal is still around 20 dB above the noise floor, hence we expect to demonstrate much longer sensing lengths in the further evolution of the setup.

After characterizing the sensitivity improvement provided by our phase-compensation technique we demonstrated its operation with actual excitation in the fiber. A 15.6-Hz sinusoidal signal was applied to the PZT at the end of the sensing fiber link. Fig. 3(a) depicts the time-domain differential phase measured at the fiber end after applying the phase-noise compensation technique, where the excitation signal clearly defined in position and time can be observed. Note that without compensation the measurement was found to be completely distorted and the excitation signal could not be discerned whatsoever. The gauge length was increased to 42 m for this measurement so that it extended beyond the length of the PZT.

Fig. 3 shows the calculated spectrum for the differential phase measured at the PZT location. A clean peak 45 dB above the noise floor is obtained. In addition, the noise floor in this measurement gives the spectral density of the sensitivity, which was found to be 3.3 mrad$/\sqrt{\text{Hz}}$ which would translate to 36.8 p$\varepsilon/\sqrt{\text{Hz}}$ in terms of actual strain in the fiber for a 10-m gauge length.

The maximum slow-time sampling frequency for these measurements is around 1 kHz taking into account 500 μs of round-trip delay to the end of the fiber and another 500 μs from the LFM pulse duration. This sampling frequency can be doubled by using PPA codes in which cyclic convolution is used and the sequence repetition period can be equal to the fiber's round-trip delay [5].

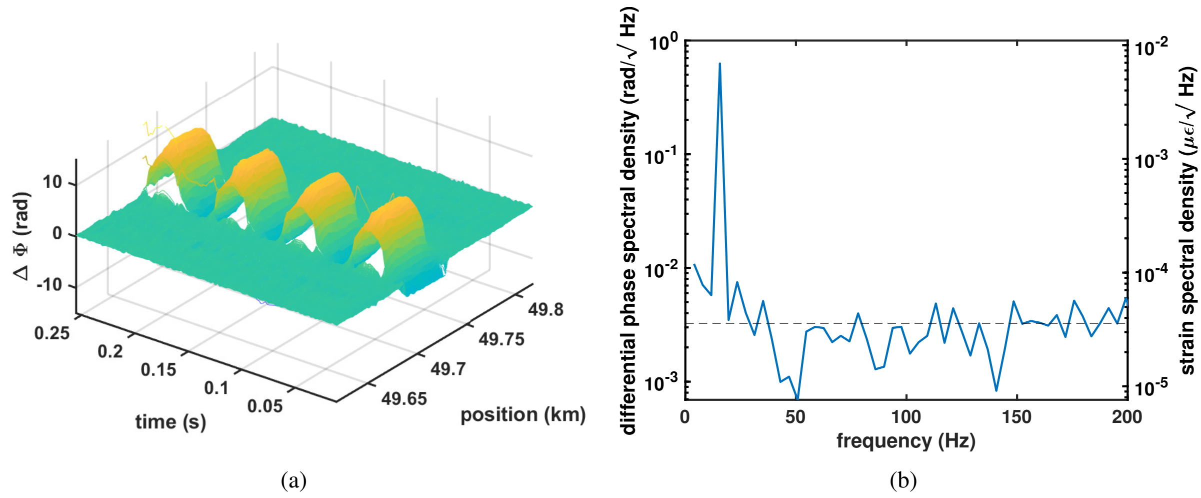

Fig. 3: (a) Time-domain differential phase measured at the end of the fiber. (b) Spectral density of the measured signal.

4. Discussion and conclusions

In summary, we have demonstrated that our technique provides compensation for the sensitivity degradation induced by the laser source. The laser used in the experiments to reach 50-km has a linewidth that is at least an order of magnitude larger than that used in other comparable long-range DAS experiments [1,2]. The use of such narrow linewidth was needed in these other systems to mitigate the performance impairments brought by the phase noise of the laser. However, even with these enhanced lasers, the longest duration pulse demonstrated to our knowledge for long-range OPC-COTDR sensors has been 100 µs. This duration is again limited by the laser's phase noise, which increases its deleterious effects as the pulse compression waveform extends in time. In comparison, our experiments have demonstrated the use of a long 500 µs pulse that can fill the fiber. This is significant since for OPC-COTDR sensors the SNR enhancement is proportional to the compression waveform duration.

This proof-of-concept demonstration can be improved by increasing the length of sensing fiber covered and also by demonstrating the compensation of the phase noise of laser sources of larger linewidth (phase noise). For the latter, one factor to take into account is that the larger the phase noise of the laser, the shorter the length of the segments around the integer-multiple optimum compensation positions z_i for which good phase-noise mitigation can be obtained. Nevertheless, this can be accommodated by reducing the relative delay in the auxiliary interferometer, which reduces the separation between optimum compensation points.

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