Impact of non-Lorentzian laser phase noise on ϕ-OTDR performance

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ABSTRACT

We highlight the importance of the laser source phase noise in sensing applications and show that the standard Lorentzian linewidth criterion is not sufficient to characterize the performance of a sensing system. We then derive a laser linewidth related to the phase noise spectral region of interest, according to the length of the fiber to sense. This is illustrated in a setup based on coded interrogation and with two sensing dedicated laser sources.

Keywords: distributed acoustic sensing, laser phase noise, network monitoring

1. INTRODUCTION

Distributed Acoustic Sensing (DAS) has recently emerged as a key feature for in-depth monitoring of telecom networks[1]. Beyond previously introduced DAS applications using dedicated fibers to sense the environment such as oil & gas wells and civil engineering structures[2], applying sensing onto a telecom network potentially shows a great advantage: the possibility to reuse already deployed fiber infrastructure, that is millions of kilometers of fiber cables spread worldwide. A fine telemetry of the optical network layer, beyond detection of static events as fiber cuts or unperfect connection, is required to monitor more acutely telecommunication networks. Any long-haul network link is split in a series of spans with optical amplification in between to compensate for losses during signal propagation in the fiber. The typical span length is between 30 and 100km, and DAS is foreseen to be implemented on a per-span basis[3].

We introduced a spread spectrum interrogation technique[4], consisting of phase-modulated polarization-diversity binary codes at the transmission side and of a polarization-diversity coherent mixer at the receiver side, after which a signal processing stage derives the round-trip propagation between the transmitter and the receiver at every fiber position along the sensed link. This technique solves the polarization fading issue and thus lowers the noise floor compared to standard methods that do not fully exploit polarization diversity[5]. Beyond fading issues, the laser source stability is a fundamental requirement to limit the phase noise floor and to enhance the detection threshold and maximum reach in DAS technology[6]. Indeed, as the vibration information is extracted from phase terms in a differential approach, a stable phase reference provided by an ultra-low-linewidth laser is needed. Several studies were conducted to assess the impact of phase noise on pulsed DAS interrogation in terms of sensitivity and reach[7,8,9]. However, it is not the case for spread-spectrum techniques such as coded DAS. This paper reports on the issue of laser phase noise in spread-spectrum DAS systems. The impact of phase noise characteristics is studied by simulation and then experimentally on coded DAS interrogations, through a comparison of two different narrow-linewidth laser sources. We modulated both lasers by the same probing codes and we show how the narrow linewidth requirement is of interest not only with regards to the length of the sensed fiber, but also to the code duration. This observation paves the way to a multiple-parameter optimization of spread-spectrum DAS probing (code design, fiber length, and laser linewidth).

2. METHODOLOGY

A schematic of our sensing setup is displayed in Fig.1(a), with a laser source in self-homodyne configuration, modulated by polarization diversity binary codes and coherent reception, hence the name "Coherent-MIMO". After a correlation based digital signal processing at the reception side, the round-trip propagation is estimated, free of polarization fading, in the form of a Jones matrix $\boldsymbol{J}_s$ at each segment position s along the fiber. The segment or gauge length is given by the symbol rate f_{symb} used at the modulator side as $L_s = c_f/(2f_{symb})$ where c_f is the light velocity in the fiber core. A probing code, made of N_{code} consecutive symbols, spreading over a time length $T_{code} = N_{code}/f_{symb}$, is sent on each polarization tributary and is repeated continuously[4].

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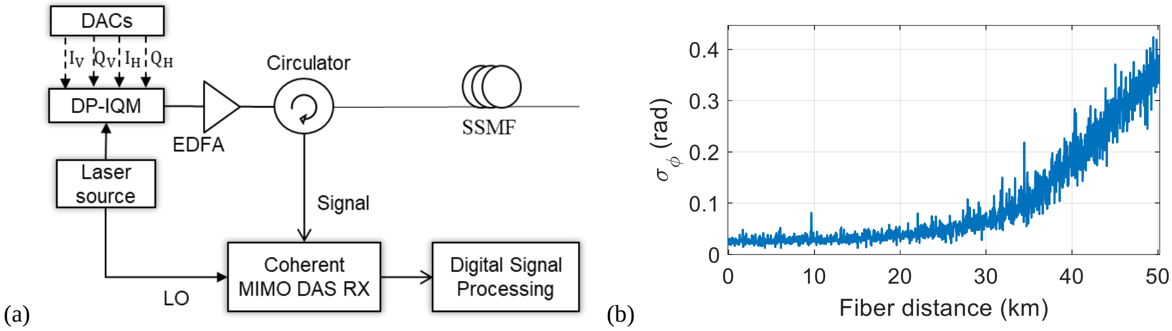

Fig.1: (a) Coherent MIMO OTDR setup. DAC: Digital to Analog Converter, DP-IQM: Dual polarization IQ Modulator, EDFA: Erbium Doped Fiber Amplifier, SSMF: Standard Single Mode Fiber. (b) Standard deviation of the backscattered optical phase along 50km fiber distance, down-sampled to 25m spatial resolution

This leads to periodic estimations $\boldsymbol{J}_{s,t}$, with a period T_{code}, of the round-trip propagation in the distance versus time plane. The backscattered intensity and the common-phase term are extracted as $I_{s,t} = |\det(\boldsymbol{J}_{s,t})|$ and $\varphi_{s,t} = \frac{1}{2}\arg(\det(\boldsymbol{J}_{s,t}))$ where det() and arg() stand for the matrix determinant and the phase term of the complex scalar, respectively. As $\varphi_{s,t}$ is cumulated in distance from the first fiber segment, the local phase term $\Delta\varphi_{s,t}$ is calculated from $\varphi_{s,t}$ by phase differentiation along the distance axis. When the fiber is not subject to any external excitation (static mode), the noise floor of the system is conveniently defined, for a given observation time, as the standard deviation of the local phase variations at each segment position, as illustrated in Fig.1(b). In this figure, the local phase variations of the differential phase at any given distance originate from the coherent fading, or speckle noise, whereas the global increase observed along the fiber length is the cumulated effect of the intensity loss (≈0.2dB/km in a Standard Single Mode Fiber (SSMF)) and of the gradual coherence loss of the laser source.

The paper focuses on the latter effect. In fact, the coherence length of the laser source is of even greater importance with spread-spectrum interrogation techniques using MIMO codes than with standard pulse interrogation since any laser instability during the code duration T_{code} corrupts the channel estimation. The laser source variations in frequency or/and in amplitude applies multiplicatively to the modulated probing code. In the specific case of polarisation diversity probing codes, these variations affect, at any time instant, both polarisation axes identically. The roundtrip channel of the probed fiber is estimated after the correlation process at the receiver side and each estimated $\boldsymbol{J}_s$ is thus potentially altered by the laser instabilities when spread-spectrum probing is used. The received signal in such a self-homodyne scheme also experiences phase noise at the coherent receiver when the signal interferes with the unmodulated local oscillator. The delay between the emitted and backscattered light waves spreads between 0 and $2L_f/c_f$ at the fiber start and end respectively to account for the round-trip time in the tested fiber of length L_f. Therefore, the estimation variance in the channel responses statistically increases along the fiber segment in practice since the laser source stability degrades with time due to its finite coherence length.

This coherence length limitation comes with a specific noise, referred to as "laser phase noise". The scalar electric field $E(t)$ associated with the light wave delivered by a single mode laser can be expressed as $E(t) = A_0 \exp(i[2\pi\nu_0 t + \phi(t)])$, where the term $\phi(t)$ describes the random phase noise fluctuations around the central frequency ν_0. The emitted amplitude term A_0 is assumed constant here. Under white frequency noise assumption, $\phi(t)$ is modelled as a Brownian motion with $\Delta\phi(t)$ a Gaussian process of zero mean and a variance proportional to the linewidth of the laser, and the Power Spectral Density (PSD) of the laser self-beating follows a Lorentzian profile, with a Full Width at Half Maximum (FWHM) $\Delta\nu$. With the Lorentzian model, $\Delta\nu$ remains constant whatever the observation time. Fig.2 displays the PSD of the frequency noise measured from two commercially available DAS compatible laser sources emitting at 1550nm. The PSD is shown between 10Hz and 10MHz, which are the limits of our measurement system. The PSD for both sources show a non-uniform frequency noise with a clear increase towards low frequencies. This behaviour has led to the introduction of alternatives to the Lorentzian profile[10], such as the Voigt profile for the line shape which results from the combination of a white noise Lorentzian profile and a *1/f* noise Gaussian profile.

Until now, the laser frequency noise was modelled as a Wiener process of variance $\sigma^2 = 2\pi\Delta\nu/f_{symb}$ with an associated coherence length defined as $L_{coh} = c_f/(\pi\Delta\nu)$. The simulation environment has recently been complemented to predict noise floor performance of the sensing system depicted in Fig.1(a), based on laser frequency noise measurements such as

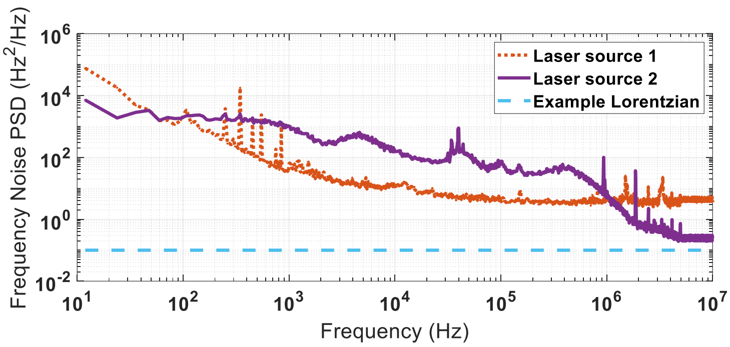

Fig.2: PSD of frequency noise measurement for two highly coherent laser sources. A Lorentzian floor example, leading to a $\Delta\upsilon$ =0.3Hz linewidth regardless of the measurement time, is also displayed for illustration

the ones in Fig.2: a random white noise (Lorentzian) is generated and then spectrally shaped according to the measured PSD[10].

3. RESULTS

From the simulator described above, we generate the linewidth of both laser sources and show the resulting line shapes in Fig. 3(a,b), accounting for the sole Lorentzian floor estimated at 10MHz here (bold lines), or in larger time windows including frequencies down to a lower limit $F_{min}= 1/T_{code}$ (dashed and dotted lines) to match different probing durations.

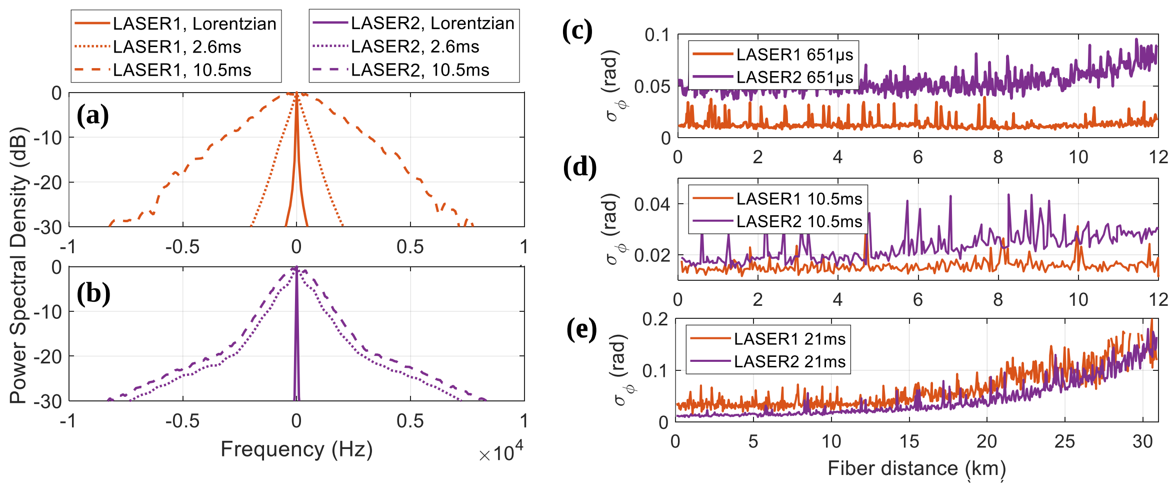

Fig.3: (a,b) Estimated spectral response, accounting for white noise floor only (bold) or including low frequency phase noise (>400Hz dotted, >100Hz dashed). (c,d): σ_ϕ simulation over 12km with probing duration 0.6ms and 10.6ms resp. (e) σ_ϕ: simulation over 31km, probing duration 21ms

We observe, in adequation with the frequency noise measurement in Fig.2, that Laser 2 displays a narrower linewidth (Lorentzian) than Laser 1 (0.79Hz vs. 13.8Hz at -3dB), whereas its actual linewidth accounting for phase noise increase down to 400Hz in Fig.3(a) is broader than laser source 1 (410Hz linewidth difference). Yet, the linewidth keeps increasing with the probing time for Laser 1, such that Laser 1 is wider than Laser 2 again in Fig.3(a,b) for 10.5ms probing time (dashed), corresponding to 95Hz probing frequency. This is consistent with the frequency noise measurement in Fig.2 where the frequency noise responses of lasers 1 and 2 cross around 100Hz.

We also perform simulations of the evolution of the differential phase along fiber distance, denoted σ_ϕ: the phase variations are averaged over 10 random fiber drawings and displayed in Fig.3(c-e) with 20m and 51m spatial resolution, respectively. Code lengths T_{code} = 651µs and 10.5ms are used for 12km probing and T_{code} = 21ms is used for 31km. The consequence of linewidth broadening is visible as the noise level is lower for Laser 1 in Fig.3(d) with the shorter probing durations whereas it is lower for Laser 2 with 31km probing in Fig.3(e).

For the experimental validation, we choose fiber distances compatible with the previous code lengths[4]: DAS measurements are conducted over 12km and 31km SSMF with probing code durations 0.65ms, 1.31ms, and 2.62ms respectively (F_{min} of 1540Hz, 763Hz, and 380Hz). The probing symbol frequency is $f_s = 50$MBaud and the receiver sampling frequency is $f_{samp} = 2f_s$. The experimental phases are filtered below 50Hz to avoid collecting the machinery noise in the lab. The σ_ϕ for each measurement is displayed in Fig.4. Fig.4(a) shows a lower noise floor with Laser 1 interrogations since F_{min} for these code durations is clearly above the frequency of intersection between PSDs in Fig.2: the assumption on the DAS

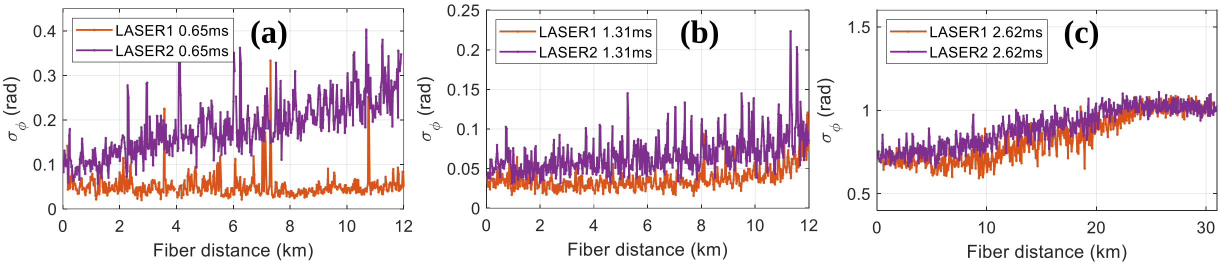

Fig.4: Interrogation using two lasers of (a,b) 12-km SSMF, 0.65ms and 1.31ms code duration (c) 31-km SSMF, 2.62ms

interrogation quality is verified as Laser 1 has a lower frequency noise in that frequency interval. When the probing duration increases, we observe that the noise floors of lasers 1 and 2 move closer, in accordance with the simulations in Fig.3(c-e). The code length in Fig.4(c), yielding F_{min}=380Hz, approaches the intersection point: a similar detection threshold is visible for both lasers after 20km. Note that the measurement of laser frequency noise at low frequencies is also subject to environmental perturbation, which could shift the intersection point.

4. CONCLUSION

Based on real frequency noise measurements, we simulated the impact of non-Lorentzian phase noise on the performance of spread-spectrum DAS interrogation. We highlighted the impact of colored frequency noise on the standard deviation of DAS-estimated phase in the absence of mechanical perturbations. The DAS noise floor was shown to strongly depend on the spectral shape of the laser phase noise, down to the 100Hz to 1kHz region, which was further confirmed experimentally. These preliminary results already give guidelines to help choose a DAS laser source in accordance with the targeted fiber distance to sense.

5. REFERENCES

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