Time-domain technique to measure amplitude and phase noises of a GHz-repetition rate optical pulse train and their correlation

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The conventionally used technique for noise characterization of a GHz-repetition rate optical pulse train is a frequency-domain technique, whose application requires to make restrictive hypotheses. In this paper, we report on the application of a time-domain technique for noise characterization of a GHz-repetition rate pulse train generated by actively mode-locked Erbium fibre laser. This technique, based on the demodulation in amplitude and in phase of the pulse train, requires no hypothesis and therefore leads to more reliable measurement of amplitude and phase noises. Moreover, it allows the measurement of the cross-correlation between amplitude and phase noises.

Introduction

Actively mode-locked Erbium-doped fiber lasers generating picosecond pulse trains at GHz repetition rates are destined for becoming flexible data sources in future optical communication systems. Such lasers, however, are very sensitive to external perturbations, which introduce irregularities in the pulse train, in particular amplitude noise and phase noise (timing jitter). Telecommunication applications require however very stable amplitude and phase of the pulses. Hence, in order to assess the quality of the pulse train and to determine if it is compatible or not with the requirements of telecommunication applications, it is necessary to characterize accurately amplitude and phase noises of the pulse train.

The technique conventionally used for measuring amplitude and phase noises of a train of optical pulses is a frequency-domain (FD) technique, originally proposed by von der Linde [1], which only requires a conventional RF spectrum analyzer. The single-sideband power spectral densities (SSB-PSD) of the detected pulse train $S_1(f)$ and $S_n(f)$ are measured around the 1^{st} and the n^{th} harmonics of the repetition rate ($n \geq 2$). Using these data, and making some assumptions on the pulse train, the power spectral densities (PSDs) of amplitude and phase noises, $S_\varepsilon(f)$ and $S_\phi(f)$ respectively, can be retrieved using simple formulas. Unfortunately, the hypotheses which have to be made in order to validate these formulas are very restrictive, in particular it is assumed that these two noises are small and that no correlation exists between them.

A time-domain (TD) technique was demonstrated for a 99.8-MHz Cr:LiSAF passively mode-locked laser [2][3], and compared with the FD technique for phase noise measurement on this laser [2]. This TD technique relies on the demodulation in amplitude and phase of the first harmonic V(t) of the detected pulse train. This first harmonic can be written as:

$$V(t) = V_0\left(1+\varepsilon(t)\right)\sin\left(2\pi f_r t + \phi(t)\right) \tag{1}$$

The two quadrature components of V(t), $V_{re}(t)$ and $V_{im}(t)$, are then extracted using a local oscillator:

$$V_{re}(t) = V_0\left(1+\varepsilon(t)\right)\cos\left(\phi(t)\right)\ ; \qquad V_{im}(t) = V_0\left(1+\varepsilon(t)\right)\sin\left(\phi(t)\right) \tag{2}$$

Finally, amplitude and phase noise signals are directly obtained by:

$$\varepsilon(t) = \frac{\sqrt{V_{re}^2 + V_{im}^2} - V_0}{V_0}\ ; \qquad \phi(t) = \tan^{-1}\left(\frac{V_{im}}{V_{re}}\right) \tag{3}$$

These signals can be used to calculate the power spectral densities (PSDs) of amplitude and phase noises, $S_\varepsilon(f)$ and $S_\phi(f)$, respectively, as well as the cross-power spectrum (XPS) $S_{\varepsilon\phi}(f)$ and the coherence function $\gamma^2(f)$, defined as:

$$\gamma_{\varepsilon\phi}^2(f) = \frac{S_{\varepsilon\phi}(f)S_{\varepsilon\phi}^*(f)}{S_\varepsilon(f)S_\phi(f)}, \tag{4}$$

Experiment

In this paper, we implemented this TD technique to measure amplitude and phase noises PSDs of an optical pulse train at 2.6 GHz from a stabilized actively mode-locked Er-doped fiber laser [4]. We also measured the XPS between amplitude and phase noises, and finally we were able to compute the coherence function. A comparison was made with the RF generator.

The optical pulse train was detected by a 20-GHz photodiode and fed into a vector signal analyzer (Agilent Technologies, 89441A). The signal, with fundamental frequency of 2.6 GHz, was first downconverted to an intermediate frequency of 3.5 MHz and was sampled at 25.6 MHz. The quadrature components were then extracted by the digital signal processor and the demodulation in amplitude and phase was performed as described by (3). These two time series were then extracted from the 89441A and used to compute the PSDs $S_\varepsilon(f)$, $S_\phi(f)$ and the XPS $S_{\varepsilon\phi}(f)$ by Welch's modified spectral estimator algorithm.

Results

Figs. 1 and 2 show the PSDs $S_\varepsilon(f)$ and $S_\phi(f)$, respectively, while Fig. 3 shows the coherence functions, for both the pulse train at 2.6 GHz and the RF generator at the same frequency. The frequency span ranges from 1 Hz to 5 kHz, and each figure was obtained by combining data from 3 measurements with different spans and resolutions. On Figs. 1 and 2, one can observe that for both the pulse train and the generator, amplitude and phase noises decrease with increasing frequency, so that the higher noise values are obtained at very low frequencies (below 10 Hz). The important contribution to the global noise lying in this frequency range can be determined with good accuracy using the TD technique, while the FD technique is usually unefficient below 10 Hz, due to the hypothesis of small perturbations.

The spurs appearing in the coherence functions displayed on Fig. 3 show that some correlation exists, at least at some frequencies, between amplitude and phase noises of both the pulse train and the generator. This leads again to the conclusion that the FD technique, if used in this case, would not have yielded trustworthy results, because of the hypothesis of uncorrelated amplitude and phase noises. Again, the TD technique is free of this assumption.

Another noticeable advantage of the TD technique is that only one measurement of the first harmonic of the pulse train is needed, while the FD technique requires measurements about two harmonics, so that at least two times the measurement bandwidth of the TD technique is necessary for the FD technique. This is particularly critical for pulse trains at high repetition rates. Moreover, the two measurements of the FD technique cannot be simultaneous if only one spectrum analyser is used. In the TD technique, both amplitude and phase noises are retrieved from the same measured data (i.e. the amplitude and phase modulated carrier), which avoids problems if the noises are not absolutely stable between two measurements.

We notice on Fig. 1 large discrepancies between the amplitude noise PSDs of the pulse train and the generator, while on Fig. 2 a good general agreement is observed between the curves of phase noises (see also Table 1). Even if we did not measure the XPS between amplitude noises of pulse train and generator, or between their phase noises, these observations confirm what AM mode-locking theory predicts [5]: the phase noise of the generator is integrally converted into timing jitter of the pulse train, while the amplitude noise is very little affected by the amplitude noise of the generator (modulation depth fluctuations). Besides, the amplitude noise of the pulse train is higher than the one of the generator, indicating that it is much more tightly linked to other factors affecting the laser (environmental perturbations,…).

The two coherence functions of Fig. 3 mainly consist of spurs. In the case of the generator, these spurs can be very high for some frequencies, the corresponding values of the coherence function being close to 1. In the case of the pulse train, most of the spurs are small, and do not match the spurs of the generator: this confirms again that amplitude and phase noises of the laser have different physical origins (mainly the generator for phase noise and other perturbation elements for amplitude noise). One exception however has to be made concerning the spurs observed at 20 Hz and some of its harmonics for the pulse train: they originate from the dithering introduced by the cavity-length stabilization feedback loop [4].

Conclusion

In conclusion, using a time-domain demodulation technique, we measured amplitude and phase noises PSDs of an actively mode-locked Er-doped fiber laser, as well as their XPS. This technique has a lot of advantages on the classical FD technique: beyond the possibility to measure XPS, it allows to measure PSDs down to very low frequencies and only requires one measurement of the fundamental of the signal. This technique provided us with a new insight into the influence of the generator noise and of the cavity length stabilisation system on amplitude and phase noises of the pulse train.

	Amplitude noise	Jitter
Pulse train	0.36 %	1.7 ps
Generator	0.10 %	1.7 ps

Table 1. Amplitude noise and jitter rms values of pulse train and generator in the 1Hz-5kHz frequency range.

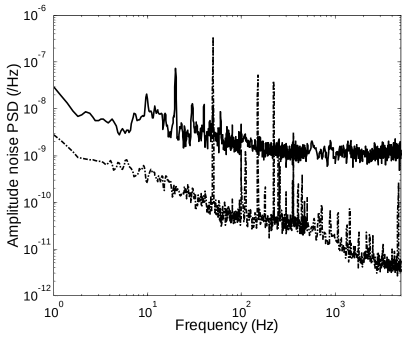

Figure 1. Amplitude noise PSDs of the pulse train (solid) and of the generator (dashed).

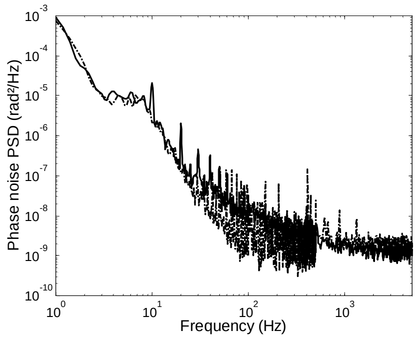

Figure 2. Phase noise PSDs of the pulse train (solid) and of the generator (dashed).

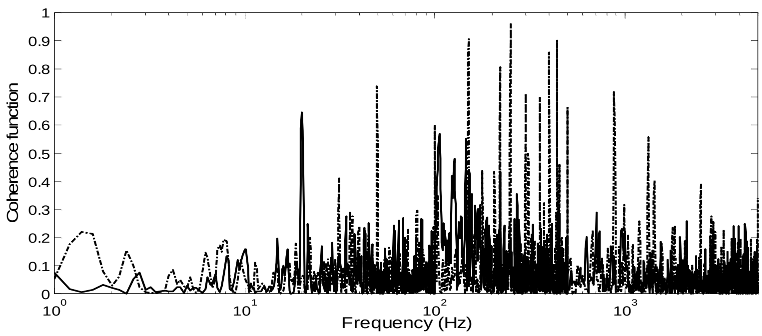

Figure 3. Coherence functions of the pulse train (solid) and of the generator (dashed).

Acknowledgements

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