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# Ultra-sensitive characterization of nonlinear instabilities via single photon dispersive Fourier-transform

Lynn Sader<sup>1</sup>, Surajit Bose<sup>2</sup>, Anahita Khodadad Kashi<sup>2,3</sup>, Romain Dauliat<sup>1</sup>, Philippe Roy<sup>1</sup>, Marc Fabert<sup>1</sup>, Alessandro Tonello<sup>1</sup>, Vincent Couderc<sup>1</sup>, Michael Kues<sup>2,3,4</sup>, Benjamin Wetzel<sup>1,5</sup>

<sup>1</sup>Xlim Research Institute, CNRS UMR 7252, Université de Limoges, 87060 Limoges, France

<sup>2</sup>Institute of Photonics, Leibniz University Hannover, Nienburgerstr. 17, Hannover, Germany

<sup>3</sup>Cluster of Excellence PhoenixD, Leibniz University Hannover, Hannover, Germany

<sup>4</sup>Corresponding author: [michael.kues@iop.uni-hannover.de](mailto:michael.kues@iop.uni-hannover.de)

<sup>5</sup>Corresponding author: [benjamin.wetzel@xlim.fr](mailto:benjamin.wetzel@xlim.fr)

**Abstract:** We report on a new dispersive Fourier transform-based characterization technique, using multiple single photon detectors, which allows the analysis of spectral instabilities with high resolution, high sensitivity, and theoretically unlimited dynamic range. © 2022 The Author(s)

## 1. Introduction

Noise-driven dynamics of modulation instability (MI) remain a subject of wide interest and are at the basis of numerous nonlinear optical processes ranging from optical source development to the study of complex phenomena such as optical rogue waves formation [1]. However, to analyze such dynamics appropriately, the ability to perform real-time measurements of fluctuating (i.e. non-repetitive) ultra-short optical pulses and broadband spectra is paramount. Over the years, a variety of complementary optical characterization techniques have been experimentally demonstrated and refined, such as the so-called time-lens [2]. Among those, the dispersive Fourier transform (DFT) technique has been widely implemented due to its inherent simplicity: It consists of a real-time “spectroscopy” method that transforms a broadband optical signal into a time-stretched waveform, thus allowing the retrieval of the optical spectrum directly from the temporal intensity profile [3,4]. Using optoelectronic detection via a fast photodiode (PD), one can readily capture single-shot spectra (Fig. 1) and perform a statistical analysis of such fluctuations to further extract spectral correlation maps and gain insight into e.g. noise-driven dynamics (e.g. to identify the interactions between various spectral components – see Fig. 2) [3-5]. Yet with all these advantages, DFT techniques still face several technical challenges: The equivalent spectral resolution is essentially limited by the detection bandwidth of the photodiode/oscilloscope which can reach a few tens of GHz at best (6 GHz in our case). Furthermore, fast photodiodes usually present limited sensitivity with relatively poor noise figures and high-speed oscilloscopes (with typical 8-12 bits digitalization) suffer from low dynamic ranges, so that one can hardly achieve real-time spectra measurements with over 30 dB contrast. While several approaches have been demonstrated to circumvent these issues (advanced processing, multipoint detector arrays, etc.) [6], these usually come at the expense of either a decreased resolution or sensitivity, thus finally imposing a performance tradeoff for the user. To overcome these limitations, we here propose an innovative variation of this technique through the use of multiple single photon detectors (SPD): Combined with DFT, SPD detection is analogous to an ultra-sensitive spectrometer [7] with a sensitivity down to the photon level and a dynamic range that is intrinsically not limited (only by the measurement time). Leveraging multiple SPDs allows us to have direct access to both inter- and intra-pulse dynamics by suitably processing the time stamps recorded from successive pulses (Fig. 1).

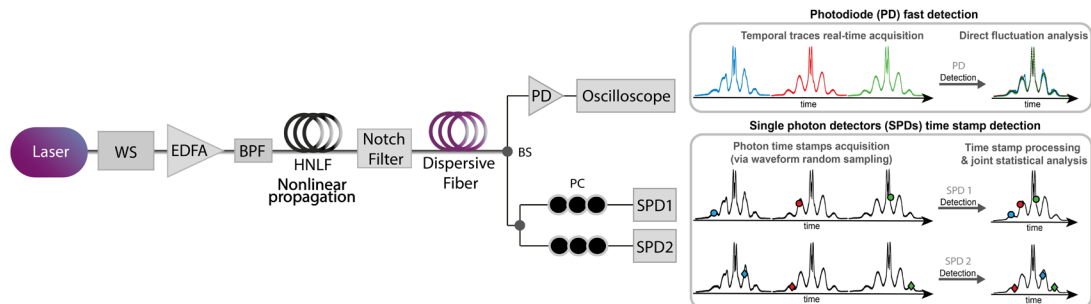


Fig. 1. Experimental setup: A femtosecond laser pulse centered at 1550 nm is spectrally “sliced” using a programmable filter (WS - Waveshaper) before amplification with an Erbium-Doped Fiber Amplifier (EDFA) and noise filtering (BPF: Band-Pass Filter). The resulting 30 ps pulse then propagates into 360 m of highly nonlinear fiber (HNLF). The MI broadening dynamics, spectrally averaged by the optical spectral analyzer (OSA), can be experimentally analyzed via DFT after propagation in a dispersive fiber. Statistics of the output shot-to-shot spectral fluctuations can be directly measured in the time domain via a fast photodiode (PD) but can also be retrieved from the analysis of coincidence photon arrival times via two single photon detectors (SPDs).

## 2. Results and Discussion

This SPD-based approach eventually allows us to gain access to spectral correlation maps similar to those obtained by standard DFT (see Fig. 2) with an excellent equivalent spectral resolution provided by the low timing jitter of the SPDs ( $\sim 25$  ps). In Figure 2, we show a succinct comparison of these two DFT techniques: Typical shot-to-shot spectral fluctuations can be recorded via PD-DFT, showing good agreement with OSA measurements, however requiring to filter out the pump around 1550 nm to resolve the MI sidebands with sufficient dynamics (Fig. 2a). The corresponding spectral correlation map (Fig. 2b) illustrates typical MI dynamics with well-defined sideband correlations but with a statistical analysis impaired by the PD impulse response and limited for the higher sideband orders (with low intensity). In contrast, SPD-based measurements provide a well-resolved correlation map (Fig. 2c) without impulse response nor sensitivity cutoff (but at the expense of prior spectral equalization to limit the measurement duration). Even without equalization, SPD-DFT measurements of the first symmetric MI sidebands (at 1545 and 1557 nm) obtained for increasing pump power (Fig. 2d) clearly resolve the evolution of correlation features between different spectral components, here arising from the four-wave mixing cascade and pump nonlinear reshaping [1-5]. This is even clearer in Fig. 2e where, at full pump power, both DFT approaches show similar signatures but with a fine structure only visible on the SPD-DFT measurements.

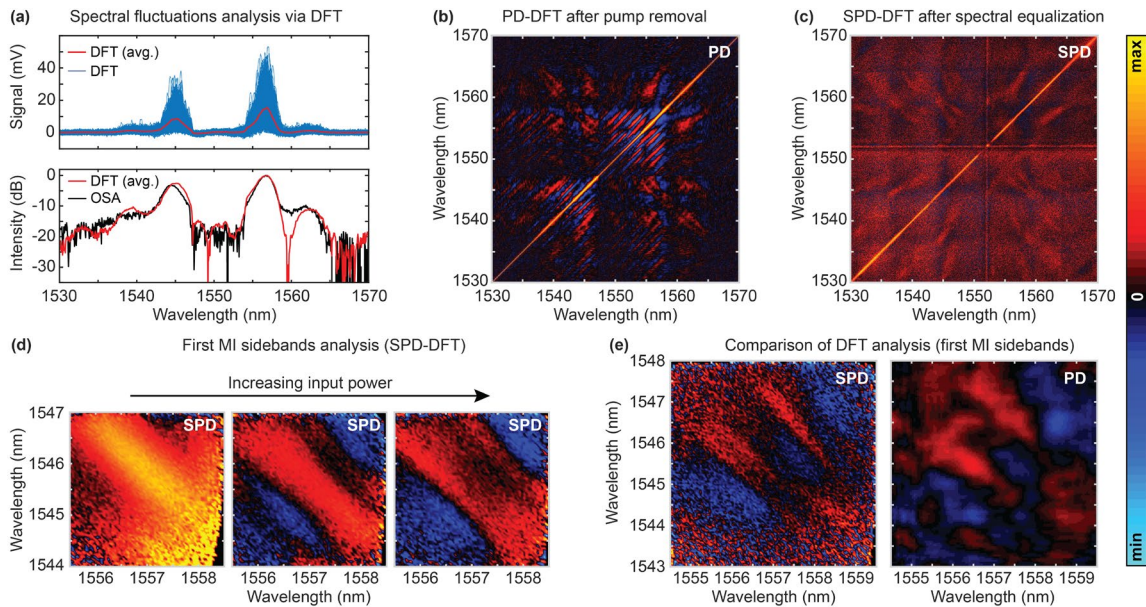


Fig. 2. (a) Typical fluctuations recorded via PD-DFT after pump filtering and comparison with OSA spectrum. (b) Corresponding spectral correlation map extracted from PD-DFT (with pump filtering). (c) Analogous spectral correlation map extracted from SPD-DFT (without pump filtering but with spectral equalization). (d) Spectral correlation maps between the first MI sidebands extracted from SPD-DFT for increasing pump power. (e) Comparison between PD and SPD based correlation map obtained at maximal pump power (first MI sidebands).

In this conference contribution, we will present this innovative approach and discuss its advantages and potential applications. In particular, we found that such SPD-DFT allows for correlation measurements between weak spectral components (e.g. between 3<sup>rd</sup> sidebands) at the limit of typical OSA sensitivity, while our setup (Fig. 1) enables testing further scenario of MI dynamics (e.g. with the addition of weak coherent seeds). We expect this approach to shed new light in noise-driven processes at the boundary between quantum and nonlinear optics. Furthermore, we anticipate this technique to be compatible with machine-learning strategies and prove useful for further tailoring nonlinear interactions in guided fiber propagation.

## 3. References

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