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Ultrasensitive Dispersive Fourier Transform Technique for Nonlinear Instability Characterization

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Abstract: We demonstrate the characterization of nonlinear noise-driven dynamics with ultra-high sensitivity, resolution, and a theoretically unlimited dynamic range using a novel approach of dispersive Fourier transform-based measurements and multiple single photon detectors. © 2022 The Author(s)

1. Introduction

In recent years, many optical characterization techniques have been experimentally demonstrated and refined to enable real-time measurements of fluctuating (i.e., non-repetitive) ultrashort optical pulses and gain insight into several complex, random noise-driven dynamics. An illustrative example of such incoherent nonlinear dynamics is the process known as Modulation Instability (MI), typically occurring as a result of nonlinear amplification of broadband noise during pulse propagation in optical fibers [1]. Within the last decades, this ubiquitous phenomenon has been intensely studied for its intriguing link with extreme event formation, exploiting a variety of real-time measurement techniques [2].

A well-known approach for characterizing such inherently random spectral fluctuations is the Dispersive Fourier Transform technique (DFT), that maps the spectrum of an optical signal into an exact waveform replica in the time domain through pure linear dispersive effects [3-4]. Using optoelectronic detection via e.g. an ultrafast photo detector, single-shot spectra (at the repetition rate of the laser source) can be captured, and a statistical analysis of such fluctuations can be performed (Fig. 1). However, fast photo detectors (e.g. photodiode - PD) are usually limited by their detection bandwidth, which can only reach a few tens of GHz at best, and thus limits the equivalent spectral resolution achieved by DFT. Furthermore, their low sensitivity with relatively poor noise figures, paired with the low dynamic range of high-speed oscilloscopes (with typical 8-12 bits digitalization), drastically hamper real-time spectra measurements at low intensity or with over 30 dB contrast (thus requiring mitigation schemes based on 2D detectors, loss compensation, etc.).

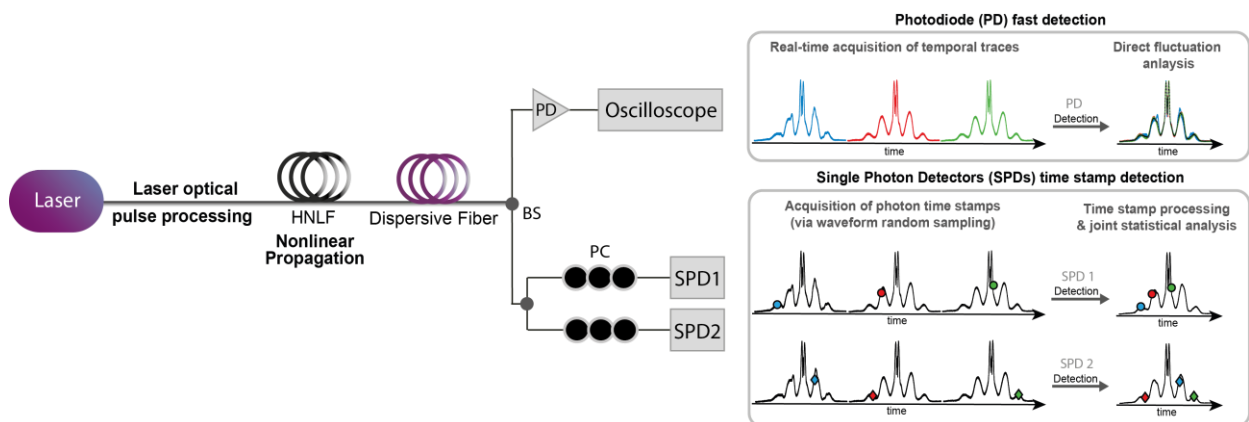


Fig. 1. Experimental setup: A femtosecond laser pulse centered at 1550 nm is filtered into a picosecond pump using a spectral programmable filter (*Waveshaper*) before propagation into a Highly Nonlinear Fiber (HNLf). The MI broadening dynamics can be experimentally analyzed via DFT after propagation in a dispersive fiber. Statistics of the output shot-to-shot spectral fluctuations can either be directly measured in the time domain via a fast photodiode (PD), or be retrieved using our new approach, from the analysis of coincidence photon arrival times via two single photon detectors (SPDs).

To overcome these limitations, we here propose a quantum-inspired variation of this technique using single photon detectors (SPD). We apply it to analyze MI dynamics. Combined with DFT, SPDs time-stamp detection of random individual photons on each event [5-6] brings about a sensitivity down to the photon level, along with a dynamic range that is intrinsically unlimited (only by the measurement time). Leveraging multiple SPDs thus allows a direct access to both inter- and intra-pulse dynamics by suitably processing the time stamps recorded from successive pulses (Fig. 1).

2. Results and Discussion

The SPD-DFT approach, allows for the retrieval of spectral correlation maps by applying a joint statistical analysis method known as Mutual Information Analysis (MIA) [7]. These maps can also be measured from the standard DFT using the well-known Pearson's correlation analysis [8]. In Figure 2, we show a succinct comparison between these two DFT techniques: The SPD-DFT provides well-resolved correlation maps compared to the PD-DFT technique, without the impulse response of the photodiode nor the sensitivity cutoff associated with dynamic range limitations (Fig. 2a). Focusing only on a small part of the MI spectrum (Fig. 2b), one can clearly see the evolution of correlation features between selected spectral components within the first MI sidebands, when increasing the input pump power. This is even clearer at full pump power, where both approaches show similar qualitative signatures, but with finer structures only visible with the SPD-based measurements being here associated with an excellent equivalent spectral resolution (40 GHz) provided by the low timing jitter of the SPDs (~25 ps).

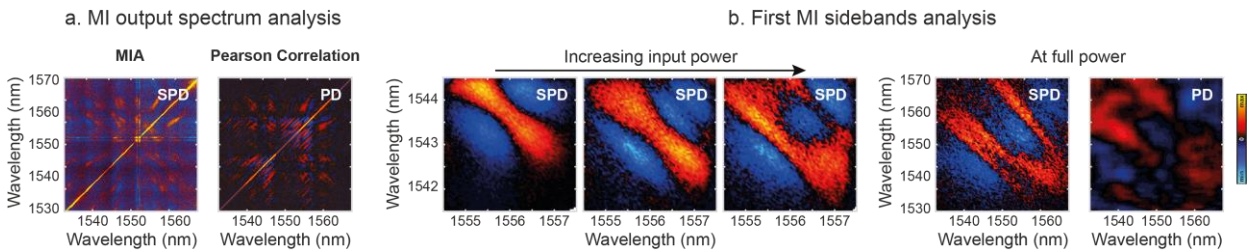


Fig. 2a. Spectral correlation maps extracted from SPD-DFT and PD-DFT of the MI output spectrum, respectively. b. Spectral correlation maps of the first symmetric MI sidebands obtained via SPD-DFT while increasing power, compared with PD-DFT results at full power.

With our scheme, we also found that SPD-DFT allows for correlation measurements between weak spectral components at very low intensities (e.g., between MI cascading processes up to the third sidebands) and further demonstrates the ability to finely adjust correlations between specific wavelengths by the addition of weak optical seeds to the initial pulse before propagation. We expect our results to pave the way towards the tailoring of nonlinear interactions in fiber optics, enabling us to control noise-driven processes at the boundary between quantum and nonlinear optics.

3. References

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