Narrowband Noise Filtering of Arbitrary Waveforms by Reversible In-Fiber Temporal Talbot Sampling

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Abstract: We effectively employ temporal Talbot effects to filter narrowband optical noise beyond optical bandpass filter capabilities in MHz-bandwidth temporal waveforms and random data signals, recovering buried optical signals and enhancing optical signal-to-noise ratio.

1. Introduction

Narrowband optical signals, characterized by sub-GHz bandwidths, are crucial in a wide range of applications, including LiDAR, bio-sensing, and microwave photonics [1, 2], and their precise transmission, processing, and detection are of utmost importance. However, a significant challenge emerges when these information-carrying signals become heavily impacted by noise. Conventional approaches to noise filtering primarily rely on optical bandpass filters. However, practical implementation of optical bandpass filters with narrowband characteristics, particularly within the sub-GHz range, poses significant challenges [3, 4]. Moreover, precise alignment of these filters' center frequencies with the information-carrier signals is a non-trivial task. In specialized applications like microwave photonics, optical signals often exhibit bandwidths well below a few hundred megahertz. This unique characteristic necessitates innovative noise filtering techniques tailored to the specific demands of these narrowband signals. In the realm of filtering narrowband optical signals, past studies have indeed explored intriguing approaches [1, 3, 4]. However, the quest for a practical, non-distorting solution remains a challenge. Notably, a recently introduced method grounded in passive amplification leverages temporal Talbot effects [5]. This technique carefully applies a balanced amount of temporal phase modulation (TPM) and group velocity dispersion (GVD) to the signal under test (SUT). The result is the creation of short pulses that effectively sample the SUT in a lossless manner. These short pulses, or the peaks they represent, outline a locally amplified version of the SUT. While this method proves beneficial for the detection of weak signals masked by noise, it introduces distortion to the signal, affecting both its time and frequency domain representations, which is undesirable in applications requiring further signal transmission and/or complex processing. Moreover, this method does not improve the optical signal-to-noise ratio (OSNR) of the input signal itself while still requiring a detection bandwidth higher than that required for direct SUT measurement.

In response to these challenges, we recently proposed an innovative approach that effectively tackles these issues. The approach is based on denoising the Talbot sampled waveform through time filtering followed by a reversal of the phase transformations involved in the Talbot sampling process. In recent work, we reported preliminary results that provided evidence of the OSNR improvements enabled by this approach on narrowband (MHz range) waveforms [6]. In this communication, we demonstrate further the efficacy of our approach to mitigate noise within the frequency band of standard optical bandpass filters, enhancing the correlation of the recovered output signals with the noise-free target signals. This is demonstrated for a variety of arbitrary waveform shapes. Moreover, we also show application of the method to denoising random data signals significantly buried under narrowband noise, leading to a noteworthy reduction in the recovered bit error rates. Notably, our approach provides an undistorted output, serving as an ideal input for subsequent applications within the optical domain or for improved signal detection.

2. Principle of operation

Our proposed method consists of three fundamental steps (see Fig. 1). The first component, known as Talbot-based passive amplification, employs an initial step involving TPM and a subsequent step utilizing a GVD unit. In TPM, we apply a quadratic discrete phase, represented by the equation $\psi = -\pi n^2(g-1)/g$ (where g signifies the Talbot amplification factor) [5, 6]. The phase-modulated signal experiences broadening in the frequency domain and

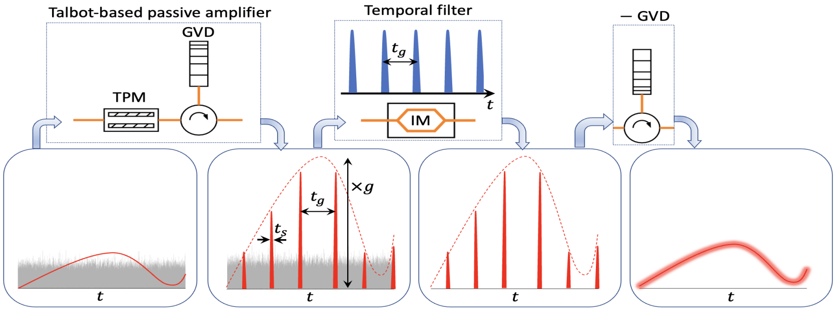

Fig. 1. The proposed noise filtering method comprises three key steps: Talbot-based amplification, temporal filtering, and GVD reversal.

acquires a quadratic phase in the process. This is followed by a specific GVD operation designed to compensate for this acquired phase. The GVD compensation is defined by a dispersion value (the slope of linear group delay versus radial frequency) of $\ddot{\phi} = g t_s^2/(2\pi)$. This transformation focuses the waveform energy into short temporal pulses, each with a width of t_s, separated by intervals of $t_g = g t_s$. As a result of this process, the waveform becomes locally amplified, with a magnification factor of g, as depicted in the Fig. 1. It is important to note that while the phase-coherent target signal concentrates its energy in consecutive short temporal slots, the high-speed noise remains unaltered. The following system component is a temporal filtering process to selectively pass the short pulses that contain valuable information, effectively rejecting the intermediate noise. This temporal filter is realized using an intensity modulator driven by a periodic pulse train with a period of t_g, synchronized with the peaks of the processed signal. To complete the process, we leverage the fact that the transformations applied in the Talbot processor are phase-only transformations, making them easily reversible. To restore the signal in the time domain, we simply utilize another GVD unit, but this time with a negative amount of dispersion, which counteracts the dispersion applied in the initial step. The proposed system is equivalent to a filter with passband of approximately $1/t_g$.

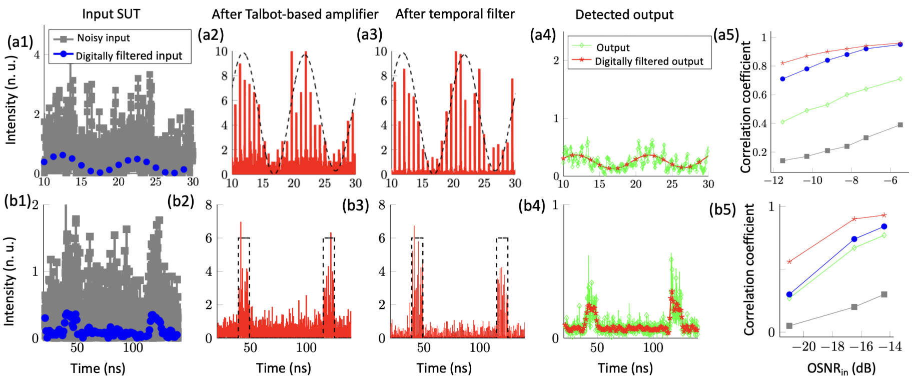

Fig. 2. Captured waveforms at different stages of the proposed system for a 100 MHz RF tone (a1-a4), and a train of rectangular pulses (b1-b4). (a5,b5) shows the correlation coefficient for each case versus the input OSNR, for both input and output signals, with the color legends for the different curves presented in (a1) and (a4). The digital filter cutoff frequency is 100 MHz for (a) and 200 MHz for (b).

3. Experimental results

The SUT is created by intensity modulating a continuous-wave (CW) laser at 1552 nm, using a 10 GHz electro-optic Mach-Zehnder modulator (EO-MZM) driven by a 92 GSa/s RF arbitrary waveform generator (AWG). To introduce narrowband noise, we utilized a superluminescent diode, which was subsequently filtered by a 22.4 GHz optical filter. Notably, this narrowband noise exceeds the bandpass filter's removal capacity, showcasing the enhanced noise reduction capabilities of our proposed system. In the implementation of the Talbot-based passive amplifier, we employed a 40 GHz electro-optic phase modulator driven by the same AWG. Additionally, a linearly

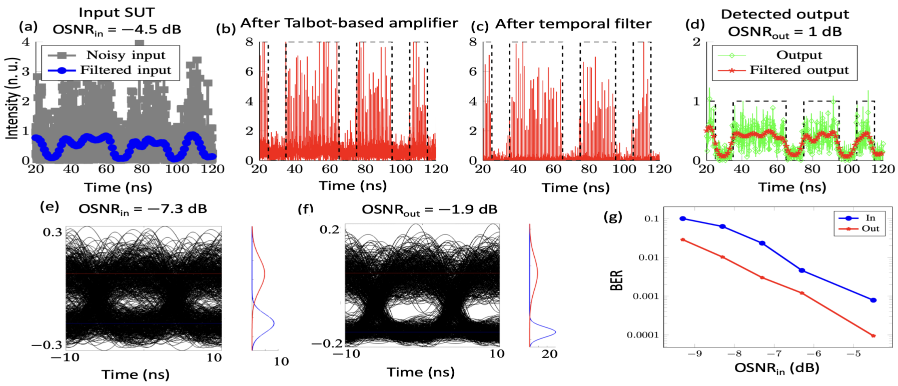

Fig. 3. (a-d) Captured waveforms at different stages of the proposed system for a 100 Mbps NRZ-OOK input. (e,f) eye diagram for input and output signals. (g) BER versus the OSNR of input.

chirped fiber Bragg grating (LCFBG) with $\ddot{\phi} = 2651\text{ps}^2/\text{rad}$ served as the GVD unit. The system is designed to achieve a Talbot amplification factor g of 35 and a pulse separation t_g of 0.76 ns, i.e., the sampling pulse time-width t_s is 21.7 ps, which determines the system's equivalent passband to be about 1.3 GHz. To implement the temporal filter, we utilized a 40 GHz EO-MZM. It was driven by a sequence of Gaussian pulses with the same period, which is t_g, and generated from the AWG. Afterward, another LCFBG was introduced to compensate for the GVD applied in the initial step. The output waveform was captured using a 10 GHz photodetector connected to a 28 GHz real-time oscilloscope. OSNR values were obtained by calculating the ratio of the average power of the signal to the average power of the noise. This measurement was carried out using a power meter when either the input SUT was active and the noise source was off, or vice versa. In our proof-of-concept demonstrations, we initially applied the proposed system to perform noise filtering on input SUTs, including a 100 MHz RF tone and a rectangular 10 ns pulse sequence with a 75 ns period, both of which were buried under noise. Figure 2 illustrates the results. Clearly, the detected output prominently exhibits a noise-mitigated replica of the SUT in both cases, with a significant OSNR improvement of approximately 8 dB. To qualitatively assess the output signal's quality, we computed the correlation coefficient as a measure of signal similarity, using the noise-free input as a reference. The results demonstrate that the output exhibits a stronger correlation with the reference. Additionally, we calculated the correlation for both the digitally filtered input and digitally filtered output, with the digitally filtered output showing again a notably better correlation, especially in the case of the rectangular pulse. Figure 3 presents the results for a 100 Mbps non-return-to-zero on-off keying (NRZ-OOK) pseudorandom binary sequence data signal with a bit length of 2^8-1. Figures 3(a-d) display the waveforms for the input signal with an OSNR$_{\text{in}}$ of -4.5 dB. With a measured output OSNR of approximately 1 dB, this additional filtering of narrowband noise allows the previously masked SUT to become detectable, demonstrating the efficacy of our approach. Figures 3(e-f) illustrate eye diagrams for both digitally filtered input and output, presenting a more challenging scenario with an OSNR$_{\text{in}}$ of -7.3 dB. In this case, the eye opening is almost entirely closed for the digitally filtered input, while for the digitally filtered output, we observe a clear eye opening. Figure 3(g) depicts the BER as a function of OSNR$_{\text{in}}$, illustrating the superior performance of the system in each case. The BER is estimated from the Q-factor obtained from the eye diagrams, where $Q = (\mu_1-\mu_0)/(\sigma_1+\sigma_0)$, with μ and σ representing the mean value and standard deviation for each logical value 1 or 0. This estimation is done according to the relation BER = erfc $(Q/\sqrt{2})/2$.

In summary, we have introduced an all-fiber method for mitigating narrowband noise based on reversible temporal Talbot effects, surpassing the capabilities of conventional optical bandpass filters. We anticipate its potential applications in optical signal processing and communication. This approach could notably impact photonic-based communication systems dealing with regeneration challenges in the analog wave domain.

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