Optical Signal-to-Noise Ratio Improvement of Narrowband Optical Signals by In-Fiber Talbot Effects

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Abstract *We present a novel approach for reducing noise in narrowband optical signals, offering significant noise reduction while maintaining signal characteristics and resulting in an undistorted version of the processed waveform. We demonstrate up to 9-dB of OSNR improvement in MHz-bandwidth signals buried in noise.*

Introduction

Microwave photonics (MWP) subsystems have greatly enhanced the potential capabilities of conventional radio frequency (RF) signal processing systems, thanks to the inherent advantages of photonics technology, such as low loss, immunity to electromagnetic interference, scalability, and tunability[1]. However, MWP faces a major obstacle in managing the stochastic noise that occurs during the generation, transmission, and detection of optical signals[2],[3]. Stochastic noise originates from various sources, including thermal fluctuations, shot noise, and spontaneous emissions. Such noise sources have the potential to impair the signal quality and to significantly affect the operation and effectiveness of MWP systems. As a result, the realization of efficient approaches to mitigate noise is crucial to tackle this challenge and enhance the performance of MWP systems.

Bandpass filtering (BPF) is a commonly used method to eliminate noise that is outside of the desired frequency range. However, for narrowband applications, conventional optical filters have limited resolution, typically extending at least above a few GHz. Nonetheless, many of the signals present in the RF targeted by the MWP actually extend over a much narrower bandwidth, below the sub-GHz range. While previous research has proposed some interesting approaches for MWP filters in the MHz regime[4]–[6], a practical and efficient solution has yet to be developed. A novel technique has recently been introduced to reduce noise in arbitrary optical signals, which involves passive amplification utilizing principles originating from the fiber dispersion - induced Talbot self-imaging phenomenon, a so-called temporal Talbot array illuminator (T-TAI)[7]–[9]. Passive amplification based on a T-TAI provides a locally amplified and sampled version of the original signal of interest without affecting the incoherent noise content. The method involves two consecutive phase transformations along the time and frequency domains, respectively, resulting in a reshaped signal with its overall energy distributed on a set of short pulses that outline the signal's envelope. However, this process translates into a significant signal bandwidth increase, which can be problematic for further transmission or processing of the resulting signal. Therefore, the method is mainly useful for mitigating noise in the detection stage, necessitating a detection bandwidth much higher than that needed for direct measurement of the signal of interest. In other applications where preserving the original signal's characteristics is critical, such as in communication or signal processing systems, the distortion and bandwidth increase may make the technique less practical.

In this communication, we demonstrate a Talbot-based approach for recovering narrowband noisy signals. Our approach builds upon the T-TAI passive amplification technique, but introduces a new method to achieve an output processed signal that is not significantly distorted but rather a nearly ideal copy of the input signal with a notably reduced relative noise content. The T-TAI method enables us to discern the valid signal from the noise along the time domain, a feature that we then exploit to mitigate the noise content using time-domain filtering, i.e., a temporal optical shutter. Once the noise is reduced, we reverse the T-TAI phase transformation along the frequency domain to recover the amplitude of the original signal in the temporal domain with significantly re-

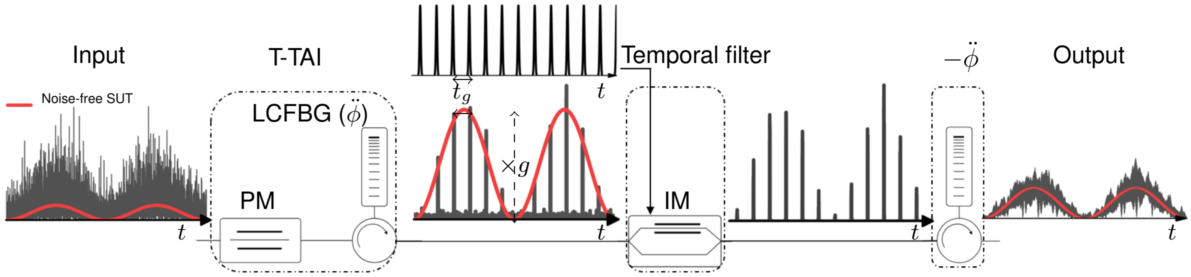

Fig. 1: Denoising of narrowband optical signals concept based on numerical simulations. The noise mitigation method is implemented by a T-TAI, consists of temporal phase modulation and group velocity dispersion units. Then the sampled and amplified signal is temporally filtered by intensity modulation, and after that the dispersion is reversed.

duced noise. Our method provides a simple and effective way to reduce noise in narrowband optical signals. We describe our proposed method and provide experimental confirmation of its effectiveness in retrieving narrowband sinusoidal signals, with MHz bandwidths, buried in noise.

Operation Principle

The proposed denoising technique is based on a T-TAI[9], which involves an appropriate temporal phase modulation (TPM) of the signal under test (SUT) followed by a group velocity dispersion (GVD) line that satisfies the appropriate Talbot conditions. As illustrated in Fig. 1, such operations focus the waveform into temporal slots of width t_s, separated by a time interval $t_g = gt_s$, creating a copy of the input signal locally amplified by a factor of g. To achieve this, the signal is temporally modulated with a quadratic discrete phase, with the n-th step satisfying $\psi = -\pi n^2(g-1)/g$. The signal then passes through a GVD unit with a dispersion value (slope of linear group delay as a function of radial frequency) of $\ddot{\phi} = gt_s^2/(2\pi)$[10],[11]. After the T-TAI, the energy of the narrowband signal of interest is locally concentrated into consecutive short temporal slots (or peaks), while the high-speed noise variation remain nearly unaltered in between these peaks, as shown in Figure 1. To retrieve the signal, which now has been focused on these time slots, we apply a temporal filter that selectively passes the peak regions and rejects the intermediate noise. In general, a temporal thresholding device could be used for this purpose. In our case, we implement the selective temporal filtering process using an intensity modulator (IM) driven by a periodic pulse train (with period t_g) that is aligned with the T-TAI signal's peaks. Finally, we can recover the SUT by taking advantage of the fact that T-TAI operations are based on phase-only transformations. We do this by passing the locally concentrated signal through another GVD unit, but with the opposite dispersion value ($-\ddot{\phi}$). This step essentially reverses the dispersion and brings the waveform back to its original form in the temporal domain. A residual temporal phase modulation remains along the recovered signal; however, notice that this is of no importance if the useful information is carried by the optical wave intensity, as in typical signals found in MWP applications.

Experimental Results

To verify the effectiveness of the proposed denoising method for narrowband optical signals, experiments were conducted on a 100 MHz sinusoidal SUT. The SUT was generated by electro-optic intensity modulation of a 1552-nm CW laser. In order to generate a noisy SUT with programmable optical signal-to-noise ratio (OSNR), the target signal was combined with a noise source. The latest was based on an amplified superluminiscent diode which was subsequently filtered by a 22.4 GHz (3 dB-bandwidth) optical filter centered at 1552 nm. This was done to demonstrate the noise-mitigation capabilities of the proposed method beyond the capabilities of standard narrowband optical BPFs. As shown in Figure 1, the proposed denoising scheme uses a 40 GHz bandwidth electro-optic phase modulator (PM) driven by an RF arbitrary waveform generator (AWG) to impart the required T-TAI phase modulation. This is followed by a linearly chirped fiber Bragg grating (LCFBG) with a dispersion coefficient of $\ddot{\phi}$ = 2651 ps^2/rad that operates in reflection mode to implement the required GVD. The T-TAI was designed with an amplification factor of g = 35, and temporal slots' width of t_s = 21.7 ps, which resulted in t_g = 0.760 ns. To realize the temporal filtering process, we utilized a 40 GHz-bandwidth intensity modulator driven by a sequence of Gaussian pulses each with a 16.6 ps full width at half maximum (generated from the same AWG). The signal is then passed through another LCFBG with dispersion $-\ddot{\phi}$. The output

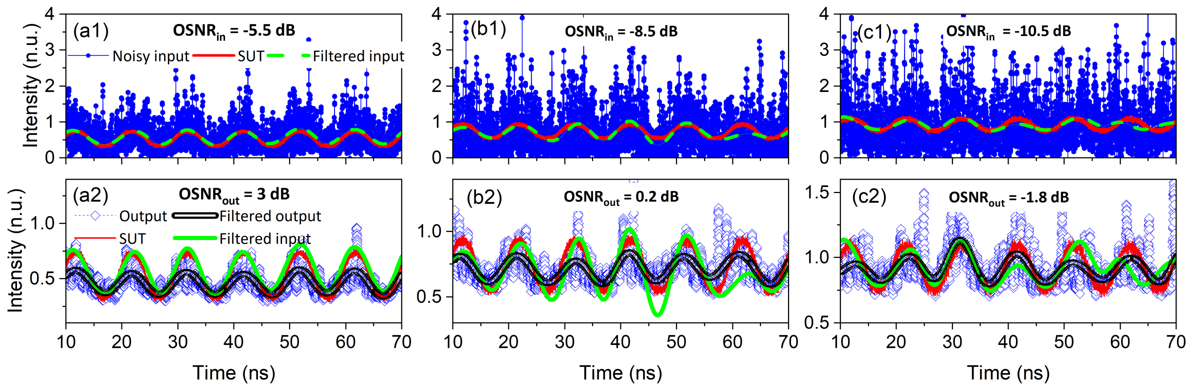

Fig. 2: Experimental results on the noise mitigation of a 100-MHz sinusoidal SUT, for OSNR levels of (a) -5.5 dB, (b) -8.5 dB, (c) -10.5 dB. The digital filter utilized has a passband of 200 MHz. The green and black traces represent the input and output signals, respectively, after detection and digital bandpass filtering with a bandwidth of 200 MHz.

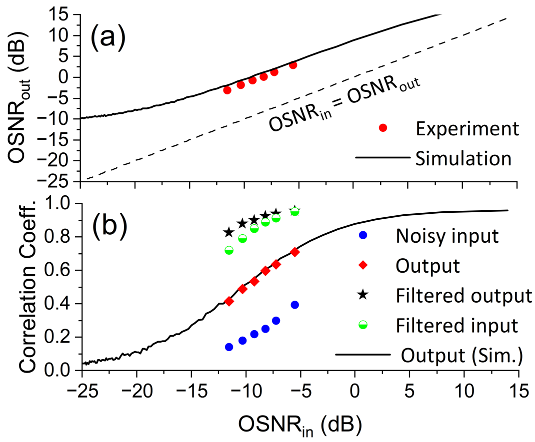

Fig. 3: (a) Comparison of OSNR improvement of output versus input as a function of the input OSNR, both numerically and experimentally. (b) Cross-correlation coefficient versus OSNR of input.

waveform is recorded by a 10 GHz bandwidth photodiode connected to a real-time oscilloscope. The OSNR values for the system are obtained by utilizing a power meter to measure the optical power when the SUT is present and the noise is absent at both the input and output of the system, as well as when the noise is present and the SUT is absent.

Figure 2 shows results of the denoising process of a 100 MHz sinusoidal SUT at input OSNR levels of -5.5 dB, -8.5 dB, and -10.5 dB. By analyzing the output waveforms, it is clear that the proposed system successfully eliminated a considerable amount of noise from the signal. The OSNR measurements demonstrate that the system improved the OSNR of the sinusoidal SUT (from the input to the output) over 8.5 dB in all tested cases, indicating that the system was effective in significantly reducing the amount of noise present in the signal. Additionally, we compared the digitally filtered (filter with passband of 200 MHz) input and output waveforms in Fig. 2, and we observed that for a higher amount of noise, the digitally filtered output of the system preserved the characteristics of the sine waveform more effectively.

Figure 3a illustrates the denoising performance of the of the system in terms of OSNR for both numerical simulations and experimental results. The results show that the system provides significant OSNR improvement over a wide range of input OSNR levels, where an increase in the OSNR by up to 9 dB was experimentally observed. This demonstrates the effectiveness of the proposed denoising method in removing noise from narrowband optical signals. In order to compare the quality of the recovered temporal signals, we used the cross-correlation coefficient[12], which is a measure of how similar two signals are, with a value of 1 indicating perfect similarity and a value of 0 indicating no correlation. In Figure 3b, we show the obtained cross-correlation coefficient of the input and output signals of the system, where the noise-free input SUT was taken as the reference. It is evident from the figure that the output of the system has a better correlation with the SUT compared to the input. Additionally, the digitally filtered output has a better performance than the digitally filtered input, with a correlation coefficient of over 0.8.

Conclusions

In summary, our proposed method significantly improves the OSNR of narrowband optical signals buried under significant noise, even in the case in which the noise is relatively narrowband and it cannot be removed through conventional optical filtering technologies. Unlike previous methods, our approach provides an undistorted copy of the input signal, making it suitable for further transmission in an optical communication or processing system.

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