All-fiber noise-mitigating sampling of temporal waveforms enabling broadband operation and high passive amplification

Manuel P. Fernández[1,2,*], Saket Kaushal[1], Laureano A. Bulus-Rossini[2], Pablo A. Costanzo-Caso[2], José Azaña[1]
[1]*Institut National de la Recherche Scientifique – Énergie Matériaux et Télécommunications (INRS–EMT), Montréal, QC H5A 1K6, Canada*
[2]*Laboratorio de Investigación Aplicada en Telecom. (CNEA) & Instituto Balseiro (UNCuyo-CNEA) & CONICET, Bariloche (RN), Argentina*
[*]*manuel.fernandez@inrs.ca*

Abstract: We propose an all-fiber design concept for Talbot-based denoising passive enhancement of temporal waveforms using four-wave-mixing, and demonstrate about an order-of-magnitude improvement in the operation bandwidth × amplification factor (>150 GHz) versus previous electro-optic designs.

1. Introduction

Accurate detection of ultrafast optical signals is fundamental to many fields, including information and communication technologies [1], microwave photonics [2], and sensing and ranging [3]. In all these applications, stochastic noise arising in the generation, transmission, and/or detection of the signals often represents a main limitation to the measurement accuracy, especially when the relevant signal is much weaker than the background noise [4]. In such a case, one could use optical amplifiers, such as Erbium-doped fiber amplifiers (EDFAs), to boost the signal. However, besides injecting additional noise, both the signal and the pre-existent noise are simultaneously amplified, leading to a deterioration in the optical signal to noise ratio (OSNR). A band-pass filter can be used to reject out-of-band noise, but this requires a precise a-priori knowledge of the signal's central wavelength and bandwidth.

Recently, a noiseless and wavelength-independent passive amplification approach based on the temporal Talbot array illuminator (T-TAI) concept has been demonstrated to offer excellent noise mitigation capabilities on both optical narrowband signals (such as those found in microwave photonic systems) [5] and high-speed telecom data signals [6]. In a T-TAI amplifier, the noisy incoming signal undergoes a suitable stepwise temporal phase modulation (PM) followed by linear group-velocity dispersion (GVD). These operations redistribute the signal energy into discrete peaks outlining an amplified copy of the waveform of interest (i.e., lossless optical sampling) while leaving the non-coherent noise nearly unaltered. Specifically, the required PM is a sophisticated stepwise function in time-bins of length T/m, with T and m being the target sampling period and the local amplification factor, respectively. This can be implemented using an electro-optic modulator driven by an electronic arbitrary waveform generator [5, 6]. For a faithful signal recovery, the TAI sampling rate ($= T^{-1}$) must be higher than the signal's full bandwidth, such that a PM bandwidth at least m times higher than the signal bandwidth is required. This implies a fundamental design trade-off between maximum input signal bandwidth and achievable amplification factor, and in particular, this main figure of merit is limited to a few tens of GHz using electro-optic schemes (< 20 GHz in previously reported demonstrations [5, 6]). To overcome this limitation, an implementation of the T-TAI based on cross-phase modulation was proposed [7], but this still requires a bulky free-space waveshaper to synthesize the pump as per the stepwise modulation profile.

In this work, we propose a simple all-fiber implementation of the T-TAI amplifier based on four-wave mixing (FWM), i.e., *Time-gated T-TAI* design. In this scheme, the required periodic stepwise-phase pump signal is easily obtained by exploiting the inherent temporal phase profile of a Talbot rate-multiplied pulse train induced by GVD in an optical fiber. In proof-of-concept experiments, we demonstrate passive amplification by a factor approaching 10 at sampling rates exceeding 15 GHz, significantly outperforming state-of-the-art electro-optic schemes.

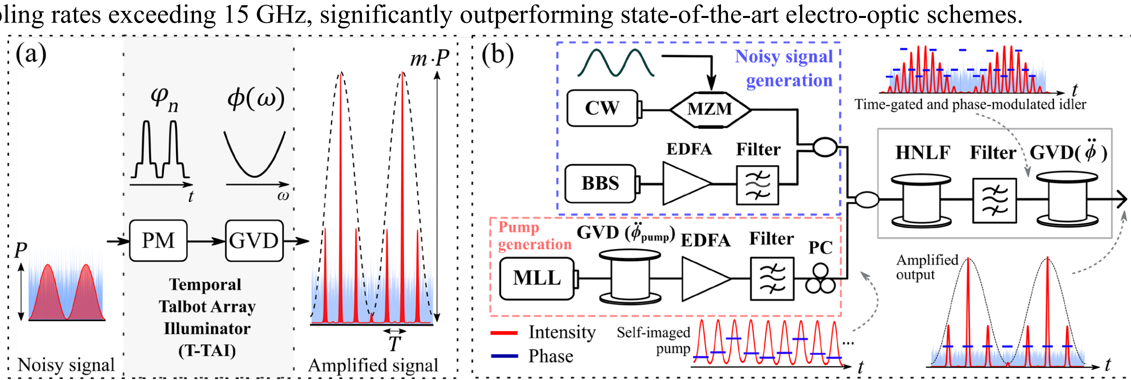

Figure 1. (a) Principle of the T-TAI denoising system. (b) Experimental setup of the Time-gated T-TAI; the required PM is achieved by mixing in a highly nonlinear fiber (HNLF) the SUT and the GVD-induced fractional self-image of order m of a pulse train from a mode-locked laser (MLL). CW: Continuous-Wave laser, MZM: Mach-Zehnder Modulator, BBS: Broadband Source.

2. Operation principle

The basic principle of the T-TAI [5-6] is illustrated in Fig. 1(a). The noisy signal under test (SUT) first undergoes a periodic stepwise temporal PM, where the phase value of the n^{th} time-bin is determined by the Talbot condition, $\varphi_n = \sigma\,\pi\, n^2\, s/m$, with $\sigma = \pm 1$ and where s and m are co-prime natural numbers. Each time-bin has a duration T/m, and since φ_n is m-periodic, the period of the applied PM is T. Subsequently, the phase-modulated SUT propagates through a second-order dispersive medium satisfying $2\pi\ddot{\phi} = -\sigma\, T^2 p/m$, with $\ddot{\phi}$ being the slope of group delay versus radial frequency, and with p depending on (s, m) as per the relations outlined in Ref. [8]. This leads to the coherent addition of m consecutive time-bins, resulting in the generation of a train of pulses of width T/m and pulse spacing (sampling period) T. If the temporal variations of the SUT are slower than the sampling period T, then the pulse-to-pulse amplitude follows the envelope of the SUT, with a peak power locally increased by m with respect to the input (apart from insertion losses of the system). Therefore, m is referred to as the passive amplification factor. Since the T-TAI only acts on the coherent part of the SUT, the non-coherent fast noise is not amplified, hence obtaining a sampled and noise-mitigated version of the SUT, in such a way that a higher m leads to an improved noise mitigation performance.

In order to overcome the inherent limitations of electro-optic PM designs, we propose an all-fiber implementation of the T-TAI, which exploits the FWM between the SUT and an all-fiber synthesized pump to achieve the required PM. This method will be referred to as Time-gated T-TAI. The experimental setup used to demonstrate the concept is shown in Fig. 1(b). First, the output of an actively MLL emitting pulses at a repetition rate T^{-1} propagates through a fiber-optics dispersive medium ($\ddot{\phi}_{\text{pump}}$) that satisfies a fractional temporal self-imaging (Talbot) condition given by $2\pi\ddot{\phi}_{\text{pump}} = \sigma\, T^2\tilde{p}/m$. The self-imaged pulse train, which is used as the pump, presents a reduced period of T/m and a pulse-to-pulse phase profile $\tilde{\varphi}_n = \sigma\,\pi\, n^2\, \tilde{s}/m$ [8]. The coupling of the pump $u_{\text{p}}(t)$ and the SUT $u_{\text{s}}(t)$ in a HNLF creates an idler wave, whose complex electric field can be written as $u_{\text{i}}(t) \propto u_{\text{p}}^2(t)u_{\text{s}}^*(t)$ [9]. Ignoring the conjugate operation on the signal, it can be seen that the idler is a time-gated and phase-modulated version of the input SUT, where the phase of the pump is transferred to the idler multiplied by two, such as the generated pulse-to-pulse PM is $\varphi_n = 2\tilde{\varphi}_n$. Finally, filtering and propagating the idler through the appropriate dispersion ($\ddot{\phi}$), as defined above, leads to the amplified SUT. Here, the filter's purpose is to remove the pump and input SUT and, thus, a precise knowledge of the SUT central wavelength is not required, as long as the idler lies within the pass-band of the filter.

The key to the Time-gated T-TAI is that we take advantage of the inherent pulse-to-pulse phase that is simply obtained by linear propagation of an input pulse train through the appropriate GVD complying with the temporal Talbot condition, as described. This provides a simple all-fiber approach to obtain the target PM profile at rates of hundreds of GHz and beyond. Also, it is worth noting that the Time-gated T-TAI works on top of a FWM parametric amplification process, where here, the FWM mechanism is simultaneously used to perform the required Talbot PM.

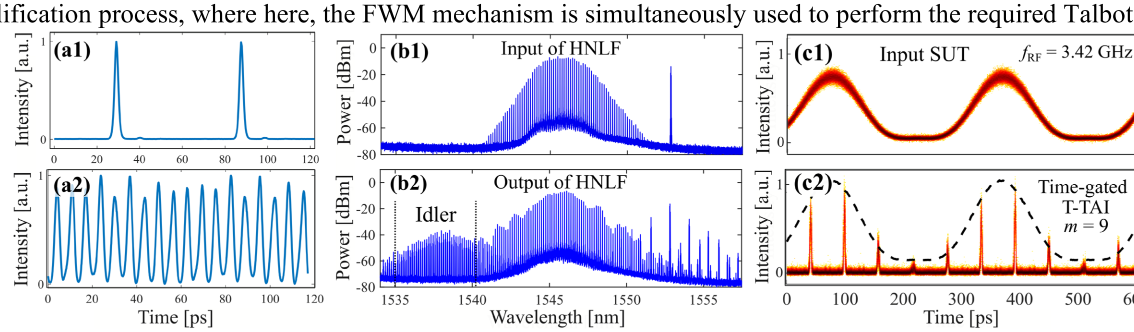

Figure 2. (a1, a2) MLL output and its self-image for $m = 9$, respectively. (b1, b2) Measured spectrum at the input and output of the HNLF, respectively. (c1, c2) Measured temporal traces of the input SUT and sampled output, respectively. Waveform's intensities are normalized for illustration purposes. Black dashed lines represent the envelope of the input SUT.

3. Experimental results

We carried out proof-of-concept experiments to demonstrate passive amplification of arbitrary signals for a design amplification factor of $m = 9$. Concerning the pump pulse train generation stage (see Fig. 1(b)), the MLL output is centered at 1546 nm and its repetition rate is set to $T^{-1} = 17.1$ GHz. Thus, the operation bandwidth × amplification factor product is 153.9 GHz. We designed the dispersions to achieve a target phase modulation φ_n with parameters $(\sigma = -1, s = 8, m = 9)$, for which the pulse-to-pulse pump phase $\tilde{\varphi}_n$ is designed to be $(\sigma = -1, \tilde{s} = 4, m = 9)$. Such pump is obtained by propagation of the MLL pulse train through a dispersion of $\ddot{\phi}_{\text{pump}} = -423$ ps^2, for which we used 20.56 km of standard single-mode fiber (SSMF), producing the target fractional self-image of the input pulse train, i.e., with a multiplied repetition rate by $m = 9$ times. The input pulse train and self-imaged pump are shown in Fig. 2(a). For the defined parameters, the required output dispersion is $\ddot{\phi} = -60$ ps^2, for which we used 3 km of SSMF. The HNLF has a nonlinear coefficient $\gamma = 11$ (W·km)$^{-1}$ and a length of 1 km. In the first experiments, the average pump power is set to 14.3 dBm. The SUT is generated by carving a tunable CW source centered at 1554 nm using a MZM. Firstly, the CW is modulated with a sinusoidal-like signal of frequency f_{RF} = 3.42 GHz. Figure 2(b) shows the spectrum at the input and output of the HNLF. The idler is generated at 1538 nm, and it is filtered by a band-pass filter with a bandwidth of ~570 GHz. The input SUT and the output sampled signal acquired by an optical sampling oscilloscope are shown in Fig. 2(c). It can be appreciated how the output signal is a sampled version of the input signal, with a sampling rate of 17.1 GHz, thus obtaining 5 samples per period.

Next, we show the capability of operation over a broad wavelength range. Figure 3(a) shows the average idler power as a function of the central wavelength of the SUT (λ_{CW}) when the pump power is set to 17 dBm, the average SUT power is 3.4 dBm and the SUT frequency is f_{RF} = 2.1375 GHz. With the used HNLF, we obtained a 3 dB-wavelength span of ±10 nm around the pump, which can be further extended using optimized nonlinear fibers or integrated waveguides. The corresponding temporal traces are depicted in Fig. 3(b) for a central wavelength of the SUT ranging from 1554 nm to 1560 nm, showing proper optical sampling regardless of the SUT central wavelength.

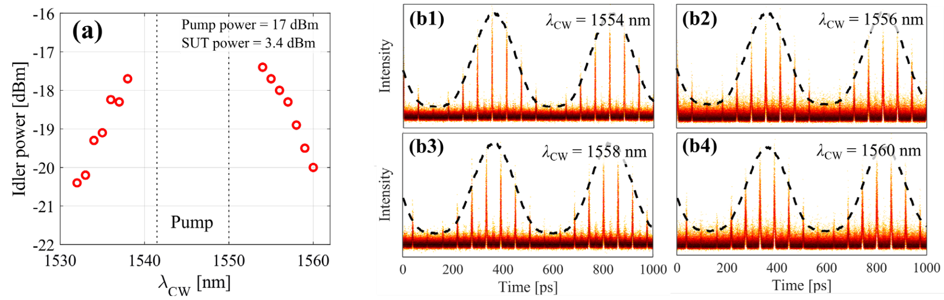

Figure 3. Wavelength dependence of the Time-gated T-TAI. (a) Measured idler power as a function of the central wavelength of the incoming SUT, λ_{CW}. (b) Output waveform for a SUT centered at different λ_{CW}.

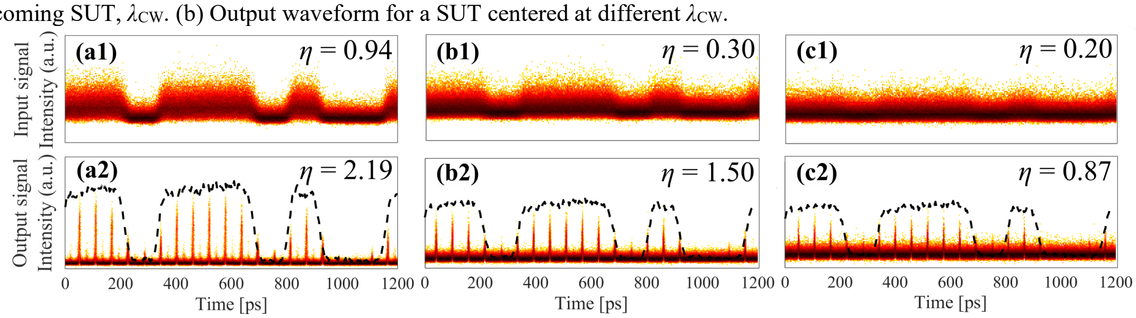

Figure 4. Amplification of 8.55 Gbps OOK signals for different OSNR; input SUT (upper plots) and sampled output (lower plots).

Finally, we demonstrate the noise mitigation capabilities of the Time-gated T-TAI (with the specifications defined above) on an 8.55 Gbps On-Off Keying (OOK) signal. To do this, the modulated signal is combined with an optically amplified BBS to create scenarios with different OSNR. The OSNR is the ratio of signal power and noise power in a bandwidth of ~570 GHz measured at the input of the HNLF. The evaluated cases are $OSNR_1 \approx 6$ dB, $OSNR_2 \approx 0$ dB and $OSNR_3 \approx -3$ dB, representing cases ranging from medium to rather pessimistic OSNR scenarios. The noisy SUT and the signal after the Time-gated T-TAI are shown in Fig. 4. It is seen how the OOK signal is passively amplified over the broadband noise, enabling to recover its envelope (here with 2 samples per bit) even when the input SUT is completely buried in noise. For each case, we compare the visibility, defined as $\eta = (\mu_1 - \mu_0)/(\sigma_1 + \sigma_0)$, with μ_0, μ_1 being the estimated mean values of the 'on' and 'off' levels in the detected signals and σ_0, σ_1 the corresponding standard deviations. As expected, we observe a significant improvement in the signal visibility after the T-TAI.

We anticipate that the proposed all-fiber scheme will enable demonstration of denoising passive amplification with input signal bandwidth × amplification factor figures exceeding the THz range.

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