Adaptive non-uniform photonic time stretch for blind RF signal detection with compressed time-bandwidth product

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Abstract: Photonic time stretch significantly extends the effective bandwidth of existing analog-to-digital convertors by slowing down the input high-speed RF signals. Non-uniform photonic time stretch further enables time bandwidth product reduction in RF signal detection by selectively stretching high-frequency features more. However, it requires the prior knowledge of spectral-temporal distribution of the input RF signal and has to reconfigure the time stretch filter for different RF input signals. Here we propose for the first time an adaptive non-uniform photonic time stretch method based on microwave photonics pre-stretching that achieves blind detection of high-speed RF signals with reduced time bandwidth product. Non-uniform photonic time stretch using both quadratic and cubic group delay response has been demonstrated and time bandwidth product compression ratios of 72% and 56% have been achieved respectively.

Keywords: Analog to digital conversion, data compression, dispersion, microwave photonics, photonic time stretch, time bandwidth product

1. Introduction

Microwave photonics [1, 2] studies interaction between microwave and optical waves and has found rich applications in imaging, instrumentation, and communications. Photonic time stretch (PTS), also known as dispersive Fourier transform (DFT) [3], which converts broadband spectrum of an ultrashort optical pulse into a time stretched waveform using chromatic dispersion, has become an emerging and enabling technique for various microwave photonics applications [4]. In particular, photonic time stretch analog-to-digital conversion (PTS-ADC) provides a promising solution to difficulties in conventional ADC systems, such as jitter effect and limited sampling bandwidth due to electronic bottleneck [5, 6]. This is made possible by using chromatic dispersion to stretch the highly-stable RF-encoded optical pulses to effectively slow down the fast RF signal before being captured by conventional ADCs [7]. Improving the jitter and speed performance being one aspect, it is also of crucial importance to limit the overall captured data volume, i.e., time bandwidth product (TBWP) of the captured signal. Despite that PTS-ADC techniques offer greatly reduced effective Nyquist sampling rate [7-10], the record time has been increased by the same factor due to the signal stretching, resulting in an unchanged TBWP.

Recently, non-uniform photonic time stretch, also known as anamorphic stretch transform (AST) [11-13], has been proposed to address this issue based on selective stretching: the information rich (high-frequency) region of the input signal is stretched more with non-linear group delay such that it can be sampled with finer resolution than the slower temporal features [14]. With a normal uniform sampling at a back-end ADC, the total volume of recorded data for a given RF signal, and hence TBWP of the ADC system, can be significantly compressed. However, AST-based methods need to have the prior knowledge of the spectral-temporal profile of the input RF signal in order to design the signal-specific AST filter [15], which is usually not feasible and practical in real-time detection of unknown high-speed RF signals. Moreover, the AST filter needs to be reconfigured for new RF signals with different instantaneous frequency profiles, making the implementation of AST filter with engineered nonlinear group delay response even more challenging. Therefore a generalized adaptive non-uniform photonic time stretch design for blind detection of arbitrary RF signals with TBWP reduction is highly desired.

In this paper, we propose, for the first time, an alternative system which can overcome this limitation thanks to the joint use of a microwave photonic phase filter for pre-chirping the input RF signal and an AST filter to non-uniformly stretch the optical pulse carrying transformed RF signal. The microwave photonic phase filter with frequency-dependent time delay separates the high frequency (information-rich) part of an unknown RF signal from its low frequency components across the entire duration of the time limited signal. A following non-uniform photonic time stretch system (the AST filter) is designed based on the spectra-temporal distribution pre-defined by the microwave photonic stretching filter. Without the needs of knowing the spectral-temporal distribution of the unknown RF signal in advance and reconfiguring the non-uniform stretch filter for different RF signals, the proposed approach enables reduction of TBWP in blind detection of time-limited RF signals using non-uniform photonic time stretch.

2. Principle

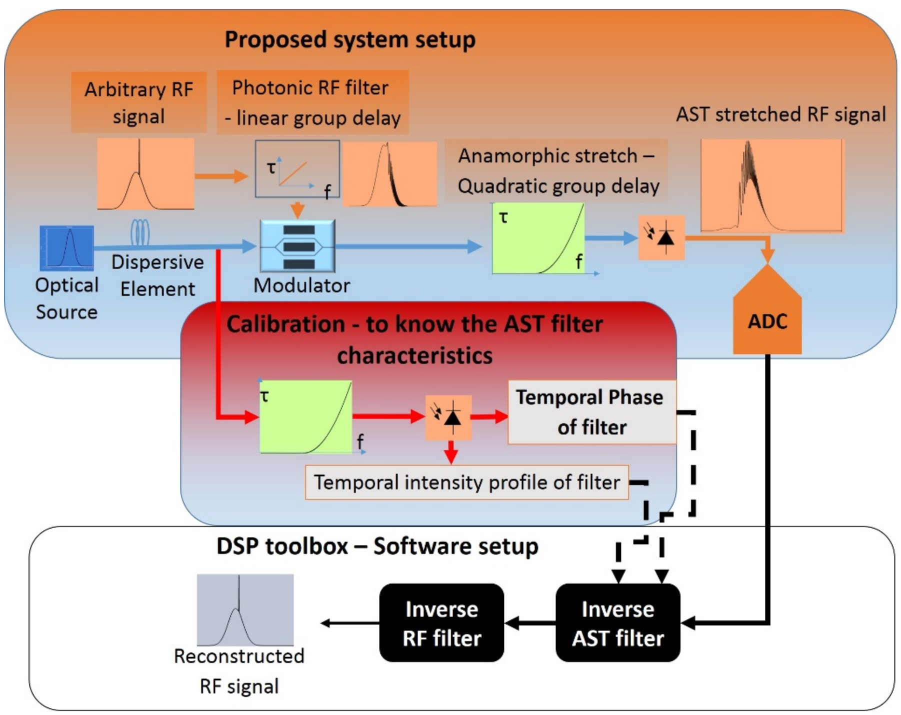

Fig. 1. Schematic diagram of the proposed adaptive non-uniform photonic time stretch system. AST: anamorphic stretch transform, ADC: analog-to-digital convertor, DSP: digital signal processing.

Schematic diagram of the proposed adaptive non-uniform photonic time stretch system for blind detection of arbitrary RF signals with compressed TBWP is shown in Fig. 1. Ultrashort optical pulses generated from a passively mode-locked laser are pre-stretched by a first dispersive element. The initially time stretched optical pulse serves as the quasi-continuous wave optical carrier. Different from previous PTS-ADC [7-10] and AST [11-15] systems, in the proposed method the input RF signal is first pre-stretched by a microwave photonic phase filter with frequency-dependent time delay response before direct modulation on the stretched optical carrier at an electro-optical modulator. Thanks to the large microwave dispersion introduced by the microwave photonic phase filter, the high frequency (information-rich) components of the unknown RF signal is separated from its low frequency elements in time, leading to a frequency-chirped RF signal with its spectral-temporal profile mainly determined by the microwave photonic phase filter. The transformed RF signal then modulates the optical carrier at the modulator.

A second dispersive element, serving as the AST filter, further stretches the modulated optical pulse to slow down the high-speed RF signal such that the high-speed RF signal can be captured using a lower-speed photodetector (PD) and electronic ADCs. To achieve the reduction of TBWP for the photonic RF signal detection system, the AST filter has a non-uniform group delay response such that particular part of the optical spectrum carrying high-frequency components (fine features) of the RF signal will be selectively stretched (slowed down) more than those carrying low-frequency RF elements. Therefore, TWBP of the detected RF signal can be greatly reduced. Design of AST filter is usually signal-dependent in previous systems [11-15]. In the proposed system, as the time frequency distribution of the modulating RF signal is uniquely determined by the microwave photonic phase filter, the AST filter can be designed based on the time delay response of the microwave photonic phase filter, which is independent on the unknown RF signals.

Finally the non-uniformly stretched optical pulse, which carries the selectively slowed RF signal is detected by a low-speed PD with a reduced TBWP. RF signal recovery is implemented in the digital domain. Signal recovery algorithm consists of two steps: inverse AST processing and inverse RF phase filtering. Note that an optical calibration process, where an un-modulated optical pulse passes through the same AST filter, is included to remove the effect of Gaussian envelope of the optical carrier, as shown in Fig. 1.

3. Results and discussions

Numerical simulations are implemented using a commercial simulation tool (VPIphotonics) to demonstrate the utility of the proposed approach in TBWP-reduced blind detection of arbitrary RF signals. In the proposed system, an input RF signal under test is firstly pre-stretched by a microwave photonic phase filter, which provides deliberately designed nonlinear phase response corresponding to a frequency-dependent time delay, or microwave dispersion. The pre-stretched RF signal then modulates an optical carrier at a Mach-Zehnder Modulator (MZM), which is biased at quadrature point to ensure linear intensity modulation. The optical carrier is obtained by stretching ultrashort optical Gaussian pulses from a 50 MHz passively mode-locked laser with full-width at half-maxim (FWHM) pulse width of 800 fs using a first dispersive element with total group velocity dispersion (GVD) of 1050 ps/nm. An optical AST filter with deliberately designed nonlinear time delay response then selectively slows down the RF-encoded optical pulse to compress the TBWP of the detected RF signal.

3.1 AST filter with quadratic time delay

As a proof-of-the-concept demonstration, a time-limited RF signal involving both high frequency features (a narrow Gaussian spike) and low frequency components (a slow Gaussian envelope with limited time duration) is used as the first original input RF signal under test, as shown in Fig. 2(a). Figure 2(c) shows the spectrogram of the input signal, from which we can see that most RF frequency components are confined within a narrow time window.

The microwave photonic phase filter is designed to provide quadratic phase response corresponding to a linear frequency-dependent group delay of 2 GHz/ns. Despite that microwave photonic filters normally provide amplitude-only variation with linear phase response or constant microwave delay [16], microwave photonic phase filters with tunable highly nonlinear phase response, hence frequency-dependent group delay response up to several GHz/ns have been reported based on nonlinear optical chromatic dispersion [17, 18] and successfully applied in chirped microwave waveform compression [19].

Enabled by microwave frequency-dependent time delay, the high frequency Gaussian spike in the original input RF signal is shifted with longer delay and stretched as per the designed chirp rate. As a result, the instantaneous frequency components of the transformed RF signal are separated in ascending order as shown in Fig. 2(b). Figure 2(d) presents the spectrogram of the RF signal after microwave photonic pre-stretching, clearly showing a frequency chirp rate of 2 GHz/ns. Therefore, significant microwave dispersion from the microwave photonic phase filter has transformed the input RF signal with unknown frequency profile to a linearly chirped microwave waveform with its spectra-temporal profile determined by the microwave photonic filter. Note that despite the increased TBWP for the transformed chirped microwave signal due to pre-stretching, overall TBWP compression will be achieved thanks to the following non-uniform optical time stretch at the designed AST filter.

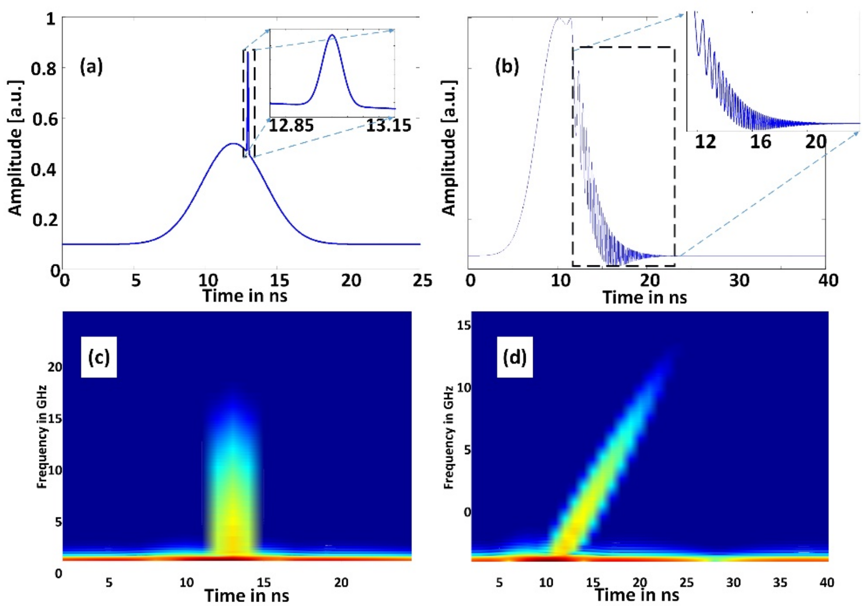

Fig. 2. Simulation results on the microwave photonic phase filtering. (a) The original input RF signal under test. (b) Stretched RF signal by the microwave photonic phase filter with a linear frequency-dependent time delay response. (c) Spectrogram of the original RF signal. (d) Spectrogram of the RF signal after microwave photonic filtering, showing a frequency chirp rate of 2 GHz/ns.

The pre-stretched RF signal then modulates an optical carrier at an MZM. The stretched optical pulse carrier also has a temporal Gaussian shape as shown in Fig. 3(a), which verifies the dispersion-induced wavelength-to-time mapping [20]. After intensity modulation at the MZM, the observed modulated optical pulse is shown in Fig. 3(b) and the corresponding optical spectrum is shown in Fig. 3(c). By comparing the spectral and temporal representations of the modulated optical pulse, a linear relationship between time and frequency is obtained as shown in Fig. 3(d). Thanks to this one-to-one mapping, we can see that the RF signal is encoded onto the optical spectrum of the pulse carrier.

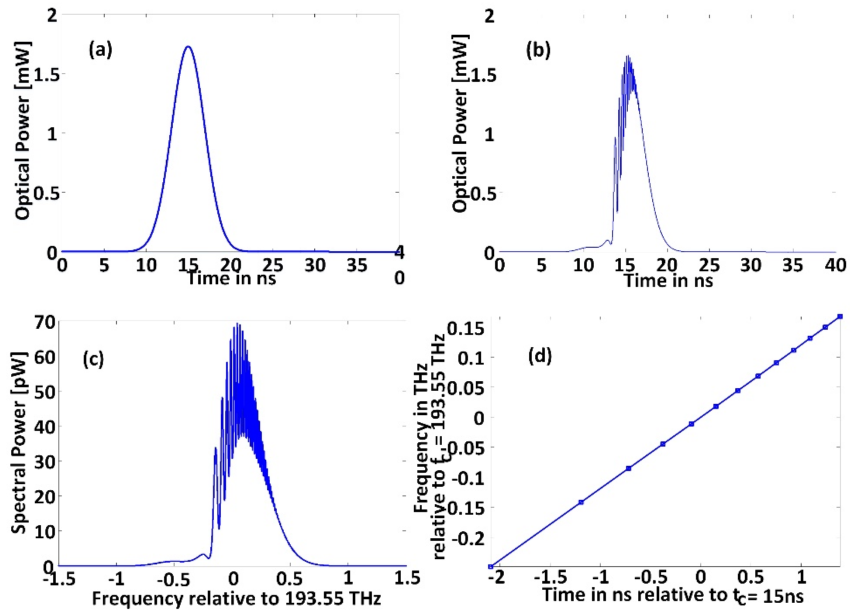

Fig. 3. (a) Time stretched optical pulse by the first dispersive element. (b) Optical pulse modulated with the pre-stretched RF signal. (c) Corresponding optical spectrum verifying that the RF signal is also encoded in to spectral domain. (d) One-to-one mapping between time and frequency according to (b) and (c).

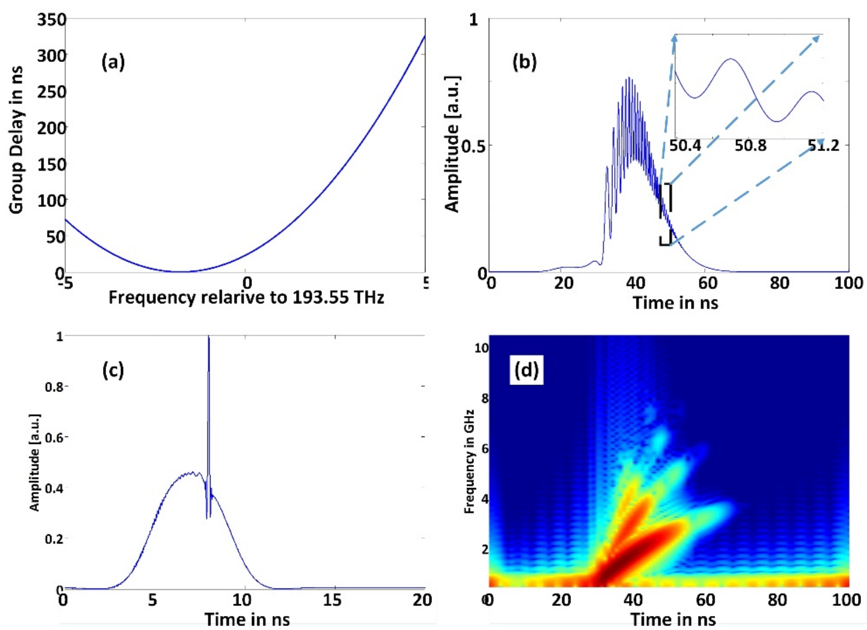

Fig. 4. (a) The time delay function of the designed AST filter with quadratic group delay. (b) Non-uniformly stretched optical pulse by the AST filter. (c) The reconstructed RF signal following the signal recovery algorithm implemented in digital domain. (d) Spectrogram of AST stretched optical pulse after photo-detection showing the non-uniform photonic time stretch.

To achieve the desired TBWP compression through non-uniform optical time stretch, an AST filter providing quadratic time delay is first designed according to the quadratic phase response of the microwave photonic filter. The group delay response of the AST filter is given by

$$\Delta\tau(f) = K_1 \times (f - f_0)^2 \tag{1}$$

where f is the instantaneous optical frequency, f_0 denotes the central optical frequency with zero time delay, and K_1 is the second-order dispersion coefficient of the AST, which can be determined by the chirp rate of the microwave photonic phase filter. The time delay characteristics of the designed AST filter is shown in Fig. 4(a). The central frequency f_0 is carefully selected such that the whole optical pulse spectrum falls in the frequency region $f > f_0$. Therefore, higher optical frequency components of the modulated optical pulse, which also carry higher RF frequency information, will experience higher chromatic dispersion and hence being stretched more than those carrying lower RF frequency. As a result, the modulated optical pulse is selectively stretched due to nonuniform dispersion in the AST filter and TBWP of the resulting signal can be greatly compressed.

Figure 4(b) shows the non-uniformly stretched optical pulse by the AST filter. The selectively stretched RF signal is detected using a high-speed PD and its spectrogram is shown in Fig. 4(d). We can clearly see that RF frequency chirp becomes nonlinear and higher frequency components have been stretched more compared to lower frequency parts. TBWP of the captured RF signal is reduced in our proposed system. Table I summaries TBWP of the original RF signal (#1) and the non-uniformly stretched signal in our proposed system. We can see that TBWP value has been reduced by 28%, corresponding to a compression ratio of 72%.

TABLE I. TBWP REDUCTION FOR TWO DIFFERENT RF SIGNALS USING AST FILTER WITH QUADRATIC TIME DELAY

Parameters	*Original RF signal #1*	*Stretched RF signal #1*	*Original RF signal #2*	*Stretched RF signal #2*
Time duration	25 ns	45 ns	25 ns	40 ns
Max frequency	15GHz	6 GHz	15GHz	7 GHz
Time-bandwidth product	375	270	375	280

Reconstruction of the original RF signal from the captured stretched RF signal is implemented in digital domain following two steps: (1) inverse AST processing, which recoveries the pre-stretched RF signal before AST stretching; (2) inverse RF phase filtering, which transforms the pre-stretched RF signal back to the original one according to the microwave photonics filter response. Note that a small portion of pre-stretched optical pulse bypasses MZM but goes through the same AST filter to allow an optical calibration process, which removes the effect of Gaussian envelope of the optical carrier. The reconstructed RF signal is shown in Fig. 4(c). Compared to the signal as shown in Fig. 2(a), a good match with the original RF signal has been clearly evidenced.

To demonstrate that the proposed approach is valid for different RF signals with unknown instantaneous frequency profile, a second RF signal #2 with high frequency information occurring at different position is selected as the original input signal, as shown in Fig. 5(a). Figure 5(b) shows the pre-stretched RF signal by the same microwave photonic phase filter with a chirp rate of 2 GHz/ns. Figures 5(c) and 5(d) present the corresponding spectrograms for the original and filtered RF signals respectively. The recovery results for the second RF signal are shown in Fig. 6. The reconstructed RF signal matches well with the original signal as shown in Fig. 5(a). Characteristics of non-uniform time stretch for the second RF signal are also summarized in Table I, and TBWP reduction by 25% has been achieved. It has been verified that the proposed method works for time-limited RF signals with different spectra-temporal profiles.

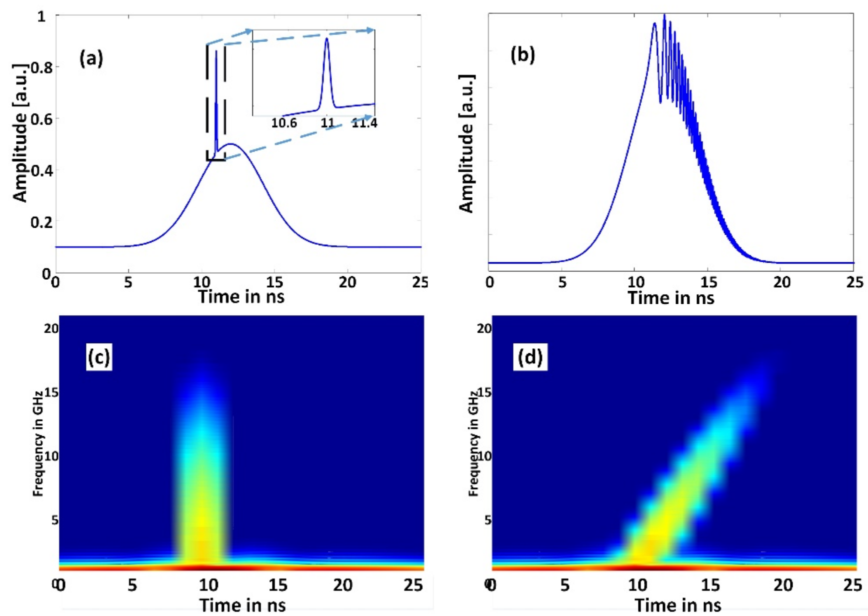

Fig. 5. (a) A second RF signal under test. (b) Pre-stretched RF signal by the same microwave photonic phase filter with linear frequency-dependent time delay response. (c) Spectrogram of the original RF signal. (d) Spectrogram of the pre-stretched RF signal by the microwave photonic phase filter.

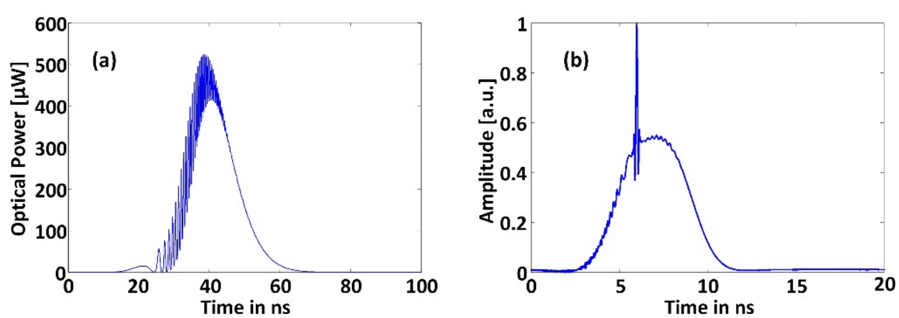

Fig. 6. (a) Modulated optical pulse carrier after non-uniform stretching at the AST filter. (b) The reconstructed RF signal after digital signal recovery.

3.2 AST filter with cubic time delay

To explore the capability of the proposed approach for better TBWP reduction in high-frequency RF signal detection, a second AST filter providing cubic time delay response has been designed. The group delay response of the AST filter is given by

$$\Delta\tau(f) = K_2 \times (f - f_0)^3 \qquad (2)$$

where K_2 is the third-order dispersion coefficient of the AST filter, which can be determined by the chirp rate of the microwave photonic phase filter. The characteristic of the designed AST filter is shown in Fig. 7(a). The central frequency is selected such that the whole pulse spectrum falls in the region $f > f_0$. The RF signal #1 as shown in Fig. 2(a) is used again as the original input signal. Figure 7(b) presents the modulated optical pulse carrying the transformed RF signal after being non-uniformly stretched by the AST filter with cubic time delay response. Its spectrogram is shown in Fig. 7(d). We can clearly see that RF frequency chirp becomes nonlinear and higher frequency components have been stretched more compared to lower frequency parts.

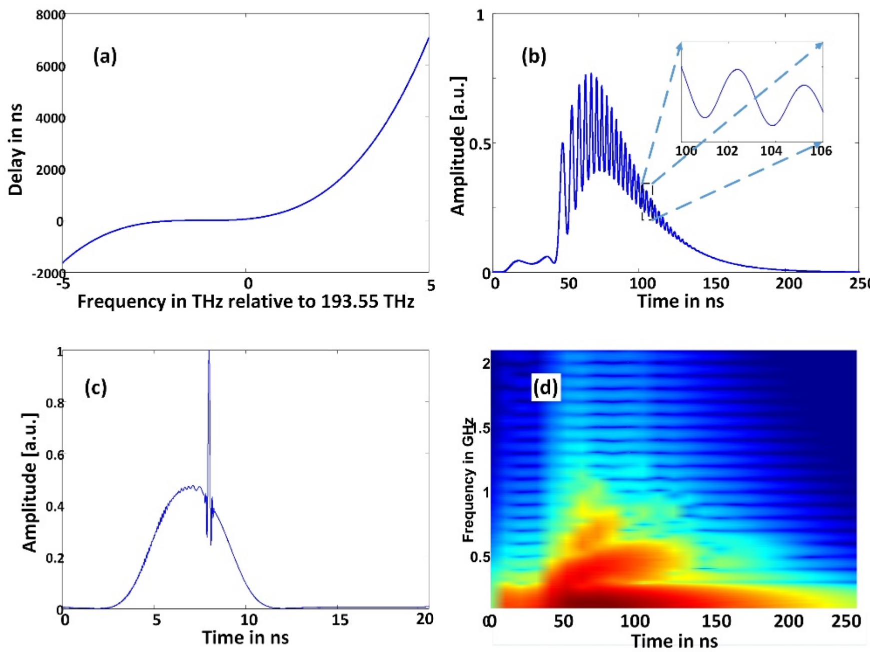

Fig. 7. (a) Time delay as a function of optical frequency in the AST filter with cubic group delay response. (b) Non-uniformly stretched optical pulse carrying RF signal by the AST filter. (c) The reconstructed RF signal following the signal recovery algorithm implemented in digital domain. (d) Spectrogram of non-uniformly stretched optical pulse confirming TBWP reduction of the captured RF signal.

Due to the large nonlinear time delay produced by the AST filter, the resulting non-uniformly stretched optical pulse has a longer time duration (140 ns). At the same time, the maximum RF frequency carried by the stretched optical pulse has been reduced to 1.5 GHz. Therefore, the overall effect is that TBWP of the captured RF signal is reduced in our proposed system thanks to the highly nonlinear time delay at the AST filter. Table II summaries the TBWP of the original RF signal and the corresponding non-uniformly stretched signal in the case of an AST filter with cubic time delay response. We can see that TBWP value has been reduced by 44%. Reconstruction of the original RF signal is implemented in digital domain following the two above-mentioned steps, with the result shown in Fig. 7(c), which matches well with the original RF signal as shown in Fig. 2(a).

TABLE II. TBWP REDUCTION FOR THE FIRST RF SIGNALS USING AN AST FILTER WITH CUBIC TIME DELAY

Parameters	*Original RF signal #1*	*Stretched RF signal #1*
Time duration	25 ns	140 ns
Max frequency	15GHz	1.5 GHz
Time-bandwidth product	375	210

The AST filter with cubic time delay is also tested with a different input RF signal #2 as shown in Fig. 5(a) to demonstrate that the proposed system is independent of the instantaneous frequency profile of the input RF signals. The same microwave photonic phase filter with a chirp rate of 2 GHz/ns is used to pre-stretch the input RF signal before modulating the optical carrier. Figure 8(a) shows the modulated optical pulse after non-uniform stretching at the AST filter. We can see that the high frequency components have been stretched further, evidenced by TBWP reduction of 44%. The recovery result for the second RF signal is shown in Fig. 8(b). It can be seen that the proposed method works for RF signals with different time-frequency distributions.

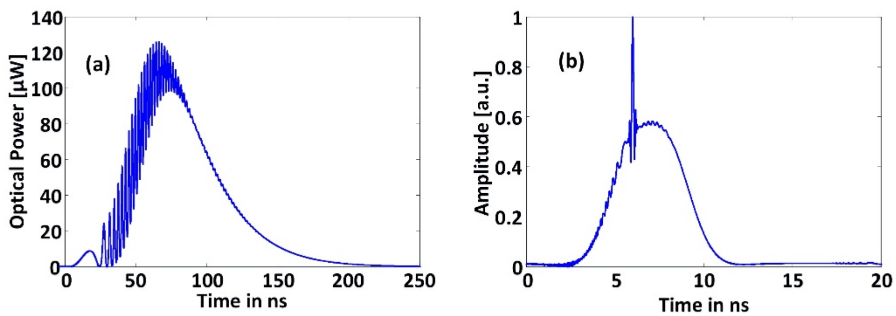

Fig. 8. (a) Modulated optical pulse after non-uniform stretching with the AST filter with cubic time delay. (b) The recovered RF signal #2 after digital signal processing.

3.3 Discussions

The utility of the proposed adaptive approach in RF signal detection with reduced TBWP has been demonstrated using numerical simulations. The most important element in the system is the microwave photonic phase filter with frequency dependent time delay, which transforms the spectra-temporal profile of the RF signal. The designed microwave photonic phase filter can be implemented based on nonlinear optical chromatic dispersion [17, 18], optical delay to microwave delay conversion [19], and non-uniformly spaced delay-line filter [21].

A second key element in the proposed system is the AST filter. Despite extensive theoretical and simulation studies on the AST approach including this work, quite little experimental study on this topic has been reported so far, mainly due to the lack of good optical filter offering an engineered group delay or dispersion profile. Potential good candidates to achieve the particularly designed AST filter include customized fibre Bragg gratings [14, 22, 23], chromo-modal dispersion mechanism [24] with the aid of mode-selective excitation [25], and photonic crystal fibre (PCF) with precisely controlled chromatic dispersion profile [26].

In the presented demonstrations, only time-limited RF signals have been tested using the proposed method. This is due to the limited time aperture of the photonic time stretch system, which is the reciprocal of the pulse repetition rate. Passively mode-locked laser has a repetition rate in the order of 10 MHz, corresponding to a time aperture of 100 ns, which would suffice for many high-frequency RF signals. Note that our proposed system can also operate in continuous time using a segmentation-interleaving structure [27]. In such a case, a multiple channel AST filter having deliberately designed group delay response for individual channels is required, which can be implemented using a spatially discrete chirped fibre Bragg grating [28].

4. Conclusion

Non-uniform photonic time stretch enables time bandwidth product (TBWP) reduction in high-speed RF signal detection by selectively stretching the RF spectrum of interest. However, prior knowledge of the spectra-temporal profile of the RF signal is always needed. In this paper, a new adaptive photonic time stretch scheme by pre-chirping the input RF signal using a microwave photonic phase shift is proposed to overcome this limitation. Using the proposed approach, blind detection of RF signals with different spectra-temporal profiles have been demonstrated. TBWP compression ratios of 72% and 56% have been achieved using non-uniform time stretch filters with quadratic and cubic time delays respectively. The proposed adaptive photonic time-stretch system works without the knowledge of the unknown RF signals, hence providing a more promising solution for real-time detection of arbitrary RF signal with reduced TBWP. The concept developed can be adapted to address data compression issues in wider fields such as high-speed communications, ultrafast measurement and massive sensor network.

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