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On the undesired frequency chirping in photonic time-stretch systems

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A B S T R A C T

The technique of photonic time stretch (PTS) has been intensively investigated in the past decade due to its potential in the acquisition of ultra-high speed signals. The frequency-related RF power fading in the PTS systems with double sideband (DSB) modulation has been well-known, which limits the maximum modulation frequency. Some solutions have been proposed to solve this problem. In this paper, we report another effect, i.e., undesired frequency chirping, which also relates to the performance degradation of PTS systems with DSB modulation, for the first time to our knowledge. Distinct from the nonlinearities caused by nonlinear modulation and square-law photodetection, which is common in radio frequency analog optical links, this frequency chirping originates from the addition of two beating signals with a relative delay after photodetection. A theoretical model for exactly describing the frequency chirping is presented, and is then verified by simulations. Discussion on the method to avoid the frequency chirping is also presented.

1. Introduction

Microwave photonics is an interdisciplinary field with an increasing research effort in the past decade, which covers the distribution, generation, processing and acquisition of microwave signals in photonic ways [1–4]. In modern radar and communication systems, high speed analog-to-digital converters (ADCs) are highly desired in order to achieve wideband signal acquisition and processing. However, the performance improvement of electronic ADCs in the past decade lags far behind the increase of bandwidth requirement in many applications. Therefore, photonics-assisted ADCs have attracted lots of research interest due to the advantages of wide bandwidth, low loss and immunity to electro-magnetic interference offered by photonics [5–8]. The technique of photonic time stretch has shown high potential to realize photonics-assisted ADC, in which the high-speed analog signal (in a time window) is slowed down in a photonic way prior to digitization with an electronic ADC [9]. In this approach, the bandwidth requirement on electronic ADCs is largely relaxed, and it is reported that the PTS-based photonic ADC has achieved an equivalent sampling rate over Tera samples per second [10].

One of the major issues that influence the performance of PTS systems is the frequency-related RF power fading, which is owing to the double sideband (DSB) modulation of the signals in the Mach–Zehnder modulator (MZM) [11]. This phenomenon is similar to the RF power fading in a millimeter-wave radio over dispersive fiber link with DSB modulation, which limits the maximum modulation frequency that can be handled by the PTS system [12]. The power fading effect can be eradicated by using single sideband (SSB) modulation instead of the DSB modulation [13] or using dual-output MZM in PTS systems [14]. The power fading effect can be removed by processing the digitization results of the two output ports. Other issues related to the PTS performance include the suppression of spurious signals caused by the nonlinear modulation in MZM [15,16], the improvement of effective number of bits of the system by using low-noise amplifier [10], and the continuous-time operation of digitization [17].

In this paper, we report another phenomenon affecting the performance of PTS systems, which is the unwanted frequency chirping in the stretched signals. Unlike the nonlinearities caused by the nonlinear modulation and square-law detection, which is common in radio frequency analog optical links [18,19], this frequency chirping is a unique effect in PTS systems. It relates to the interaction between DSB modulation and chromatic dispersion, and will appear even if ideal linear modulators are employed. To the best of our knowledge, this is the first time that this effect is proposed and discussed. Full theoretical model to explain the frequency chirping is presented, which is verified by simulation results. We also propose and then verify an idea of using SSB modulation to avoid this frequency chirping.

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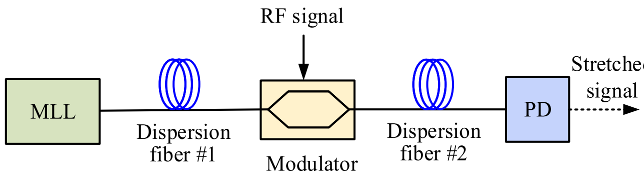

Fig. 1. Schematic illustration of a typical PTS system (MLL: mode-locked laser. PD: photodetector).

2. Principle

The schematic illustration of a typical PTS system is shown in Fig. 1. A short optical pulse from a mode-locked laser (MLL) is firstly dispersed in the time domain after propagating through a coil of dispersive fiber, which results in a broadened and chirped optical waveform. The electrical signal to be digitized is then modulated on the chirped waveform via an MZM, leading to a waveform with time-to-wavelength mapping. The modulated waveform is then further dispersed in the time domain after propagating through a second coil of dispersive fiber, leading to a time-stretched envelope of the waveform.

The short pulse generated by the MLL is assumed Gaussian-shaped expressed as $g(t) = \exp\left(-t^2/2\tau_0^2\right)$, where τ_0 is the half-width at $1/e$ maximum of the pulse. The dispersion amounts of the two coils of dispersive fibers are denoted by $\ddot{\Phi}_1$ and $\ddot{\Phi}_2$, respectively. We first consider the situation that a single-arm MZM is utilized. The modulation index is denoted by m, which relates to the amplitude of input signal and the half-wave voltage of the MZM. In order to focus on the frequency chirping phenomenon, the value of m is chosen to be sufficient small to achieve small signal approximation in the derivation. According to [20], if the input signal is a single tone sinusoidal signal with an angular frequency of Ω, the electrical field of the optical signal at the output of the second coil of fiber can be described by

$$\begin{aligned} e(t) &= \frac{\tau_0}{2\sqrt{\tau_0^2 + j\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)}} \cdot \exp\left[\frac{-t^2}{2\tau_0^2 + 2j\beta_2\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)}\right] \\ &\quad \cdot \left\{1 + \sum_{k=-\infty}^{+\infty} J_k(m)\exp\left(jk^2\Phi_d\right)\exp\left(j\frac{k\Omega t}{M}\right)\right\} \\ &\approx e_{env}(t)\cdot\left\{\left[1+jJ_0(m)\right] - J_1(m)\exp\left(j\Phi_d\right)\exp\left(j\frac{\Omega t}{M}\right)\right. \\ &\quad \left. - J_1(m)\exp\left(j\Phi_d\right)\exp\left(-j\frac{\Omega t}{M}\right)\right\} \end{aligned} \tag{1}$$

where second and higher order sidebands are ignored under small signal modulation. In Eq. (1) $e_{env}(t)$, denotes the Gaussian envelope of the output optical pulse, M is a complex value relating to the stretch factor as

$$M = \frac{1 + j\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)/\tau_0^2}{1 + j\ddot{\Phi}_2/\tau_0^2} \tag{2}$$

and Φ_d is a phase factor induced by the chromatic dispersion, which is given by

$$\Phi_d = \frac{\ddot{\Phi}_2}{2M}\Omega^2. \tag{3}$$

In the analysis of previous works [9,11,20], the imaginary part of M is ignored under the condition $\left|\ddot{\Phi}_1\right|, \left|\ddot{\Phi}_2\right| \gg \tau_0^2$. However, it is found by us that the imaginary part must be taken into consideration in order to explain exactly the phenomenon of frequency chirping. To simplify the derivation, we rewrite Eqs. (2) and (3) to be

$$\frac{1}{M} = \frac{1 + j\ddot{\Phi}_1/\tau_0^2}{1 + j\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)/\tau_0^2} \approx \frac{\ddot{\Phi}_1}{\ddot{\Phi}_1+\ddot{\Phi}_2} - j\frac{\ddot{\Phi}_2\tau_0^2}{\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)^2} = \frac{1}{S} - jI \tag{4}$$

and

$$\Phi_d = \frac{1}{2}\ddot{\Phi}_2\Omega^2 \cdot \frac{1}{M} = \frac{\ddot{\Phi}_2\Omega^2}{2S} - j\frac{I\ddot{\Phi}_2\Omega^2}{2}, \tag{5}$$

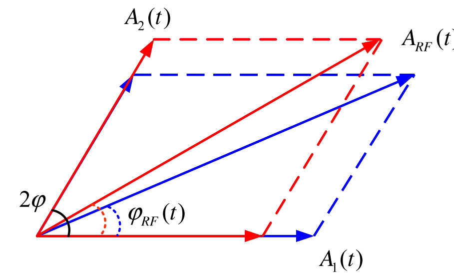

Fig. 2. Addition of two vector signals with fixed phase difference and time-variant amplitude ratio.

where $S = \left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)/\ddot{\Phi}_1$ and $I = \ddot{\Phi}_2\tau_0^2/\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)^2$. Thus, Eq. (1) can be rewritten as

$$\begin{aligned} e(t) &= \left[1+jJ_0(m)\right]e_{env}(t) - J_1(m)\,e_{env}(t) \\ &\quad \cdot \exp\left(-I\frac{\ddot{\Phi}_2\Omega^2 + 2\Omega t}{2}\right)\exp\left(j\frac{\ddot{\Phi}_2\Omega^2}{2S} + j\frac{\Omega t}{S}\right) \\ &\quad - J_1(m)\,e_{env}(t)\cdot\exp\left(-I\frac{\ddot{\Phi}_2\Omega^2 - 2\Omega t}{2}\right)\exp\left(j\frac{\ddot{\Phi}_2\Omega^2}{2S} - j\frac{\Omega t}{S}\right) \\ &= e_0(t) + e_1(t) + e_{-1}(t) \end{aligned} \tag{6}$$

in which, $e_0(t)$, $e_1(t)$ and $e_{-1}(t)$ denote the carrier, the upper sideband and the lower sideband, respectively.

The output electrical signal after O/E conversion can be viewed as the addition of the beating signals of $e_0(t)$ and $e_1(t)$, and that of $e_0(t)$ and $e_{-1}(t)$, which is given by

$$\begin{aligned} i_{RF}(t) &\propto \left[e_0(t)e_1^*(t) + e_0(t)e_{-1}^*(t)\right] + \left[e_0^*(t)e_1(t) + e_0^*(t)e_{-1}(t)\right] \\ &\propto \exp\left[\frac{-\tau_0^2}{\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)^2}\left(t + \frac{\ddot{\Phi}_2\Omega}{2}\right)^2\right]\cos\left(\frac{\Omega t}{S} + \frac{\ddot{\Phi}_2\Omega^2}{2S} + \varphi_0\right) \\ &\quad + \exp\left[\frac{-\tau_0^2}{\left(\ddot{\Phi}_1+\ddot{\Phi}_2\right)^2}\left(t - \frac{\ddot{\Phi}_2\Omega}{2}\right)^2\right]\cos\left(\frac{\Omega t}{S} - \frac{\ddot{\Phi}_2\Omega^2}{2S} - \varphi_0\right) \\ &= A_1(t)\cos\left(\frac{\Omega t}{S} + \varphi\right) + A_2(t)\cos\left(\frac{\Omega t}{S} - \varphi\right) \end{aligned} \tag{7}$$

where $\varphi_0 = \arctan\left[J_0(m)\right]$, $A_1(t)$ and $A_2(t)$ denote the Gaussian envelopes. Note that the higher order harmonics generated by photodetection are not taken into consideration in analyzing the instantaneous frequency of fundamental signal. It is found from (5) that the generated signal consists of two single tone sub-signals with Gaussian envelopes, which have a relative delay of $\ddot{\Phi}_2\Omega$ in the envelopes and a phase difference of 2φ in the RF carriers. Eq. (7) tells us that the output electrical signal is the addition of two beating signals, as expected, which is similar to the millimeter-wave radio over fiber systems with DSB modulation and dispersive link. The relative time delay results from the imaginary part of M and the phase shift is related to the real part. If the relative delay is ignored, we can derive the frequency-dependent RF power fading from Eq. (7), the same as in [12].

Here, we investigate the instantaneous frequency of the output signal based on Eq. (7). The instantaneous phase of the signal can be calculated according to the theory of vector addition. As shown in Fig. 2, since the envelope amplitude ratio $A_1(t)/A_2(t)$ varies with the time, the phase of the combined signal changes with the time accordingly even if the two signals have fixed phase difference. The time-variant instantaneous phase results in the frequency chirping effect.

The amplitude of the combined signal can be calculated according to the cosine formula for triangles, which is given by

$$A_{RF}(t) = \left[A_1^2(t) + A_2^2(t) + 2A_1(t)A_2(t)\cos(2\varphi)\right]^{1/2} \tag{8}$$

and the instantaneous phase of the combined signal is as

$$\varphi_{RF}(t) = \frac{\Omega}{S}t - \varphi \pm \arccos\left[\frac{A_{RF}^2(t) + A_1^2(t) - A_2^2(t)}{2A_{RF}(t)A_1(t)}\right] \tag{9}$$