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Relaxed dispersion requirement in the generation of chirped RF signals based on frequency-to-time mapping

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ABSTRACT

Photonic generation of chirped RF signal based on frequency-to-time mapping (FTM) is investigated in this paper. A new criterion on system parameters (dispersion amounts and pulse duration) for the generation of well-shaped linearly chirped signals is given, which is proved to be less restrictive than the currently known conditions. Therefore, requirement on the dispersion amount can be relaxed, which is highly desired in practical implementation of the FTM-based system. Theoretical results are presented, the correctness of which is verified by numerical and experimental results. The reported theory is a good guidance in designing the photonic system for the generation of chirped signals based on FTM.

1. Introduction

When an ultra-short optical pulse propagates through a dispersive medium, the output time-domain waveform is an analog to the spectrum of the input pulse. This phenomenon is known as the frequency-to-time mapping (FTM). If both the time-domain waveforms of the input and output pulses are concerned, the envelope of output pulse is proportional to a scaled Fourier transform of the input pulse envelope. Therefore, the FTM is also known as the real-time Fourier transform [1]. The theory of FTM has found many applications such as temporal pulse shaping, arbitrary waveform generation, photonic time stretch for analog-to-digital conversion, microwave frequency identification, ultra-fast photonic camera, and so on [2–11]. Among these applications, the FTM-based photonic generation of chirped RF signals is of considerable interest due to its potential for generating signals with ultra-high time-bandwidth product [9–11]. In an FTM-based photonic system for the generation of chirped signals, an input short pulse should be spectrally carved using a filter with a desired transfer function, which can be realized by a specially-designed fiber Bragg grating or a programmable spectral shaper based on a spatial light modulator (SLM). Then, based on the theory of FTM, the spectrally-shaped pulse converts to a waveform with a desired shape by passing through a medium with an amount of dispersion.

Due to the space-time duality between the spatial paraxial diffraction of light beams and the temporal dispersion of narrow-band pulses through dielectrics, a condition should be satisfied in the FTM as the far-field condition in the Fraunhofer diffraction, which was discussed in [1]. Recently, Torres-Company et al. demonstrated that a less restrictive condition, inspired by the antenna-designer's formula, could replace the far-field criterion in the FTM for arbitrary waveform generation, which largely relaxes the requirement of the minimum dispersion amount [12]. In this paper, we show that for the FTM in the generation of chirped RF signals, the requirement on the minimum dispersion amount can be further relaxed. Theoretical results as well as a new criterion are given. Numerical and experimental results are presented to verify the theoretical findings.

2. Principle

A schematic illustration of the photonic generation of chirped RF signals based on the FTM is shown in Fig. 1. A pulsed laser source is employed to provide coherent short pulses, the spectrum of which is altered by a spectral shaping device with a predetermined frequency response. The spectrally-shaped pulses are then made to pass through a dispersive medium to implement FTM. Desired electrical waveforms are obtained after the optical-to-electrical conversion.

To simplify the theoretical analysis, we assume that the input pulse is Gaussian shaped, the complex amplitude of which is expressed as $g(t)=(E_0/\sqrt{2\pi}\tau_0)\exp[-t^2/(2\tau_0^2)]$, where τ_0 is a measure of the pulse duration. The spectrum of the Gaussian pulse is $G(\omega)=E_0\exp(-\tau_0^2\omega^2/2)$. For the generation of chirped signals, the frequency response of the spectral shaper can be designed as $H_s(\omega)=\cos(a\omega+0.5b\omega^2)$, where the parameters a and b determine the center

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frequency and chirp rate of the final signals, respectively. If there is only first-order dispersion in the dispersion medium and the dispersion amount is $\ddot{\Phi}$, its frequency response can be expressed as $H_d(\omega) = \exp(-0.5j\ddot{\Phi}\omega^2)$, in which the terms denoting the phase shift and the group delay are ignored. The complex envelope of the broadened pulse to be detected is derived as

$$\begin{aligned} E(t) &= F^{-1}\{G(\omega)H_s(\omega)H_d(\omega)\} \\ &= \left(\frac{2\pi}{\tau_0^2 + j(\ddot{\Phi}-b)}\right)^{1/2} E_0 \exp\left\{-\frac{(t+a)^2}{2[\tau_0^2 + j(\ddot{\Phi}-b)]}\right\} \\ &\quad + \left(\frac{2\pi}{\tau_0^2 + j(\ddot{\Phi}+b)}\right)^{1/2} E_0 \exp\left\{-\frac{(t-a)^2}{2[\tau_0^2 + j(\ddot{\Phi}+b)]}\right\} \\ &= E_1(t) + E_2(t) \end{aligned} \tag{1}$$

where $F^{-1}\{\cdot\}$ denotes the inverse Fourier transform. It is found from Eq. (1) that the final pulse is comprised of two broadened and chirped pulses with different delay. If the dispersion amount $\ddot{\Phi}$ is sufficiently large, i.e.

$$|\ddot{\Phi}| >> |b| \quad \text{and} \quad |\ddot{\Phi}| >> \tau_0^2. \tag{2}$$

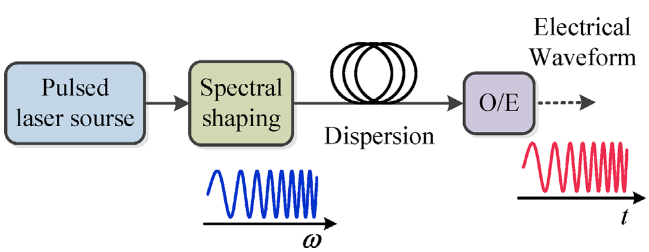

Fig. 1. Schematic illustration of the FTM-based photonic generation of chirped RF signals.

The detected chirped signal can be thought as the beating product of $E_1(t)$ and $E_2(t)$, which is derived as

$$\begin{aligned} i(t) &\propto E(t)E^*(t) \\ &= E_0^2 \exp\left[-\frac{(t+a)^2}{(\ddot{\Phi}/\tau_0)^2}\right] + E_0^2 \exp\left[-\frac{(t-a)^2}{(\ddot{\Phi}/\tau_0)^2}\right] + 2E_0^2 \exp\left[-\frac{\tau_0^2 a^2}{\ddot{\Phi}^2}\right] \\ &\quad \times \exp\left[-\frac{(t+2ab/\ddot{\Phi})^2}{(\ddot{\Phi}/\tau_0)^2}\right] \cos\left[2a\left(\frac{t}{\ddot{\Phi}}\right) + b\left(\frac{t}{\ddot{\Phi}}\right)^2 + \frac{a^2 b}{\ddot{\Phi}^2}\right] \end{aligned} \tag{3}$$

The detailed derivation of Eq. (3) is given in the Appendix. Note that in the derivation, only the condition in Eq. (2) is assumed. The third term of the product in Eq. (3)shows the chirping characteristic of the generated signal, while the first two terms in Eq. (3) denote the low-frequency components near dc. Apparently, the FTM process is achieved under the condition described in Eq. (2). To make a comparison, the result based on the far-field approximation is given as

$$\begin{aligned} i_{FF}(t) &= |G(t/\ddot{\Phi})H_s(t/\ddot{\Phi})|^2 \\ &\propto E_0^2 \exp\left[-\frac{t^2}{(\ddot{\Phi}/\tau_0)^2}\right] + E_0^2 \exp\left[-\frac{t^2}{(\ddot{\Phi}/\tau_0)^2}\right] \cos\left[2a\left(\frac{t}{\ddot{\Phi}}\right) + b\left(\frac{t}{\ddot{\Phi}}\right)^2\right] \end{aligned} \tag{4}$$

It is not difficult to find that under the condition of Eq. (2) and that $|\ddot{\Phi}|$ is larger than or on the same order of magnitude as a^2, our result in Eq. (3) can be simplified to Eq. (4).

For comparison, here we give the condition for the far-field approximation [1]

$$|\ddot{\Phi}| >> \Delta t_0^2/(2\pi) \tag{5}$$

and the condition with less restriction given in [12]

$$|\ddot{\Phi}| > \Delta t_0^2/\pi \tag{6}$$

Note in Eqs. (5) and (6), Δt_0 means the width of the spectrally-shaped pulse, which is usually much larger than τ_0. The condition

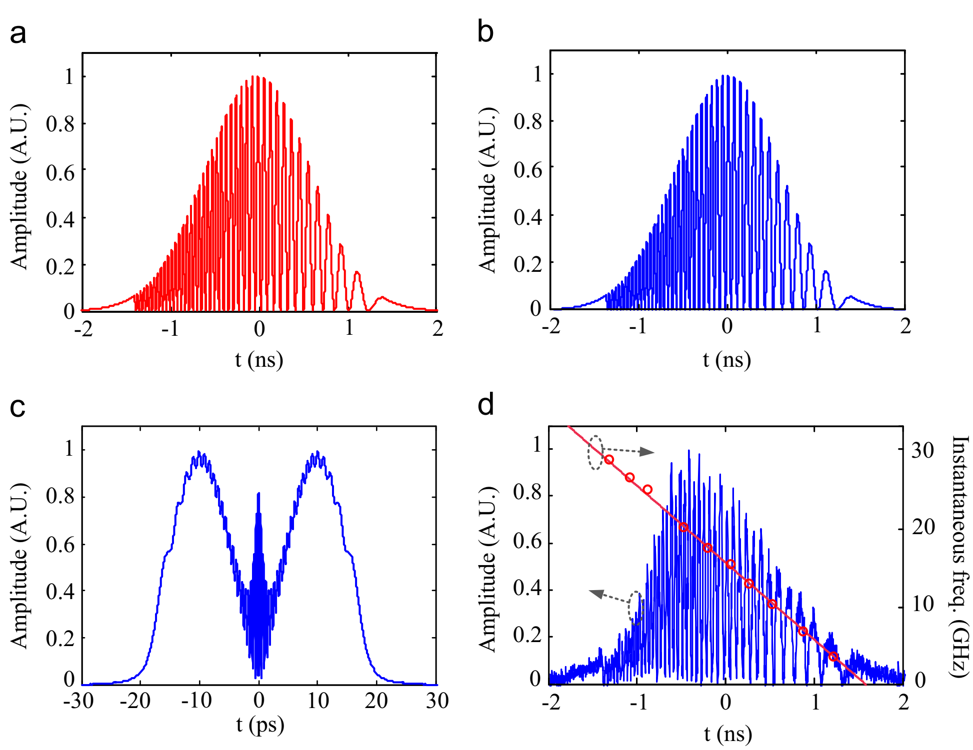

Fig. 2. Numerical and experimental results of (a) the generated waveform predicted by our theory; (b) the generated waveform obtained by simulation; (c) the spectrally-shaped pulse obtained by simulation; and (d) the measured waveform and the instantaneous frequencies calculated from the measured waveform (circles) in comparison with the theoretically predicted values (solid line).