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Microwave waveform generation with reconfigurable envelope and high fidelity based on spectrum compensated frequency-to-time mapping

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ABSTRACT

A photonic approach for generating radio frequency (RF) chirped and non-chirped waveforms with reconfigurable envelope and high fidelity is proposed and experimentally demonstrated based on frequency-to-time mapping (FTM). A space light modulator based pulse shaper is used for spectral shaping. To make full use of the available bandwidth of the pulse shaper, the output of an amplified mode-locked laser is used as a broadband optical source. A feedback scheme is proposed to compensate the absence of the amplified spontaneous emission spectrum in frequency-to-time mapping. Based on the spectrum compensated FTM, chirped and non-chirped waveforms with different envelopes and high fidelity are experimentally generated.

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1. Introduction

Arbitrary waveforms generation (AWG) has attracted much attention in many fields, such as radar wireless communication, high-speed mobile communication and high-resolution remote sensing [1–3]. Compared with the electronic AWG methods, optical approaches for AWG have advantages of high frequency, wide bandwidth and high resistance to electromagnetic interference [4,5]. Up to now, many photonic methods have been put forward for arbitrary waveforms generation, including direct space-to-time (DST) mapping, spectral shaping and wavelength-to-time mapping, temporal pulse shaping, delay-line based filter and so on [4]. Among these schemes, more attention has been paid on the method of spectral shaping and frequency-to-time mapping (FTM) due to its high flexibility [5]. FTM is a phenomenon that once sufficient dispersion has been introduced onto ultra-short optical pulses propagating in dispersive medium, the temporal profiles of the pulses become a scaled replica of the optical spectrum [6]. Besides radio-frequency AWG (RF-AWG), FTM has also been applied in the waveform measurement [7] and ultrafast imaging [8]. To achieve FTM, a dispersion medium is required to introduce sufficient dispersion. According to the far-field condition, the minimum dispersion amount is too ambiguous to satisfy in a precise situation, which also limits the generation of complex pulses [5,6]. In order to relax the dispersion requirements, "antenna condition" [6] and near-field FTM [5] have been demonstrated. In addition, for chirped microwave signal, a more relaxed requirement only related to the chirp rate is proposed [9], and it lowers the required dispersion by an order-of-magnitude for most kinds of chirped waveforms. All these dispersion conditions guide the direction of FTM-based arbitrary waveforms generation.

On the other hand, spectral shaping is also a key stage in the FTM-based AWG system. To achieve RF-AWG, two commonly used pulse shapers are space light modulator (SLM) [10] and all-fiber filter (e.g. fiber Bragg grating, FBG) [11,12], respectively. For FBG-based shaper, the central frequency and chirp coefficient of the desired waveform are tunable through adjusting the second-order and third-order dispersion values, but the profile deteriorates as the frequency is increased [13]. Using Spatially Discrete Chirped fiber Bragg grating (SD-CFBG) can generate linear, nonlinear and step chirping waveforms, but it also leads to undesired spectral response and envelopes [14]. With regard to the SLM, the time-bandwidth product (TBWP) of the generated waveform is limited by the resolution and available optical bandwidth of the shaper [15]. So, if the bandwidth of a SLM is fully used, the TBWP can be increased.

Up to now, many FTM results about AWG have focused on the generation of simple pulses, such as parabolic pulses [16], triangular pulses [17] and ultra-wideband pulses [12,18]. On the other hand, to make full use of the available bandwidth of a SLM-based shaper, a broadband optical source is required and it can be achieved by amplifying the output of a mode-locked laser with an erbium-doped fiber amplifier (EDFA) [19]. However, the

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amplified spontaneous emission (ASE) noise of the EDFA at short wavelength does not contribute to the FTM [20], which will result in the distortion of generated waveform in this situation. For this reason, only long wavelength portion about 20 nm in a supercontinuum (SC) spectrum can be applied for FTM [20].

In this paper, we propose a scheme of spectrum compensated FTM. By performing a feedback spectral shaping with compensation for the distortion resulted from ASE noise in the FTM system, chirped and non-chirped waveforms with different envelopes are experimentally demonstrated, and all the generated waveforms are with a fidelity higher than 98%. Here, the fidelity represents the similarity between the generated pulses and the target waveforms. Our work differs from those in [20] for with our scheme the effects of ASE noise in a SC source is cancelled and the 40 nm bandwidth of a SLM-based pulse shaper is fully used. In this way, more complex waveforms with a lager time duration are generated.

2. Principle

Our proposed scheme is shown in Fig.1. The output of a mode-locked (ML) laser is amplified by the EDFA and used as broadband optical source. The spectrum is shaped according to the desired waveform with a SLM-based pulse shaper, and an optical fiber is used to perform frequency-to-time mapping conversion. Theoretically, an optical signal after propagating through a second-order dispersive medium can be described as [21]

$$y(t) \propto \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right)\int_{-\infty}^{+\infty} x(t')\exp\left(j\frac{t'^2}{2\ddot{\Phi}}\right)\exp\left(-j\frac{1}{\ddot{\Phi}}tt'\right)dt' \quad (1)$$

where $\ddot{\Phi}$ is the second-order dispersion, $x(t)$ and $y(t)$ are input and output optical signal, respectively. The desired FTM occurs when the quadratic phase factor inside the integrand of Eq. (1) is ignored with a sufficient large $\ddot{\Phi}$. In this case, Eq. (1) can be simplified as

$$y(t) \propto \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right)\left\{F[x(t)]|_{\omega=t/\ddot{\Phi}}\right\} \quad (2)$$

where F[ ] represents the Fourier transform. Eq. (2) clearly reveals that the output temporal intensity profile is an analogy to the shaped spectrum. As a result, a proper criterion consists of satisfying

$$|\ddot{\Phi}| \gg \frac{\tau^2}{2\pi} \quad (3)$$

where τ denotes the duration of the input optical signal. By using this phenomenon, waveforms with different envelopes can be generated by shaping the input spectrum followed by propagation through a dispersive medium satisfying condition in Eq. (3). In our study, the chirped waveforms with different envelopes are generated, and the shaped spectrum can be written as

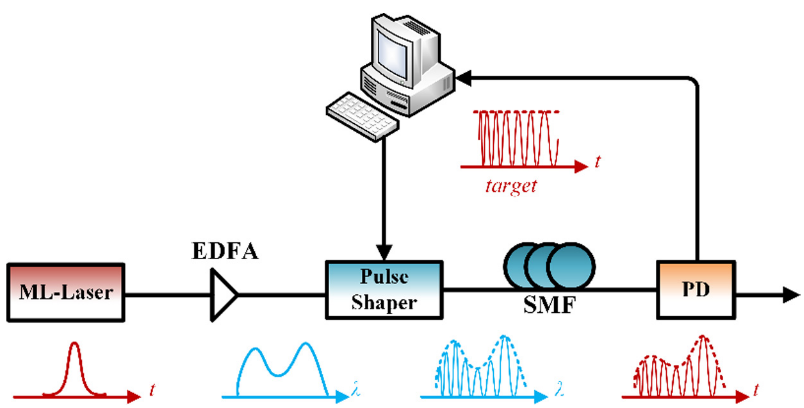

Fig. 1. Diagram of spectrum compensated frequency-to-time mapping.

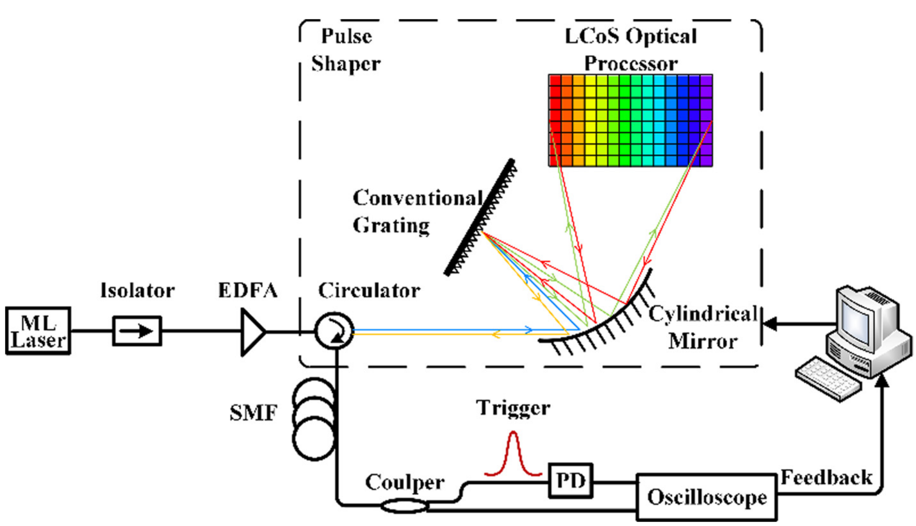

Fig. 2. Experiment setup of waveform generation based on FTM with spectrum compensation.

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