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Time and wavelength interleaved pulse trains generation based on pure phase processing of optical spectral comb

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ABSTRACT

By applying linear phase to optical spectral comb, we experimentally demonstrate that the time interval of the compressed pulse trains with different wavelength can be precisely controlled for the generation of time and wavelength interleaved pulse train. The time and wavelength interleaved pulse train with the repetition rate of 40 GHz and 80 GHz are generated based on this and the possibility to improve the performance of the generated pulse train is also discussed. We also measure the precision of time delay obtained by applying linear phase to the comb.

1. Introduction

Optically sampled analog to digital conversion (ADC) has attracted great interest due to the ability to overcome the bottleneck of electrical jitter [1]. One of the key parts for optically-sampled ADC is the generation of the optical sampling pulse with high repetition rate. One way to increase the repetition rate is based on optical time division multiplexing (OTDM) in which multiple replicas of the optical pulse with precisely controlled time delay are combined to form sampling pulse with increased repetition rate [2]. Another way based on wavelength division multiplexing (WDM) to multiply the repetition rate, where the generated sampling pulse is time and wavelength interleaved with equal pulse interval, shows significant promise for further applications due to the ability of reducing the bandwidth requirements of photodetectors and electronic ADCs by demultiplexing the optically sampled pulse train into multiple channels for parallel processing [3–4].

There are several schemes to generate the time and wavelength interleaved pulse train. Generation of time and wavelength interleaved pulse train by using multiple mode locked lasers with different wavelengths has been demonstrated [5] and it is very complex and expensive especially for high repetition rate since more mode locked lasers are needed. The scheme based on slicing the optical spectrum of a mode locked laser to generate time and wavelength interleaved pulse train has also been experimentally demonstrated [6–8]. However, as the repetition rate of the mode locked laser is low, the spectrum needs to be sliced into more channels in order to increase the repetition rate of the generated time and wavelength interleaved pulse train, which needs broadband spectrum mode locked laser or supercontinuum source. Another popular method for generating time and wavelength interleaved pulse train, using chromatic dispersion to compress and temporally equally separate different wavelength pulses, has also been proposed and shown various applications [9–16]. Although the method shows great flexibility as the repetition rate is tunable, it also has shortcomings that influence the performance of the generated pulse train. The pulse compression and temporally equal pulse separation are realized by dispersion effect simultaneously, so the pulse may not be compress short enough as the dispersion value is firstly determined by the repetition rate of the pulse train.

In all the schemes referred above, the time delay between different wavelength pulse trains is realized by time delay line or dispersion effect, which cannot ensure precise pulse interval between different wavelength pulse trains as the precision of time delay line is limited and the dispersion varies for different wavelength. This influences the performance of the finally generated time and wavelength interleaved pulse train and its further applications.

In this letter, by applying linear phase shift to the optical spectral combs after quadratic phase compensation for pulse compression, equal time interval of the compressed pulse trains with different wavelength can be precisely controlled. In our experiment, different wavelength pulse trains are equally separated by adding certain linear phase shift to corresponding optical spectral combs without restricting the pulse compression, which improves the quality of the generated pulse train. Experimentally,

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the time and wavelength interleaved pulse train with repetition rate of 40 GHz and 80 GHz are generated, respectively.

2. Operation principle

The schematic diagram of our method to generate time and wavelength interleaved pulse train is illustrated in Fig. 1. The N optical spectral combs shown in Fig. 1(a) are firstly generated from N CW lasers at different wavelengths using cascaded phase modulator and intensity modulator driven by microwave signal with the period T [17]. According to the derivation of phase modulation shown in [14], the imposed temporal phase can be approximated to as

$$\phi(t) = \pi \frac{V}{2V_\pi} \cos\left(\frac{2\pi t}{T}\right) \approx -\frac{\pi^3 V}{T^2 V_\pi} t^2 \tag{1}$$

where V is the peak-to-peak voltage of the driven microwave signal, V_π is the half-wave voltage of the phase modulator. The quadratic phase in frequency domain corresponds to $\phi(t)$ can then be expressed as

$$\Phi(\omega) \approx \frac{T^2 V_\pi}{4\pi^3 V} \omega^2 \tag{2}$$

which means the pulse is linearly chirped and hence can be compressed in time domain [17]. So, quadratic phases shown in Fig. 1(b) are then applied to the combs to compensate the linear chirp and compress the temporally sinusoidal waveform to be Gaussian-like pulses. As shown in Fig. 1(c), the compressed pulses with repetition rate of $f_R = 1/T$ are made up of different wavelength pulses that are center aligned in time domain. In order to temporally separate these synchronous different wavelength pulses, extra phases must be applied to the combs. According to the character of Fourier transform

$$f(t-\Delta t) \Leftrightarrow F(\omega)\exp(j \times \omega \times \Delta t) \tag{3}$$

certain time delay Δt corresponds to certain phase shift $\omega \times \Delta t$ varying linearly with frequency. This linear mapping enables the time interval of different wavelength pulse trains can be controlled very precisely which will significantly enhance the quality of the generated time and wavelength interleaved pulse train. Therefore, linear phases shown in Fig. 1(d) are then added to the combs, and the pulse trains are equally separated in time domain. The slopes of these linear phases equal to different time delay with increment of T/N between each pulse train. Finally, the time and wavelength interleaved pulse train is generated with different wavelength pulses repeating periodically and the repetition rate is increased to N/T, as shown in Fig. 1(e).

3. Experiment and results

The pulse train with repetition rate of 40 GHz is firstly demonstrated according to the experimental setup shown in Fig. 2. Four CW lasers, with wavelength of $\lambda_1 = 1547.72$ nm, $\lambda_2 = 1554.92$ nm, $\lambda_3 = 1550.12$ nm, $\lambda_4 = 1552.52$ nm, are multiplexed with their polarization maintained. The multiplexed multi-wavelength CW light is then temporally carved by an intensity modulator, which is biased at the quadrature point and driven by a 10 GHz sinusoid signal generated by the microwave source producing pulses with nearly 50% duty cycle. The carved pulses are then phase modulated by a phase modulator with V_π of 5.6 V and the driven sinusoid signal is amplified to be about 30 dBm, leading to four combs with approximate quadratic phase. The phases applied to the generated combs by the programmable optical waveshaper (Finisar Waveshaper 1000S with an approximate frequency resolution of 4.5 GHz) are calculated according to

$$\varphi = \bmod\left(\frac{1}{2}\beta \times \omega^2 + \omega \times \Delta t,\ 2\pi\right) \tag{4}$$

which consists of two parts: quadratic phase for pulse compression; and linear phase with certain slope Δt, for time delay. In Eq. (4), ω is the frequency offset relative to the center frequency of CW laser. $\beta = -T^2 V_\pi / 2\pi^3 V \approx -50 ps^2$ according to Eq. (2) for quadratic compensation, which corresponds to a chromatic dispersion of about 40 ps/nm. As the phase value applied by the waveshaper is limited between 0 and 2π, it is necessary to recalculate the phases as original phase mod 2π. When the four combs are passed through the programmable optical waveshaper, the prior calculated phases are applied to the corresponding combs. Finally, pulse compression and temporal equal pulse separation are implemented.

With four CW lasers working simultaneously, four spectrum combs with 13 lines in the 3 dB bandwidth are generated as shown in Fig. 3a(1)–a(4) which are measured by the optical spectrum analyzer (Advantest Q8384). The four combs show almost the same optical signal-noise-ratio (OSNR) of about 30 dB of the optical sampling pulse trains. The 10 GHz frequency space between adjacent lines of the comb is larger than the resolution of the waveshaper, so the phase and intensity of the combs can be adjusted line by line very precisely [18]. When calculating the

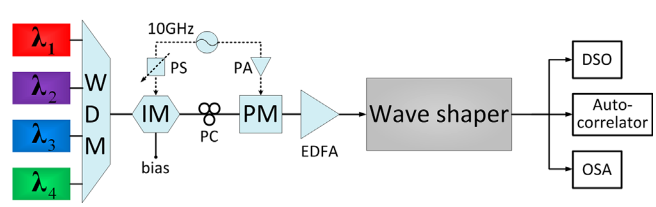

Fig. 2. Experimental setup for generation of time and wavelength interleaved pulse train. IM, intensity modulator; PM, phase modulator; PA, power amplifier; PS, phase shifer; PC, polarization controller; EDFA, erbium-doped fiber amplifier; DSO, digital sampling oscilloscope; OSA, optical spectrum analyzer.

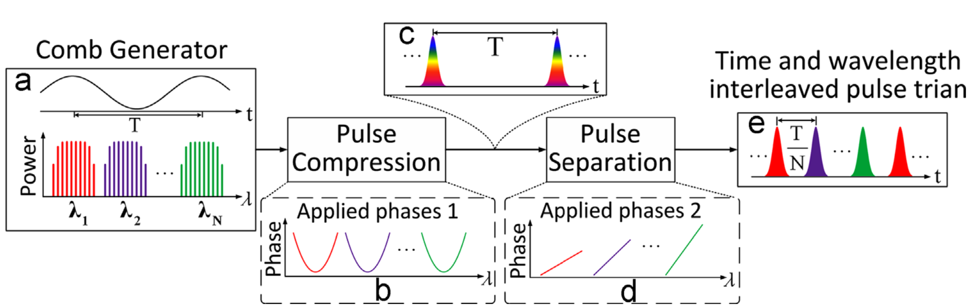

Fig. 1. Schematic diagram of our method to generate time and wavelength interleaved pulse train.