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Time- and wavelength-interleaved optical pulse train generation based on dispersion spreading and sectional compression

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A method to generate time- and wavelength-interleaved optical pulse trains based on dispersion spreading and sectional compression is proposed and demonstrated. A 4×2 GHz time- and wavelength-interleaved pulse train is generated from an input 2 GHz mode-locked pulse train. The advantages of the proposed scheme are its simplicity and robustness, since no microwave component or multiwavelength laser source is required. In addition, we demonstrate supercontinuum generation of an ultraflat 18 nm bandwidth spectrum with less than 0.5 dB fluctuation over the 3.2 nm central bandwidth. © 2012 Optical Society of America

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Sampling of analog electronic signals using a high speed optical pulse train has shown great promise for ultrahigh speed signal processing [1,2]. The challenge is to split the high speed optical pulse train into multiple channels for parallel processing at lower speed. A conventional method is to use a switch to demultiplex the pulse train in the time domain [3]. However, this method is limited by the response speed of the switch and involves complex timing signals to control the switch. A much simpler and more efficient method to deliver the pulse train to multiple channels is wavelength demultiplexing (WDM), which requires only passive optical components [4]. The pulse train used in this demultiplexing technique must consist of pulses with different wavelengths. Therefore, much effort has been made to generate time- and wavelength-interleaved pulse trains (TWIPTs) [5–7]. However, the requirement for high frequency microwave components and multiwavelength laser sources in those methods limits the pulse performance and makes the system more complex. Temporal offsetting and then combining N pulse trains at different wavelengths was also proposed to generate time- and wavelength-interleaved pulse trains [4]. The N pulse trains can be obtained either by using N mode-locked lasers operating at different wavelengths or by slicing from a common multiwavelength pulse train using drop-filters. The challenge of this method is to ensure the proper time offset (delay) of the N pulse trains before combination to make the pulses evenly spaced.

In this paper, we present a simple method to generate time- and wavelength-interleaved pulse trains by dispersion spreading and sectional compressing a mode-locked laser source. In this scheme, a single-channel dispersion module (SCDM) is used to disperse a wideband optical pulse to a chirped and spread pulse. The chirped pulse is then compressed by a commercial off the shelf (COTS) multichannel dispersion module (MCDM) to form multiple pulses with different wavelengths. No microwave component or multiwavelength laser source is required. Moreover, the output pulse repetition rate is also increased by N times from the input pulse repetition rate.

Figure 1 shows a schematic of a time- and wavelength-interleaved pulse train generator which produces a temporally repetitive sequence of optical pulses, wherein the optical pulses in each sequence have wavelengths different from one to another. The setup consists of an optical pulse generator, an optical supercontinuum (SC) generator, an optical bandpass filter, a SCDM, and a multichannel dispersion module.

The single-wavelength narrow-band optical pulse train with repetition rate of $f_R = 1/T$ from the optical generator is first spectrally broadened by being passed through the optical SC generator. The optical bandpass filter is used to limit the signal spectrum to the bandwidth of interest from λ_L to λ_H .

The output signal from the optical bandpass filter is then dispersed in the SCDM. The SCDM has a group delay characteristic, as plotted in Fig. 2. Given the input pulse bandwidth of $\Delta\lambda = \lambda_H - \lambda_L$ and the SCDM's dispersion of $T/\Delta\lambda$, the output pulses are broadened by T . Moreover, the pulses become chirped over a time period of T with wavelength increasing from λ_L at the leading edge to λ_H at the trailing edge.

The output pulse train is then passed through the MCDM, which has a group delay characteristic shown in Fig. 3. The MCDM has a group delay characteristic repeated from channel to channel. There are N channels,

Fig. 1. Setup of a system to generate time- and wavelength-interleaved pulse train.

Fig. 2. Group delay of the single-channel dispersion module.

λ_1 to λ_N , evenly spaced within the bandwidth $\Delta\lambda$ from λ_L to λ_H with a channel spacing of $\Delta\lambda/N$. Within one channel, the MCDM has a negative group delay dispersion of $-T/\Delta\lambda$, which exactly compensates for the dispersion imparted by the SCDM. The chirped pulses, which are output from the SCDM, are thus locally compressed within each channel when passing through the MCDM. Each input pulse of the MCDM is thus segmented and compressed to form a sequence of N evenly spaced pulses at N different wavelengths. Therefore, the output pulse train of the MCDM is a time- and wavelength-interleaved pulse train with a repetition rate N times faster than that of the original pulse train.

Figure 4 presents the experimental setup for generation of a time- and wavelength-interleaved pulse train. A homemade actively mode-locked fiber laser that generates a pulse train at 1550 nm with a repetition rate of 2 GHz was employed as the pulse source. The full width at half maximum of the pulse is 14 ps and the pulse bandwidth is 0.32 nm. The spectrum of the pulse train was first broadened through an SC generation process. The SC generator consisted of a high power erbium doped fiber amplifier (EDFA), an optical isolator, and a spool of highly nonlinear fiber (HNLF). The isolator was used to protect the EDFA from damage caused by any back-reflection from downstream components. Since the pulse amplitude of each wavelength in the TWIPT depends on its spectrum distribution, a flat output spectrum from the SC is desired. SC generation in an abnormal dispersion medium with soliton effect generates a wide spectrum, but the spectrum has large fluctuation due to soliton fission. In this experiment, we managed to generate a flat spectrum through the interplay between the linear frequency chirp induced by self-phase modulation and the normal dispersion. The HNLF had a nonlinearity parameter of $11.5 \text{ W}^{-1} \text{ km}^{-1}$ and dispersion of -1 ps/nm/km . Figure 5 shows spectra of the pulses at the input and output of the SC module. An 18 nm 1 dB bandwidth flat spectrum with a fluctuation of less than 0.5 dB over 3.2 nm at the center of the spectrum has been achieved.

The output pulse train was then filtered by a band-pass filter with a 3.2 nm bandwidth from 1548.11 to

Fig. 3. Group delay of the multichannel dispersion module.

Fig. 4. Experimental setup to generate time- and wavelength-interleaved pulse train.

1551.31 nm. A spool of 9.19 km of single mode fiber, which gives a dispersion of 156 ps/nm, was used as the SCDM. The dispersed pulses from the SCDM became linearly chirped with a pulse width of 500 ps. These pulses were then passed through an MCDM. The MCDM is a COTS tunable multichannel dispersion compensation module consisting of two superimposed fiber Bragg gratings connected to an optical circulator. The MCDM has a channel spacing of 100 GHz or 0.8 nm. There are four channels equally spaced within the 3.2 nm from 1548.11 to 1551.31 nm. The channel dispersion of the MCDM is -156 ps/nm , which is exactly opposite to that of the SCDM. The MCDM hence segmented and compressed the input dispersed pulse to four equally temporally spaced pulses with central wavelengths increasing from 1548.51 to 1550.91 nm. This led to a time- and wavelength-interleaved pulse train with a repetition rate that was four times higher than that of the input 2 GHz pulse train, as shown in Fig. 6. The slight difference in the pulse amplitude is due to the fluctuation in the optical spectrum. The pulses of the four channels have the same pulsewidth and bandwidth, which is about 9.5 ps and 0.52 nm, respectively.

The number of interleaved wavelengths and thus the output pulse repetition rate can be increased by using a wider bandwidth filter. By using a 16 nm bandwidth filter, which covers 20 channels, and adjusting the dispersion of the SCDM and MCDM to 31.2 ps/nm and -31.2 ps/nm , respectively, we can obtain a 40 GHz pulse train with 20 wavelengths interleaving.

It is noticed that the setup can be made simpler by removing the SC generator if the input pulse's spectrum is wide enough, for example if a passively mode-locked laser with bandwidth of 20 nm is used [8]. Instead of single mode fiber, the SCDM can also be implemented by using a fiber Bragg grating connected to an optical circulator or

Fig. 5. (Color online) Optical spectra of the pulses at the input and output of the SC generator; the optical spectrum analyzer's resolution is 0.02 nm.

Fig. 6. Oscilloscope traces of the 2 GHz input pulse train (a) and the generated time- and wavelength-interleaved 8 GHz pulse train (b).

by using other dispersion fibers, including photonic crystal fiber (PCF), dispersion crystal fiber (DCF), or high order mode fiber [9]. Furthermore, the MCDM can also be implemented using other techniques such as virtual imaged phase array, ring resonator, Gires-Tournois etalon [10,11].

In summary, by dispersion spreading a wideband optical pulse train and then sectional compressing it with a multichannel dispersion, we have generated a time- and wavelength-interleaved optical pulse train whose repetition rate is four times that of the input pulse train. Besides that, we also demonstrated the generation of an ultraflat SC with over 18 nm bandwidth with less than 0.5 dB fluctuation within the central 3.2 nm spectrum.

The advantages of this scheme are its simplicity and robustness, because no microwave component or multi-wavelength laser source is required. Only COTS devices are needed. Simplicity and the maturity of the COTS devices make the pulse generator more robust and suitable for applications requiring stability. The generated time- and wavelength-interleaved pulse train is very useful for high speed photonic analogue-to-digital conversion

(ADC) and optical signal processing since demultiplexing high speed pulse train into multi low speed channels is made simple with only a WDM demux.

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