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40-Gbps time- and wavelength-interleaved pulse-train generation in wavelength-demultiplexing analog-to-digital conversion

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Abstract. A method for generation of a time- and wavelength-interleaved pulse train is demonstrated, that can be used to attain a multiwavelength pulse train with a 40-Gbps or a potentially even higher repetition rate. This method is highly flexible because the repetition rate, the intensity, and pulse width of each wavelength and the time interval between adjacent wavelengths can be readily and independently adjusted. A time- and wavelength-interleaved pulse train with a repetition rate of 40-Gbps is experimentally demonstrated. Potential of generating a multiwavelength pulse train with a 100-Gbps repetition rate is also discussed.
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Subject terms: analog-to-digital conversion; pulse train generation; chirp compression; wavelength demultiplexing.

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1 Introduction

Photonic analog-to-digital conversion (ADC) has attracted many research interests during the last several decades[1–6] due to the merits of high repetition rate and low time jitter of optical pulse sources. Among all these ADCs, wavelength demultiplexing analog-to-digital conversion (WDM-ADC) is a promising technique, that can fully take advantages of the ultra high repetition rate of the optical pulse sources and the mature high-resolution electrical ADCs.[4,5] In WDM-ADC, time and wavelength-interleaved pulse-train (TWIPT) generation is one of the key technologies. Apart from WDM-ADC, TWIPT generation is also widely used among many of other high-speed applications, such as photonic arbitrary waveform generation,[7] optical clock division,[8] optical time division multiplexing (OTDM) systems,[9] multiwavelength regeneration, reshaping and retiming,[10] etc. Up to now, most of the TWIPTs employed in these applications are generated by mode-locked lasers,[8,11–14] which have the merits of ultralow jitter and very high stability. However, the intensity equalization and time-interval equalization between all wavelengths are difficult to achieve and maintain in multiwavelength mode-locked lasers, partly because all the wavelengths use the same gain media [typically, erbium-doped fiber amplifier (EDFA) or semiconductor optical amplifier (SOA)] and interact with each other in a complicated way. Much great research has been done, that has improved the stability and reliability performance of multiwavelength mode-locked fiber lasers.[13,14] However, many problems have yet to be solved before a multiwavelength fiber ring laser can operate reasonably stable and reliable in a practical system.

In order to address this problem, in this paper, a highly flexible TWIPT generation method is proposed and demonstrated in which most of its parameters (including pulse width and repetition rate) can be easily tuned. The setup of this method is illustrated in Fig. 1. This method is based on chirp compression[15] and high-speed optical switching technology.

2 Principle of Operation

As shown in Fig. 1, N CW-lasers with different wavelengths are multiplexed, intensity modulated (by EOM-1), and phase modulated (by EOPM), generating a chirped pulse train with a repetition rate of 10 Gbps. Then, this pulse train goes through another intensity modulator (EOM-2) where a 16-bit-long, 10-Gbps electrical pattern signal (the duration of one pattern pulse is $\sim$100 ps) is applied. The ODL is used to adjust the relative position of the 10-Gbps optical pulse train and the "switching window" created by the electrical pattern signal. When the 10-Gbps pulse train goes through the EOM-2, only those optical pulses that correspond to time slots where there is a pattern "1" pass through EOM-2 with minimal insertion loss and other pulses are eliminated. Therefore, the 10-Gbps pattern generator and the EOM-2 can be viewed as a high-speed optical switch that is used to select certain pulses in the original 10-Gbps pulse train.

There are four variables in this method: the number of CW lasers N, the microwave power fed into the EOPM, the dispersion d, and the 10-Gbps pattern signal. For equally spaced TWIPT applications, three parameters can be readily and independently adjusted: the per-wavelength repetition rate, the total repetition rate, and the pulse width.

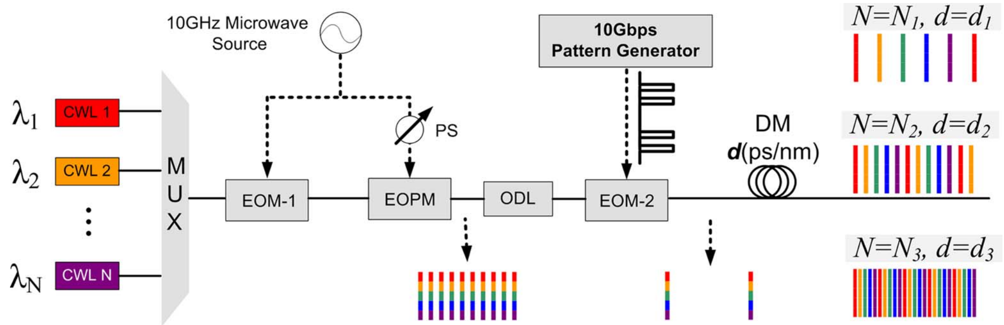

Fig. 1 Setup of the proposed TWIPT generation method (CWL: continuous wave laser; MUX: multiplexer; PS: microwave phase-shifter; EOM: electro-optic modulator; EOPM: electro-optic phase modulator; ODL: optical delay line; DM: dispersion module).

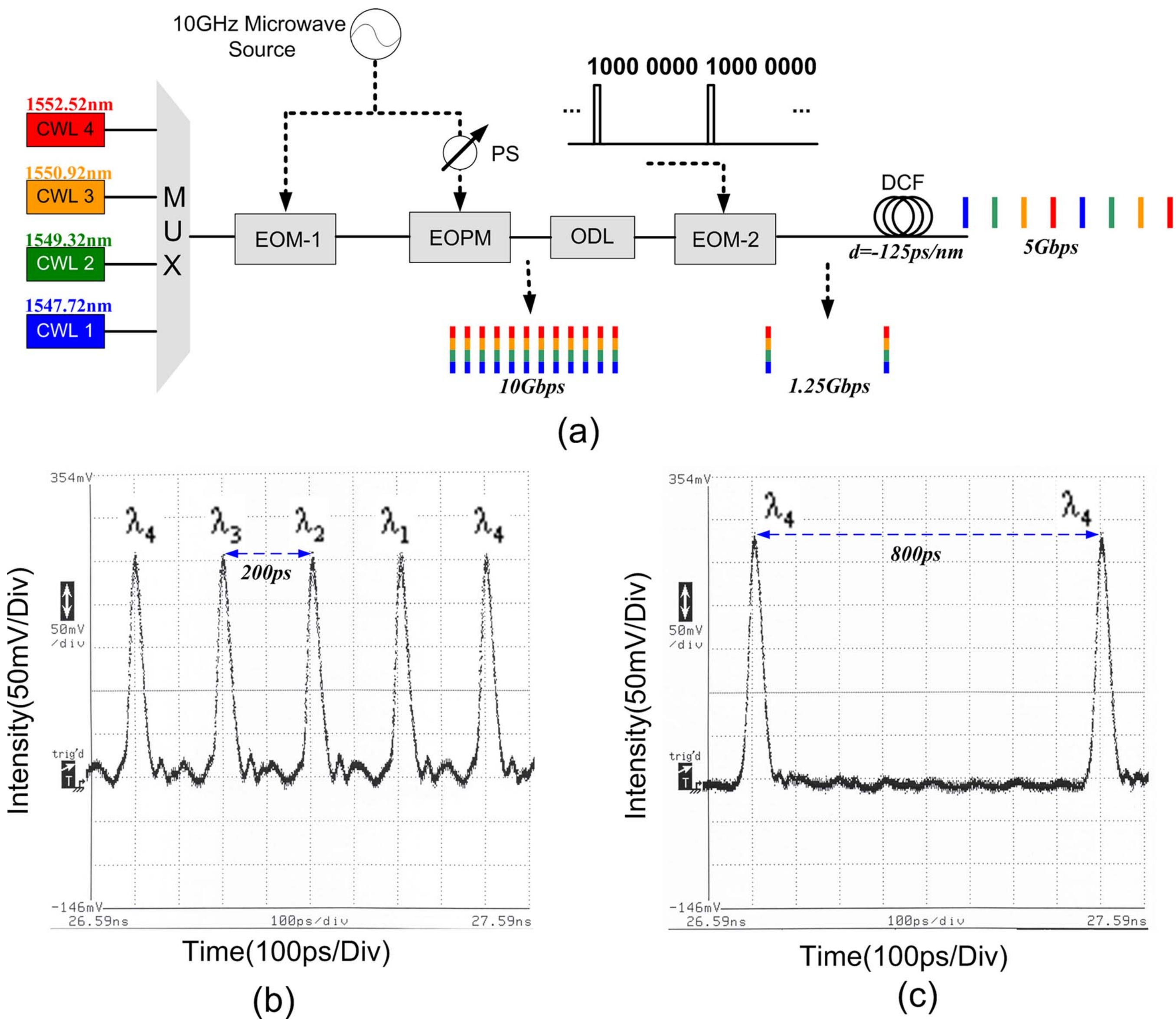

Fig. 2 (a) Experimental setup, (b) TWIPT waveform, and (c) waveform for 1552.52 nm in a 5-Gbps, four-wavelength TWIPT generation system.

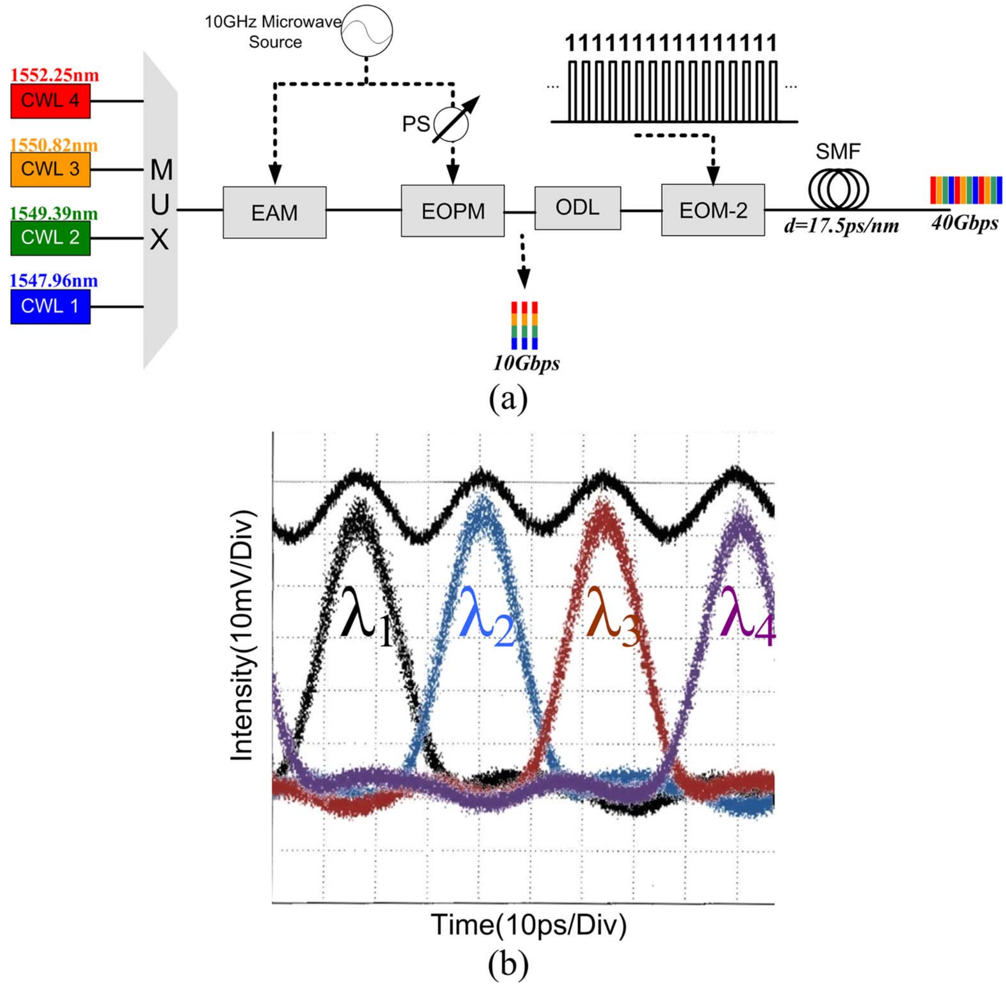

Fig. 3 (a) Experimental setup and (b) waveform of the four-wavelength TWIPT and waveforms of each wavelength in a 40-Gbps TWIPT system.

The per-wavelength repetition rate only depends on the 10-Gbps, 16-bit-long pattern signal. The total repetition rate is the product of the per-wavelength repetition rate and the number of CW lasers *N*. In equally spaced TWIPT applications, the dispersion *d* is determined by the per-wavelength repetition rate and the number of CW lasers *N*. Once the dispersion *d* is determined by other required parameters, such as the total repetition rate and wavelength difference of CW lasers, the pulse-width can be changed by altering the microwave power applied on the EOPM.

By adjusting the ODL prior to EOM-2, some pulses out of 16 pulses pass through EOM-2 and others are eliminated, depending on the pattern signal applied on EOM-2. Therefore, after passing through EOM-2, the repetition rate of the pulse train typically becomes lower (10 Gbps, 5 Gbps, 2.5 Gbps, 1.25 Gbps, or 625 Mbps), while each pulse still contains *N* wavelengths. After that, the pulse train is dispersed and all wavelengths are separated in the time domain. Today, most semiconductor CW lasers (such as NEC NX8570 Series) is wavelength tunable, though the tunable range is limited in several tenth of nanometers. Therefore, by carefully selecting the equally spaced wavelengths of the *N* CW lasers (Δ_λ is the wavelength difference between two adjacent wavelengths) and the dispersion amount *d*, after the dispersion module, those *N* wavelength components are equally separated in the time domain and

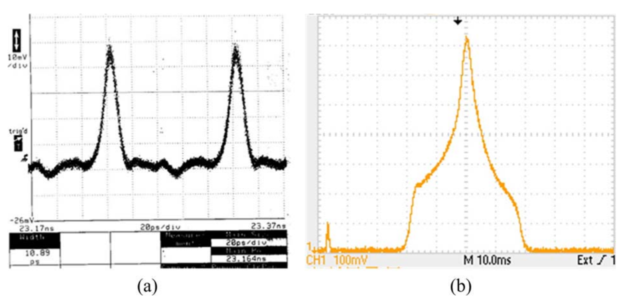

Fig. 4 (a) Optical pulses after further compression and (b) autocorrelation trace of these pulses.

the total repetition rate is multiplied by a factor of N. Thus, a TWIPT with repetition rate of ($f_{base}*N$) Gbps is attained based on high-speed optical switching and dispersion, where f_{base} is the per-wavelength repetition rate, which can be one of 10 Gbps, 5 Gbps, 2.5 Gbps, 1.25 Gbps, or 625 Mbps, depending on the pattern signal that is applied on EOM-2. At the same time, the pulse width of the resultant pulse train can be controlled by adjusting the microwave power applied on the EOPM.

3 Experiments and Discussions

As shown in Fig. 2(a), a principle-of-proof experiment is carried out where $N=4$, $\Delta_\lambda=1.6$ nm, $d=-125$ ps/nm and the pattern applied on EOM-2 is "1000 0000 1000 0000." The equally spaced four wavelengths used are $\lambda_1=1547.72$, $\lambda_2=1549.32$, $\lambda_3=1550.92$, and $\lambda_4=1552.52$ nm. The EOM-1 is a CODEON's Mach-10 $LiNbO_3$ intensity modulator, and EOPM is an AVANEX's IM10-P $LiNbO_3$ phase modulator. The EOM-2 is a COVEGA's Mach-10 $LiNbO_3$ intensity modulator. The ODL is a manually adjustable optical delay line from General Photonics. The dispersion module is a section of dispersion compensation fiber (DCF) with a dispersion amount of -125 ps/nm. Thus, the per-wavelength repetition rate f_{base} equals 1.25 Gbps, and the time interval between two adjacent wavelengths [such as λ_3 and λ_2 in Fig. 2(b)] is $|-125 \text{ ps/nm}*1.6 \text{ nm}| = 200$ ps and the total repetition rate is $1.25 \text{ Gbps}*4 = 5$ Gbps. The intensity of each wavelength can be readily adjusted by tuning the intensity of the corresponding CW laser.

As shown in Fig. 3(a), another experiment of four wavelengths, 40-Gbps TWIPT is carried out and the recorded waveforms are shown in Fig. 3(b). The four wavelengths used are $\lambda_1=1547.96$, $\lambda_2=1549.39$, $\lambda_3=1550.82$, and $\lambda_4=1552.25$ and $\Delta_\lambda=1.43$ nm. In order to obtain a narrower pulse width, the EOM-1 in Fig. 1 is replaced with an electro-absorption modulator (CIP-PS-EAM-1550). A section of single-mode fiber (SMF) with a dispersion of $d=17.5$ ps/nm is used as the dispersion module. The pattern applied on the EOM-2 is "1111 1111 1111 1111," which means all pulses go through the "optical switch" with minimal loss; therefore, the per-wavelength repetition rate f_{base} equals 10 Gbps. The full width at walf maximum (FWHM) pulse width of this 40-Gbps TWIPT is ~15 ps (measured by Tektronix 11801C), and the time interval between two adjacent wavelengths is 25 ps ($=1.43 \text{ nm}*17.5 \text{ ps/nm}$). Therefore, pulses of each wavelength overlap with each other. However, no interference exists because the adjacent pulses belong to different wavelengths.

As stated above, the pulse width of the resultant pulse train is determined by the dispersion d and the microwave power applied on the EOPM. However, once the total repetition rate and the per-wavelength repetition rate are determined, the dispersion d is determined. Therefore, for this kind of application, the pulse-width compression can only be tuned by changing the chirp generated in EOPM, which has practical limits (such as twice of its half-wave voltage). The higher the repetition rate is, the smaller the dispersion d is. This introduces a problem: Does the pulse width attained in this method is short enough for pulse train repetition rate as high as 40 Gbps? To verify this, the resultant multiwavelength pulse train is further compressed by passing through a high-saturation-power (~17 dBm) EDFA and a comblike dispersion profiled fiber (CDPF).[16,17]

Figure 4(a) shows the pulse train after further compression, and Fig. 4(b) shows the autocorrelation trace of these pulses, which is recorded by using Femtochorme FR-103PD autocorrelator. According to this autocorrelation trace, the pulse shown in Fig. 4(a) has a FWHM pulse width of 5.1 ps. If used in 40-GS/s WDM-ADC, such a short pulse train can achieve a good bandwidth.

Apart from equally spaced pulses, unequally separated pulses are also attainable by the proposed method. For example, in Ref. 7, a similar technique is used to generate unequally separated pulses, which are further exploited to generate arbitrary waveform photonically.

4 Conclusions

In summary, a highly flexible method for generation of a TWIPT is proposed and experimentally demonstrated, which is based on chirp compression and high-speed optical switching. In this method, independent control of the intensity, time interval, and pulse width is achievable. Moreover, by selecting the wavelengths used and the dispersion amount, TWIPT with repetition rate ($f_{base}*N$) Gbps can be obtained (f_{base} can be 10 Gbps, 5 Gbps, 2.5 Gbps, 1.25 Gbps, or 625 Mbps). In this paper, the realization of 40 Gbps TWIPT is experimentally demonstrated. This method is highly flexible because most parameters of the resultant TWIPT can be readily controlled, including the pulse width, the per-wavelength repetition rate, the total repetition rate, etc.

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