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Adjustable repetition-rate multiplication of optical pulses using fractional temporal talbot effect with preceded binary intensity modulation

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ABSTRACT

We demonstrate a simple approach for adjustable multiplication of optical pulses in a fiber using the temporal Talbot effect. Binary electrical patterns are used to control the multiplication factor in our approach. The input ~10 GHz picosecond pulses are pedestal-free and are shaped directly from a CW laser. The pulses are then intensity modulated by different sets of binary patterns prior to entering a fiber of fixed dispersion. Tunable repetition-rate multiplication by different factors of 2, 4, and 8 have been achieved and up to ~80 GHz pulse train has been experimentally generated. We also evaluate numerically the influence of the extinction ratio of the intensity modulator on the performance of the multiplied pulse train. In addition, the impact of the modulator bias on the uniformity of the output pulses has also been analyzed through simulation and experiment and a good agreement is reached. Last, we perform numerical simulation on the RF spectral characteristics of the output pulses. The insensitivity of the signal-to-subharmonic noise ratio (SSNR) to the laser linewidth shows that our multiplication scheme is highly tolerant to the incoherence of the input optical pulses.

1. Introduction

High-repetition-rate optical pulses play an important role in different applications, including high-speed optical communications, all-optical signal processing, and optical metrology [1]. Various methods have been demonstrated to generate such pulses. Fundamental mode-locking of a short-cavity laser can produce high-repetition-rate outputs. However, the noise performance is often limited by inherent spontaneous emission and the repetition rate is restricted by the cavity [1,2]. Harmonic mode locking has been applied to achieve low-noise and tunable repetition-rate output; nevertheless, complicated phase-locked loop circuits are needed to suppress the instability introduced by environmental disturbances [1,3]. Alternatively, commercially available optical multiplexers are frequently used to increase the pulse rate. A drawback is that precise delay tuning and power adjustment are required [3] and the implementation lacks flexibility.

Repetition-rate multiplication based on the temporal Talbot effect is attractive due to its simplicity and high energy efficiency [3–6]. By simply adding a proper spectral phase to the incident pulses, the desired repetition rate multiplication can be attained while the pulse shape and width are maintained. In conventional implementation approaches, the optical dispersion has to be changed to adapt to different multiplication factors, severely limiting its flexibility in operation [3,4,6]. Recently, Caraquitena et al. [5] used an optical processor to achieve programmable phase-only line-by-line shaping in a 45 GHz multiplied pulse train. An algorithm is applied to correct the phase error caused by the limited spectral resolution. Maram et al. [7] configured a programmable repetition-rate multiplier and achieved various multiplication factors by applying specially designed patterns to modulate the input optical phase. This scheme is attractive since it is programmable and energy efficient. Nevertheless, multilevel electrical modulating patterns are required. Tainta et al. [8] demonstrated optical pulse rate multiplication by using bilevel phase modulation. However, the required amplitude of the modulating pattern depends on the multiplication factor and thus complicates the operation.

In this paper, we report an alternative technique that combines binary intensity modulation and fiber-based temporal Talbot effect for adjustable repetition rate multiplication of optical pulses. The input pulse is prepared by external modulation and shaping of a CW laser [9]. The pulse is pedestal-free and is nearly transform-limited. The cavity-less structure allows tuning of the repetition rate and wavelength that can hardly be obtained from a mode-locked laser. In our scheme, the intensity of the generated pulse train is first modulated by a binary electrical pattern, followed by repetition-rate multiplication via the temporal Talbot effect in a fiber of fixed dispersion. The binary electrical pattern is designed based on a derived relation that governs the multiplication factor. The smaller the input pulse repetition rate, the higher is the output repetition rate after the fiber. Hence, the

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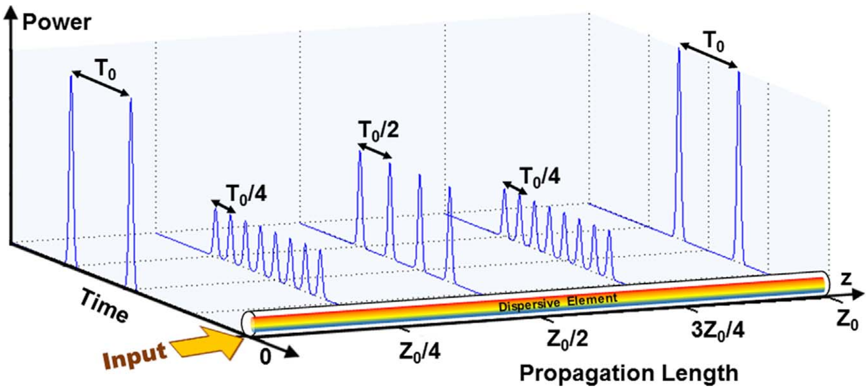

Fig. 1. Schematic illustration of the conventional temporal Talbot effect. The repetitive input pulses evolve into copies at different multiplication factors through propagation along a dispersive element.

multiplication factor can be simply controlled by the modulating binary pattern. Attributing to the temporal Talbot effect, nearly transform-limited pedestal-free pulses can be maintained after multiplication of the pulse rate. In the experiment, we demonstrate tunable multiplication of ~10 GHz pedestal–free pulses to ~20, 40, and 80 GHz, respectively. The influence of the extinction ratio of the intensity modulator on the quality of the output multiplied train is investigated numerically. The impact of the modulator bias on intensity variation of the multiplied pulses is analyzed in simulation and verified experimentally. Finally, our simulation shows that the signal-to-subharmonic noise ratio (SSNR) obtained from the output RF spectrum is highly tolerant to the temporal incoherence of the input optical pulses.

2. Operation principle

The operating principle of the repetition rate multiplication scheme is illustrated in Fig. 1. The input pulse repeats itself exactly after propagating through a dispersive element of which the dispersion satisfies the following condition [4]:

$$\beta_2 \cdot z_0 = \frac{s \cdot T_0^2}{2\pi} \tag{1}$$

where $\beta_2 \equiv \partial^2\beta/\partial\omega^2$ describes the group velocity dispersion, z_0 is the Talbot length, s is an integer indicating multiple integer temporal Talbot effect, and T_0 is the period of the input pulses.

Also, the fractional temporal Talbot effect occurs along the dispersive element. Thus, copies of the input pulses at different multiplication factors can be obtained, as shown in Fig. 1. A multiplication factor m is obtained when the optical dispersion satisfies the following condition [4]:

$$\beta_2 \cdot z_m = \frac{s \cdot T_0^2}{m \cdot 2\pi} \tag{2}$$

where s/m is an irreducible number; m=2, 3, 4 .... Therefore, multiplied optical pulses with a period of T_0/m appears at the fractional Talbot distance z_m. Consider the situation where the dispersion $\beta_2 \cdot z_m$ is equal to $\beta_2 \cdot z_0$ and s=1, if the input pulse period is intentionally increased from T_0 to T_1=N T_0, the multiplication factor m will be scaled by N^2 [10]. This can be understood by combining Eqs. (1) and (2), leading to

$$m = \frac{N^2 T_0^2}{\beta_2 \cdot z_0 \cdot 2\pi} = N^2 \tag{3}$$

Consequently, the output pulse period is $T_{out}=T_1/N^2=T_0/N$, which is N times smaller than the initial period T_0. In other words, by reducing the repetition rate of the input pulses by a factor of N before they enter the dispersive medium, the output repetition rate will be multiplied by the same factor. In this way, a dispersive medium with a fixed dispersion value can be used to support variable multiplication factors.

To explain the electrically-controlled temporal Talbot effect, time-frequency representation [7] is used in Fig. 2 to illustrate the multiplication process. In each time-frequency representation, the horizontal axis indicates the temporal variation of the pulse train and the vertical axis represents optical frequency components involved in individual optical pulses. First, Fig. 2(a) shows the case of the self-imaging effect with m=1 when an intensity modulator is biased to transmit all input pulses with an initial period of T_0. The temporal and spectral profiles of the input pulses remain unchanged at the output of the intensity modulator. A subsequent dispersive element adds a group dispersion of $\beta_2 \cdot z_0 = T_0^2/2\pi$ to the incoming pulses, introducing a T_0 time interval between adjacent discrete frequency components with spacing F, where F =1/T_0. As a result, temporal superposition of the dispersed optical frequency components leads to an exact self-imaging copy of the original pulse train at the output of the dispersive element, as depicted in Fig. 2(a). For the multiplication process, Fig. 2(b) shows the case of m=2 where a double-repetition-rate optical pulse train appears at the final output. In this situation, the intensity modulator is used to reduce the input pulse rate by a factor of two, giving rise to new frequency components generated between the original ones in the optical spectrum. Therefore, at the output of the intensity modulator, the period of the pulse train increases to 2 T_0 and the optical frequency spacing is reduced to F/2. Next, the intensity-modulated pulses are directed into the dispersive element with the same group dispersion. Group delay of $T_0/2$ is added on new adjacent frequency components with spacing of F/2. Consequently, temporal rearrangement of the optical frequency components leads to the creation of a new pulse train with a period of $T_0/2$ in the time domain, as illustrated in Fig. 2(b).

According to Eqs. (1) and (2), the required dispersion condition in our scheme is $\beta_2 \cdot z_0 = N^2 T_0^2/(N^2 \cdot 2\pi) = T_0^2/2\pi$ which is independent of the multiplication factor N. Here, s=1 is always maintained in the multiplication process. This process with the condition of s=1 is less sensitive to the coherence of the input pulses compared to a multiplication process using s > 1. The reason is because the pulses involved in the construction of the multiplied output fall within a shorter time interval [11,12]. As a result, the SSNR derived from the output RF spectrum shows a high tolerance to the incoherence of the input optical pulses. In comparison, the subharmonic noise peaks in the RF spectrum increase with the temporal incoherence of the optical pulses for the case of s > 1. The condition of s=1 is achieved by reducing the pulse rate prior to the introduction of the temporal Talbot effect. This tolerance of our scheme is supported by simulation results which will be discussed in the following Section.

3. Experimental demonstration and simulation analysis

The experimental setup is schematically illustrated in Fig. 3. An optical pulse source is first generated from a cavity-less configuration