Spectral Talbot effect using a silicon-chip time lens

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***Abstract*— We demonstrate spectral Talbot effect for a frequency comb using a time lens based on four-wave mixing in a silicon waveguide. Comb free spectral range divisions by four factors are successfully performed, respectively.**

Keywords— Talbot effect, optical frequency comb, silicon

I. Introduction

In recent decades, optical frequency combs (OFCs) have developed rapidly in many filed such as microwave photonics [1], optical communications [2], ranging [3] and so on. Among most applications, the comb free spectral range (FSR) is fixed or slightly tunable because the OFC is generated by mode-locked laser and the large tuning of its cavity length is hard to operate. Another solutions such as harmonic mode-locking would cause deteriorated output signal and spectral amplitude filter methods would lose signal energy. To control the FSR of OFCs with high energy efficiency and low signal degradation, the theory of spectral Talbot effect has been proposed due to the inherent phase-only nature [4]. The spectral Talbot effect can be achieved by a time lens where a specific temporal quadratic phase is imposed to the periodic sequence of signal pulses.

The time lens is usually realized by the cross-phase modulation (XPM) [5], electro-optic modulator (EOM) [6] and four wave mixing (FWM) [7-9] methods. However, the XPM method usually require precise control of pump power and pulse envelope in experiment. The EOM method is limited by the modulation bandwidth which is restricted to tens of GHz and thus the available repetition rate of pulse train is usually under 10 GHz. In contrast, the FWM method imposes less requirements on the precise control over the pump light power and pulse envelope, and meanwhile has much broader bandwidth. Therefore, the time lens based on FWM is a promising method for spectral Talbot effect.

Nowadays, although manipulating the OFC by FWM is mainly achieved via optical fibers, the components of the total system can be potentially integrated on chips due to the blooming of silicon integrated photonics. Hitherto, marvelous achievements have been made to promote development of OFCs in integrated photonics but no work of controlling the comb FSR by a silicon-chip time lens has been reported.

In this work, we utilize a time lens based on four-wave mixing in a silicon waveguide to experimentally achieve the spectral Talbot effects for the first time. The temporal quadradic phase profile of time lens originates from the linear frequency chirp of a Gaussian pump pulse propagating through a dispersion compensating fiber (DCF). The FSR tuning of a frequency comb can be obtained by suitably changing the propagation distance of pump pulse. This scheme provides the potential of developing a device that can realize the comb FSR adjustment by any desired factor.

II. Principle

The schematic diagram of the spectral Talbot effect using FWM process is shown in Fig. 1. The input signal is a periodic sequence of Gaussian pulses with the center frequency f_s and repetition time T, thus its spectrum is a frequency comb with FSR $f_0 = 1/T$. The temporal quadratic phase for time lens can be created when a Gaussian pump pulse at the optical carrier frequency f_p propagates through a DCF, having the form of:

$$\varphi(t) = \exp\left[-it^2 / (2\beta_2 L_p)\right] \tag{1}$$

where β_2 is the group velocity dispersion and L_p is the length of DCF. $\beta_2 L_p$ denotes the group delay dispersion (GDD) of the pump light. The output pump pulse after DCF is greatly broadened, therefore both the effects of the self-phase modulation and XPM can be ignored. The pulse width is short enough compared to the GDD, thus the phase variation keeps almost constant for each individual pulse. The output idler light after FWM process can be simply written as:

$$A_{idler}(t) = \sum_n A(t-nT)\cdot\exp(-i\frac{n^2T^2}{\beta_2 L_p})\cdot\exp[i2\pi(2f_p - f_s)t] \tag{2}$$

where $A(t\text{-}nT)$ denote the envelope of the n-th pulse. Four different division factors of FSR can be obtained when the fiber length L_p satisfies the following condition:

$$T^2 / (|\beta_2| L_p) = \pi s / m \tag{3}$$

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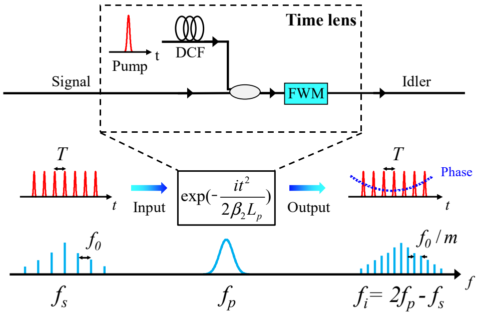

Fig. 1. Illustration of the spectral Talbot effect using FWM process.

where s and m are arbitrary positive integers. In the case of m = 1 and s = 1, the integer spectral Talbot effects can be achieved. When m > 1 and s/m is a noninteger and irreducible rational number, the fractional spectral Talbot effects can be achieved. The original OFC reproduces itself but with an FSR reduced to f_0/m, as shown in Fig. 1.

III. Experiment and Results

The experimental setup for spectral Talbot effect is shown in Fig. 2. Two mode-locked lasers (MLL) driven by an arbitrary waveform generator (AWG) are utilized to provide the input and pump light. The sinusoidal driving signal given by the AWG are set as 20 GHz and 100 MHz, respectively. The center wavelength of the OFC is set as 1547.18 nm. The Gaussian shape and 360-pm bandwidth of pump light is filtered by a waveshaper and the center wavelength is set as 1554.58 nm. The Gaussian pump pulse then is combined with the OFC by a wavelength division multiplexer (WDM) and together injected into a 1.19-cm-long silicon waveguide by a grating coupler. The FWM process happens in the waveguide and meanwhile the temporal quadratic phase is imposed to the OFC. The output of the chip can be observed by an optical spectrum analyzer (OSA) with the resolution of 20 pm. Polarization controllers (PCs) are utilized to optimize the conversion efficiency of the FWM process and erbium-doped fiber amplifiers (EDFAs) are utilized to raise the pump power to 23 dBm. The input OFC power is set as 0 dBm. The optical power inside the waveguide is maintained below 20 dBm to avoid two-photon induced free-carrier effects in the silicon. This waveguide has a cross-sectional size of 220 nm by 770 nm, a linear propagation loss of 2.5 dB/cm and a 6-dB coupling efficiency. According to Eq. (3), we utilize four DCFs with the GDD of 810.3 ps^2, 1591.3 ps^2, 2383.3 ps^2 and 3175 ps^2 to achieve the spectral Talbot effects for four conditions (s = 1, m = 1, 2, 3 and 4), respectively.

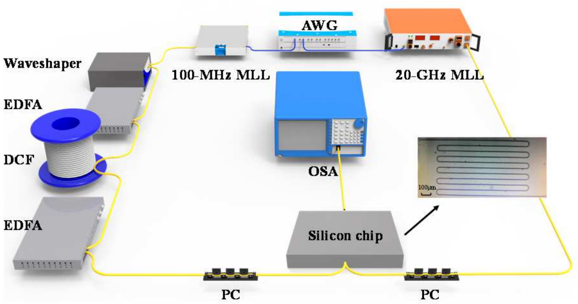

Fig. 2. Experimental setup. MLL, mode-locked laser; AWG, arbitrary waveform generator; PC, polarization controller; EDFA, erbium-doped fiber amplifier; DCF, dispersion compensation fiber; OSA, optical spectrum analyzer.

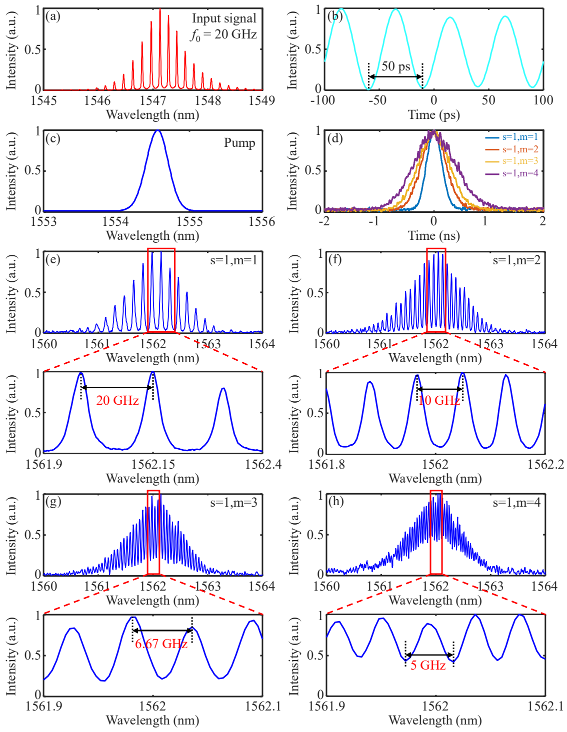

Fig. 3. (a), (b) Spectrum and temporal waveforms of the input signal. (c), (d) Spectrum and temporal waveforms of the pump light. (e)-(h) Output spectra for s =1, m = 1, 2, 3, and 4, with FSR = 20 GHz, 10 GHz, 6.67 GHz and 5 GHz.

The experimental results are shown in Fig. 3. Fig. 3(a) displays the normalized spectrum of the input 20-GHz OFC and its corresponding temporal waveform with the repetition time T = 50 ps is captured by a 33-GHz oscilloscope as shown in Fig. 3(b). Fig 3(c) displays the normalized spectrum of the pump light and its corresponding temporal waveform after different lengths of DCF is shown in Fig. 3(d).When s =1, m = 1, and the GDD is 810.3 ps^2, the OFC can be obtained at the idler of around 1562.1 nm as depicted in Fig. 3(e). The repetition frequency and profile of the idler is the same as that of the signal. Increasing the length of DCF to the GDD of 1591.3 ps^2, 2383.3 ps^2 and 3175 ps^2, respectively, the fractional spectral Talbot effect can be realized as depicted in Figs. 3(f)-3(h). In each case, some new frequency components are generated. In the condition of m = 2, 3 and 4, the FSRs of new frequency combs of 10 GHz, 6.67 GHz and 5 GHz can be obtained. The conversion efficiency of FWM process on chip is as high as −25 dB.

IV. Conclusion

We have realized the FSR divisions for a 20-GHz OFC by four factors through spectral Talbot effects using a time lens based on four-wave mixing in a silicon waveguide for the first time. New FSRs of 20 GHz, 10 GHz, 6.67 GHz and 5GHz have been achieved by tuning the GDD of time lens. The study may find potential applications in optical communication and signal processing.

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