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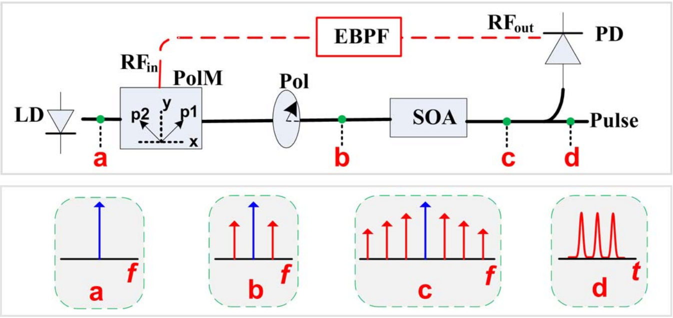

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Optical Pulse Generation Based on an Optoelectronic Oscillator With Cascaded Nonlinear Semiconductor Optical Amplifiers

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Abstract: This paper presents a high-repetition-rate pulse train generator incorporating an optoelectronic oscillator based on four-wave mixing (FWM) in a semiconductor optical amplifier (SOA). The optoelectronic oscillator is used to generate a high-stability microwave signal, by which an optical pulse train is generated using FWM effect in cascaded SOAs. The key feature of this work is that no external microwave signal source is needed for generating an optical pulse train. An optical pulse train with a repetition rate of 10 GHz and a pulsewidth of 19 ps is experimentally generated. The pulsewidth and the repetition rate can be tunable and are experimentally demonstrated.

Index Terms: Pulse generation, four-wave mixing, semiconductor optical amplifiers, optoelectronic oscillator.

1. Introduction

Optical pulse train with a high repetition rate up to tens of gigahertz have attracted much attention thanks to its important applications in high speed data transmission, optical samplers for high speed optical signal processing [1], all-optical reshaping [2], [3], and other communication systems. In the past tens of years, optical pulse generation based on both actively and passively mode-locked lasers becomes a hot research field. One main disadvantage of this technique is that it needs a complicated controlling system to keep it working stably. In addition, many other kinds of techniques have been reported to generate short optical pulses using different key photonic components such as electro absorption modulators [4], highly nonlinear fiber (HNLF) [5], ultralong semiconductor optical amplifier (SOA) [6] and cascaded electro-optic modulators [7].

In [7], optical frequency combs are generated by using cascaded intensity and phase modulators. Though some relatively flat optical frequency combs and pulses with a width of 12.8 ps are obtained, the system is complicated, high-cost and unstable, since a double-loop optoelectronic oscillator (OEO) configuration is employed in this method. In order to further improve the pulse quality, four-wave mixing (FWM) effect is used for optical pulse generation in an SOA with a length of 8 mm [6]. Due to the strong nonlinear effects in this specially-fabricated device, a large amount of

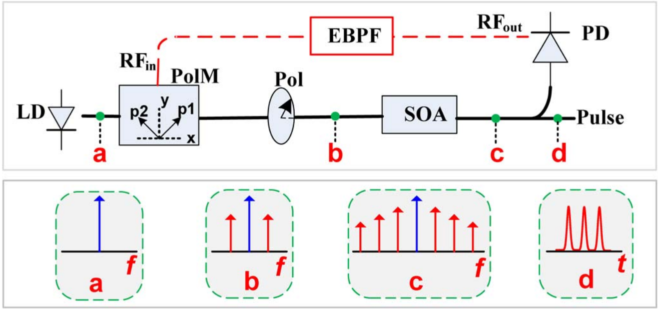


Fig. 1. Schematic diagram of the proposed system. P1 and p2 are the principal axes of the PolM. Illustration of the operation principles: a, b, c: frequency domain; d: time domain. LD: laser diode. PolM: polarization modulator. Pol: polarizer. SOA: semiconductor optical amplifier. PD: photodiode. EBPF: electrical bandpass filter.

FWM mode combs is generated and the obtained optical pulse has a pulsewidth less than 2 ps after filtering the FWM mode combs. However, this system needs an external microwave source, and the ultralong SOA is fragile and is not commercially available. Cascaded HNLFs have also been employed for generating FWM modes [5], but as the HNLF has a low FWM efficiency, only a few FWM modes are generated and so the generated short optical pulses are mainly dependent on the subsequent compression processes by the comblike profiled fiber (CPF). Since a lot of fibers are used, the stability of this system cannot be guaranteed. Another method for all-optical pulse generation using the FWM effect in a nonlinear SOA (NL-SOA) has been proposed [8], in which a fiber-loop laser consisting of two SOAs is employed. By tuning the wavelengths of the two input optical signals, the repetition rate of the optical pulses can be tuned. However, it is worth noting that both in [5] and [8], two independent laser sources are used as pump and probe signals to generate FWM modes, which will decrease the FWM efficiency due to the uncorrelated phase relationship between the two laser sources and may also introduce phase distortions among the generated FWM modes and consequently deteriorate the quality of the generated optical pulses.

In this letter, we propose and experimentally demonstrate a novel scheme for optical pulse generation with a repetition rate of 10 GHz using FWM effect in cascaded NL-SOAs, incorporating an OEO loop. The key feature of this scheme is that since a high-quality microwave signal is generated by the OEO, no external microwave source is need. As the FWM effect is induced by the intensity-modulated optical signals, the signals injected into the NL-SOA are highly phase-related and much more FWM modes are generated when the FWM efficiency is greatly increased. Since an increase of the generated FWM modes contributes to shortening the optical pulse, optical pulse with a 3 dB pulsewidth of 19 ps has been observed, accompanying with the verification of the tunability of the pulsewidth. In addition, it is easy to tune the repetition rate by tuning the oscillating frequency of the OEO and this tunability is also experimentally demonstrated by generating an optical pulse train with a repetition rate of 16 GHz.

2. Operation Principles

A simple schematic diagram of our proposal is shown in Fig. 1. The optical signal at the output of the laser source can be expressed as $A_0 \exp(j\omega_c t)$, where ω_c is the angular frequency of the optical source with its amplitude of A_0. This light is then injected into a polarization modulator (PolM), which is a special phase modulator that supports both TE and TM modes with opposite phase modulation indices [9]. When a linearly polarized light is injected into a PolM with 45° angles aligned to one principal axis, two complementary phase modulated signals are produced along the two principal axes of the PolM. The generated phase-modulated optical signals along the two orthogonal axes can be described as [9]

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \frac{\sqrt{2}}{2} A_0 \begin{bmatrix} \exp[j(\omega_c t + \beta \sin \Omega t)] \\ \exp[j(\omega_c t - \beta \sin \Omega t)] \end{bmatrix} \tag{1}$$

where β is the phase modulation index defined as $\beta = \pi V_{\mathrm{RF}}/V_{\pi}$ with V_{RF} and V_{π} the amplitude of the RF signal and the half-wave voltage of the PolM respectively, and Ω is the angular frequency of the RF signal. It is worth noting that the carrier and the sidebands at the output of the PolM are in orthogonal polarization states, so when placing a polarization controller (PC) and a polarizer (Pol) behind the PolM and adjusting the principal axis of the polarizer to align it to one principal axis of the PolM by tuning the PC, the phase-modulated signals along the two orthogonal polarization states can be converted to an intensity-modulated signals expressed as

$$E_o \propto \left(E_x + E_y e^{-j\varphi_o}\right) \tag{2}$$

where φ_{o} is a static phase term induced by the PC. It can be seen from the above expressions that the output signal at the polarizer is equivalent to a Mach–Zehnder modulator (MZM) biasing at different transmission point. The advantage to use a PolM instead of an MZM is that the PolM does not need a DC bias and so it avoids the DC bias drift problem existing in a conventional MZM. When $\varphi_{\mathrm{o}} = 0$, under a small-signal modulation condition, only the carrier and the 1st-order sidebands are needed to be taken into consideration. As a result, the output signal at the polarizer, $E_{\mathrm{Pol}}(t)$, can be expressed as

$$E_{Pol}(t) \propto J_0(\beta)\exp(j\omega_c t) + J_1(\beta)\exp[j(\omega_c + \Omega)t] + J_1(\beta)\exp[j(\omega_c - \Omega)t] \tag{3}$$

where $J_{\mathrm{n}}(\beta)$ $(\mathrm{n} = 0, 1)$ is Bessel function of the first kind.

The intensity-modulated optical signals $E_{\mathrm{Pol}}(t)$ are then injected into an NL-SOA, which usually has a low saturation power and strong nonlinear effects. Generally it is considered that the gain saturation induced by several mechanisms will ultimately lead to the generation of the nonlinear effects in SOA [10]. One of the main nonlinear effects in SOA, FWM, has been extensively studied. Detailed descriptions and analysis can be found in [11]–[13]. For a general understanding, a simple description of FWM for continuous waves from the point view of nonlinear optics is given as follows. Three linearly polarized optical signals, $A_0\exp(j\omega_{\mathrm{c}}t)$, $A_1\exp[j(\omega_{\mathrm{c}} - \Omega)t]$ and $A_2\exp[j(\omega_{\mathrm{c}} + \Omega)t]$, with the same polarization state are simultaneously injected into an SOA. Since the FWM is a 3rd-order nonlinear process, the 3rd-order component of the induced-polarization intensity can be expressed as [14]

$$P_k^{(3)}(\omega) = \varepsilon_0 \sum_{m,n,l} \chi_{kmnl}^{(3)}(\omega)E(\omega_m)E(\omega_n)E(\omega_l) \tag{4}$$

where ω is the new frequency generated by different combinations of ω_{m}, ω_{n}, and ω_{l}, such as $\omega_3 = \omega_{\mathrm{c}} + (\omega_{\mathrm{c}} + \Omega) - (\omega_{\mathrm{c}} - \Omega) = \omega_{\mathrm{c}} + 2\Omega$, $\omega_4 = \omega_{\mathrm{c}} - 2\Omega$, and $\chi_{\mathrm{kmnl}}^{(3)}$ is one component of the tensor of the 3rd-order nonlinear susceptibility $\chi^{(3)}$. Thus the 3rd-order induced-polarization field serves as a sub optical source and radiates optical signals with frequencies of ω_3 or ω_4, which is called idle signals. It is the $\chi^{(3)}$ that leads to the product of new frequencies and FWM effect. When the input signals have sufficiently large power and the FWM efficiency is relatively high, the newly generated idle signals will also cause FWM processes due to the cascaded FWM effects, i.e. optical signals with frequencies of $\omega_{\mathrm{c}} \pm 3\Omega$, $\omega_{\mathrm{c}} \pm 4\Omega \ldots$ will also be generated. Thus, the optical fields at the output of the SOA, $E_{\mathrm{SOA}}(t)$, can be expressed as

$$E_{SOA}(t) \propto \sum_m A_m \exp[j(\omega_c - m\Omega)t], \quad \mathrm{m} = 0, 1, 2, \ldots \tag{5}$$

A special feature of the generated FWM modes is that their phases are highly correlated [12]. By using this phase relationship among the FWM modes, microwave signals with frequencies up to several times multiplication of the modulation frequency have been generated based on the beating between FWM modes both in SOA [15], [16] and HNLF [17], [18]. However, the phase-matching condition in nonlinear optics among the injected signals imposes a stringent requirement for a high FWM efficiency. When this condition is fulfilled, it will select the wave-mixing effect from other

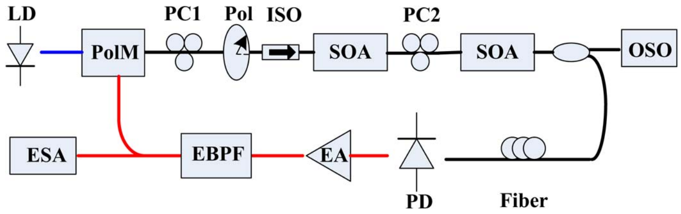


Fig. 2. Schematic diagram of the proposed experimental setup. The black and red lines represent the optical path and electrical path, respectively. The blue line represents a section of PMF. PMF: polarization-maintaining fiber. LD: laser diode; PolM: polarization modulator; PC: polarization controller; Pol: polarizer; ISO: isolator; PD: photodiode; EA: electrical amplifier; EBPF: electrical bandpass filter; ESA: electrical spectrum analyzer; OSO: optical sampling oscilloscope.

nonlinear effects; otherwise the wave-mixing effect will have a low efficiency. To enhance the FWM efficiency, it is better to use initially phase-correlated optical signals as the seed signals.

In our proposed scheme, the beating signals at the output of the PD are fed to the PolM to form an OEO loop. Since the OEO loop can generate a high-quality microwave signal, optical signals with intensity-modulation can be obtained without an external microwave source before injecting into the NL-SOA. Compared to other schemes in [5] and [8], the phases among the injecting optical signals are phase correlated and so the FWM efficiency in the SOA is highly improved.

3. Experiments and Results

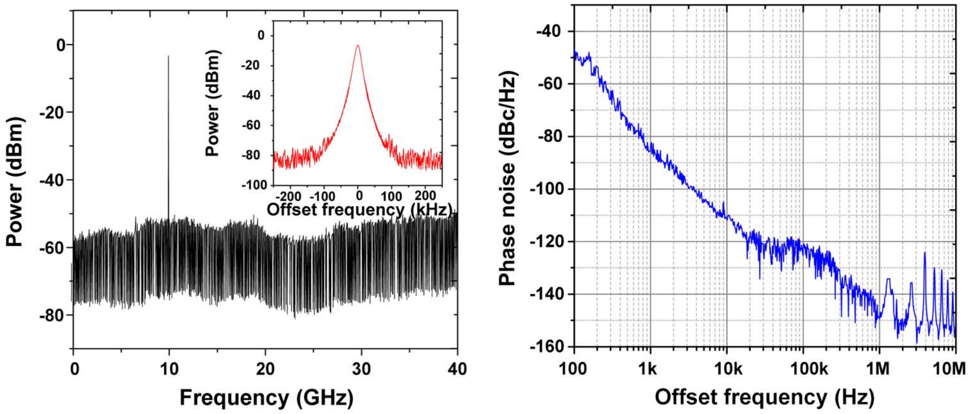
Our experimental schematic diagram is shown in Fig. 2. The light emitting from a narrow linewidth laser (LD) is directed into a PolM that has a RF modulation bandwidth over 40 GHz, followed by a PC and a polarizer. The phase-modulated signals are then converted into intensity-modulated signals, which are injected into SOA. In order to improve the number of the FWM modes, two cascaded NL-SOAs are employed in our experimental scheme. These optical devices and a photodiode (PD), an electrical amplifier (EA), an electrical bandpass filter (EBPF) form an OEO loop. The PD has a 3 dB bandwidth of 18 GHz with a conversion gain of 0.3 V/W. The EA has a power gain of 26 dB. The EBPF has a passband of 10 MHz with a center frequency at 9.9532 GHz.

In the experiment, we first adjust the PC1 to convert the phase-modulated optical signals into intensity-modulated optical signals. Once the gain in the OEO loop is larger than the loss, a microwave signal with a frequency of 10 GHz starts oscillating [19].

To improve the noise performance of the generated microwave signal, a 140 meters long delay fiber, which corresponds to a free spectral range (FSR) of ∼1.4 MHz, is used in the loop. The generated microwave signal is shown in Fig. 3(a). Inset shows a zoom-in view of a frequency span of 500 kHz using an ESA. The phase noise performance of the generated microwave signal is also evaluated by a signal source analyzer. Fig. 3(b) shows the single-sideband phase noise. As can be seen from Fig. 3(b), the phase noise at the offset frequency of 10 kHz is approximately −110 dBc/Hz.

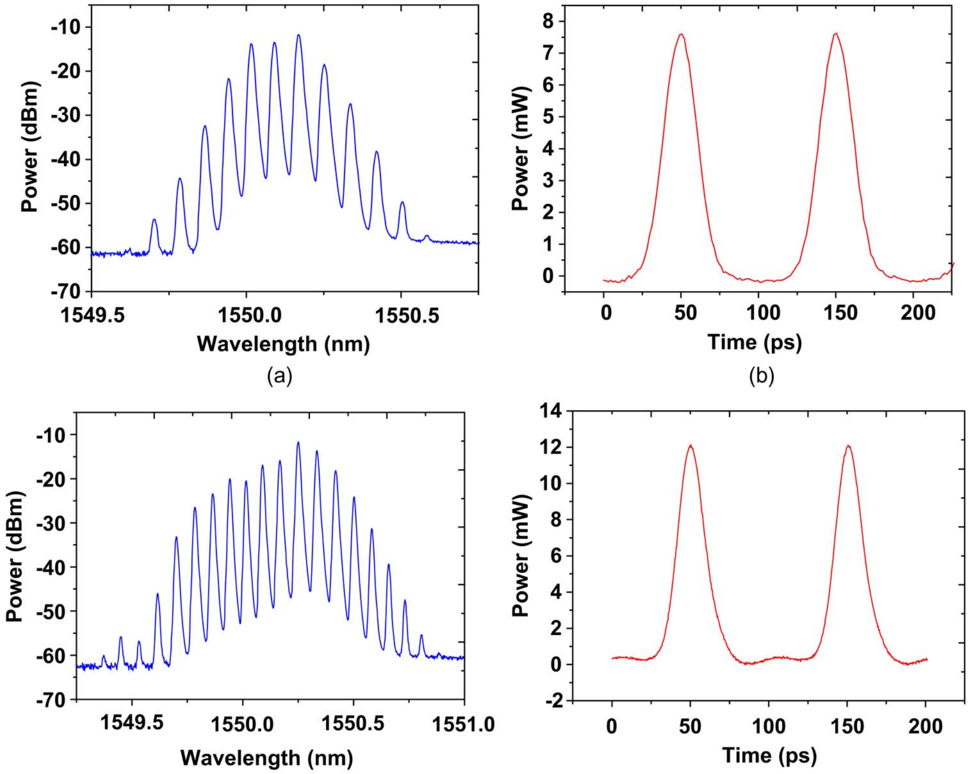
Simultaneously when the OEO starts oscillating, FWM modes with a spectrum spacing of 10 GHz are generated. The FWM modes generated by the two cascaded NL-SOAs are shown in Fig. 4(a), measured by an optical spectrum analyzer (OSA).

It can be seen that as many as 7 FWM modes are generated with an optical spectrum spacing exactly equaling to the oscillating frequency of the OEO. The FWM modes are then partially sent to an optical sampling oscilloscope (OSO). Due to the phase-correlated relationship among these FWM modes, optical pulses with a repetition rate of 10 GHz are observed, as shown in Fig. 4(b). The generated optical pulse has a full width at half maximum (FWHM) of approximately 25 ps. It is worth noting that the time jitter and stability of the optical pulse train depend on the stability and the phase noise performance of the generated microwave signal. A stable and low phase noise of microwave signal contributes to a low time jitter of the optical pulse train. The time jitter of the generated optical pulse is less than 1 ps, measured by an optical sampling oscilloscope. It is also worth noting that when a single and stable microwave signal oscillates, the optical pulses show a



(a) (b)

Fig. 3. (a) Electrical spectrum of the generated microwave signal at 10 GHz. Inset shows a zoom-in view of the 10 GHz signal within a frequency span of 500 kHz. (b) Phase noise measurement of the generated 10 GHz signal.



(c) (d)

Fig. 4. (a) FWM modes generated by the two cascaded NL-SOAs with an optical spectrum spacing of 10 GHz. (b) Pulse train with a repetition rate of 10 GHz and FWHM of 25 ps. (c) FWM modes generated by tuning the PC1. (d) Pulse train with FWHM of 19 ps.

high stability. So the methods used to stabilize the OEO loop can also be employed to improve the stability of the optical pulse, such as using an electrical filter with a high-Q factor, decreasing the ASE noise power of the SOA. In addition, by properly tuning the PC1, corresponding to tuning the transmission point of the PolM and the optical power that injects into the NL-SOAs, the FWM efficiency will increase and more mode combs will be generated, as shown in Fig. 4(c). By both

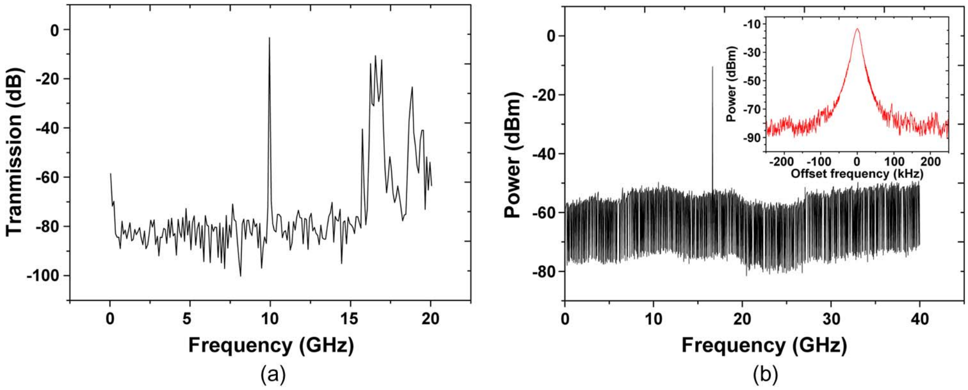


Fig. 5. (a) Transmission response of the electrical filter. (b) Generation of the microwave signal with a frequency of 16 GHz by tuning the PC1.

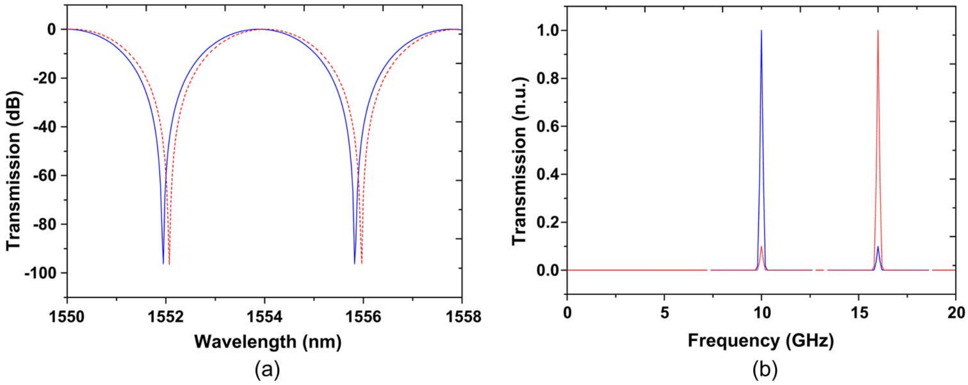


Fig. 6. (a) Simulated transmission response of the M-Z interferometer formed by the fast and slow axis of the PMF. The blue and red lines represent different phase delays induced by the polarization controller. (b) Alternative oscillating frequency in the OEO when precisely tuning the PC1.

controlling the gain of the SOA and tuning the polarization controllers which corresponds to tuning the optical power input into the SOA to enhance the FWM efficiency of the SOAs to obtain the largest number of the spectral lines. And consequently, the FWHM of the pulse reduces to 19 ps, as shown in Fig. 4(d). Thus the tunability of the pulsewidth can be achieved by simply tuning the PC1 and the injection current of the SOAs.

The tunability of the repetition rate of the optical pulse train has also been investigated by the same experimental setup as shown in Fig. 2. At first, the transmission response of the EBPF is measured by a vector network analyzer (VNA) as shown in Fig. 5(a). It can be seen that besides of a transmission response at 10 GHz, there also exists an extra transmission response at around 16 GHz.

In this experiment, we have found that by precisely tuning the PC1, the oscillating frequency of the OEO loop can be hopped from 10 GHz to 16 GHz, as shown in Fig. 5(b).

This frequency hopping can be ascribed to the interferometric effect induced by the polarization-maintaining fiber (PMF) used as a pigtail fiber at the input port of the PolM. Due to the refractive indices difference of the two principal axes, known as a fast axis and a slow axis of the PMF, there is a phase delay between the two orthogonal polarization states at the output of the PolM and thus the two branches form a Mach–Zehnder interferometer (MZI). The frequency response of the interferometer is simulated as shown in Fig. 6(a). When tuning the PC1, the phase delay between the two orthogonal axes varies and the minimum transmission point moves as shown by the dashed line in Fig. 6(a).

When the sidebands modulated by the signal with a frequency of 10 GHz fall in this minimum transmission point and the sidebands modulated by the signal with a frequency of 16 GHz are out of

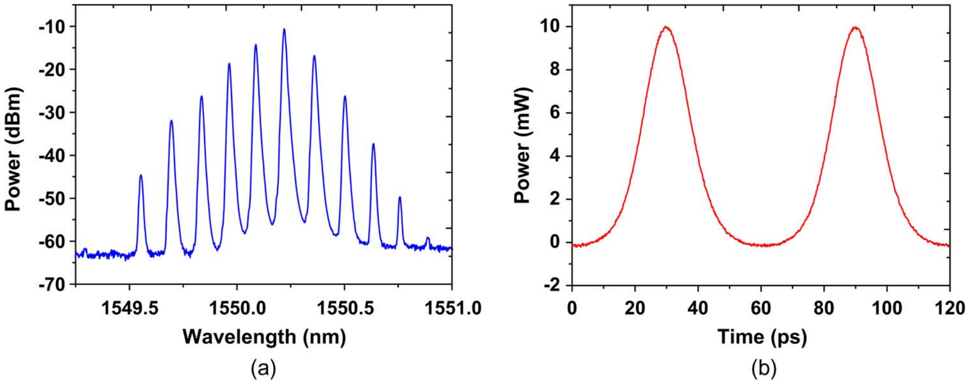


Fig. 7. (a) FWM mode combs with an optical spectrum spacing of 16 GHz. (b) Generation of the pulse train with a repetition rate of 16 GHz and FWHM of 16 ps.

this point, the gain of the signal of 16 GHz may be greater than that of the signal of 10 GHz at the output of the PD. Thus the signal with a frequency of 16 GHz obtains the highest gain, and it suppresses the modes with a frequency of 10 GHz and starts oscillating. The spectrum spacing of the FWM modes also increase to 16 GHz, as shown in Fig. 7(a). The generated optical pulse with a repetition rate of 16 GHz has a FWHM of approximately 16 ps, as shown in Fig. 7(b).

4. Discussions

A small pulsewidth is always desired in many applications. To further decrease the pulsewidth of the generated optical pulse, we should increase the number of the spectral lines generated by the FWM effect of the SOAs. These spectral lines can be optimized by controlling the FWM efficiency of the SOAs. In Ref. [6], the authors have used an ultralong SOA to improve the FWM efficiency and obtained a lot of spectral lines and narrow optical pulses. In our paper, though two cascaded NL-SOAs are used, the FWM efficiency is still not that large. As a result, a chip with a large FWM efficiency is still strongly required for the generation of narrow optical pulse.

5. Conclusion

We have proposed and experimentally demonstrated an optical pulse generator based on the FWM effect in NL-SOA. By introducing an OEO loop to the system, the optical signals injected into the SOAs are phase-correlated, and so the FWM efficiency is greatly increased. As an example, an optical pulse train with a repetition rate of 10 GHz is successfully demonstrated with a FWHM of 19 ps. In addition, the tunabilities of the pulsewidth and the repetition rate are investigated by precisely tuning the polarization controller followed the PolM, and an optical pulse train with a repetition rate of 16 GHz is also experimentally demonstrated with a FWHM of 16 ps.

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