# ГЕНЕРАЦИЯ ОПТИЧЕСКИХ ГРЕБЕНОК С ИСПОЛЬЗОВАНИЕМ МОДУЛЯТОРА ИНТЕНСИВНОСТИ В ПЕТЛЕ САНЬЯКА

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Предложен простой генератор оптических гребенок, реализующий найквистовские импульсы, использующий модулятор интенсивности внутри петли Саньяка. Ранее было теоретически показано и экспериментально продемонстрировано, что для определенного состояния поляризации излучения на выходе петли Саньяка возможно получение квазипрямоугольной пятитоновой гребенки оптических частот с найквистовской формой импульсов. Однако число тонов такой гребенки при использовании единичного модулятора интенсивности обычно ограничено числом 3. В схеме для получения максимального числа тонов, предложенной в работе, требуются только один генератор радиочастотного сигнала и один фазосдвигающий элемент, питаемый постоянным напряжением, что существенно повышает надежность системы и снижает ее стоимость.

***Ключевые слова:*** *гребенки оптических частот, модулятор интенсивности, петля Саньяка, найквистовские импульсы.*

# OPTICAL FREQUENCY COMB GENERATION BY USING OF AN INTENSITY MODULATOR IN A SAGNAC LOOP

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We propose a simple optical frequency comb generator with Nyquist temporal waveform by using of an intensity modulator in a Sagnac loop. By properly adjusting the polarization of the output from the Sagnac loop, a quasi-rectangular-shaped 5-tone optical frequency comb with Nyquist temporal waveform is theoretically and experimentally demonstrated. But it is impossible to generate Nyquist pulses with more than 3 comb lines using a single intensity modulator as reported before. In our scheme, only one radio-frequency signal with a relatively low power and only one direct-current voltage is needed, which effectively increases the system reliability and decrease the system complexity and cost.

***Key words:*** *optical frequency comb, intensity modulator, Sagnac loop, Nyquist pulses.*

OCIS codes: 060.2330, 060.5625, 190.4160

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## 1. Introduction

Optical frequency comb (OFC) has become an indispensable tool in a variety of applications, such as arbitrary waveform generation [1], microwave signal processing [2], frequency measurement [3] optical sensors [4] and so on. Many approaches have been proposed for the generation of OFC. Mode-locked lasers referenced to an external or internal optical reference can generate optical frequency combs with many comb lines [5]. However, they suffer from poor frequency space tunability due to the fixed optical resonator. Optical frequency comb can be obtained by fiber nonlinearities [6], but the application is limited due to the large insertion loss, complex fabrication of device and fixed frequency operation. Recirculating frequency shifter has been employed to generate OFC [7].

An optical frequency comb can also be generated by externally modulating a single laser source with microwave signals [8–10]. Specially tailored radio frequency (RF) waveforms were used to improve the flatness, where 38 comb lines within 1 dB spectral variation were obtained by cascade of intensity and phase modulators in Ref. [8]. 29 comb lines with spectral power variation less than 1.5 dB at 10 GHz were obtained [9]. But three modulators must be employed, which make the cost increased and the applied RF signals were greater than 2.5 Vπ. A flat and tunable seven-line OFC generation scheme based on a single polarization modulator is propose and experimentally demonstrate [10].

In this paper, we propose a novel approach to generating an optical frequency comb with Nyquist temporal waveform based on bi-directional use of an intensity modulator (IM) in a Sagnac loop (SL). As we know, this is first time to use SL for OFC generation. In the SL, due to the velocity mismatch of the modulator, only the incident light wave along the clockwise direction is effectively modulated by the RF signal. A quasi-rectangular-shaped 5-tone OFC with Nyquist temporal waveform is theoretically and experimentally demonstrated with an IM driven by a RF signal in a SL. However, OFC with Nyquist temporal waveform generated by a single IM reported before is limited to 3 comb lines.

## 2. Principle of analytical model

The schematic diagram of the proposed OFC generation is represented in Fig. 1. A linearly polarized lightwave from CW laser is injected to a polarization beam splitter (PBS) though an optical circular (OC). Twosorthogonally polarized optical carriers are fed into the SL via the PBS. The SL consists of an IM and two polarization controllers (PCs) (PC2 and PC3). Due to the IM is a traveling-wave device, which modulates the light wave in a uni-directional manner in the loop, leaving light wave in the other direction unmodulated due to the velocity mismatch. So only the light wave which travels through the IM along the clockwise direction is modulated by an RF signal. Then at the output of the SL, the two light waves are recombined at the PBS, and the polarization of the combined light wave is controlled by PC4 before it is injected into a polarizer. By properly adjusting the polarization of the light wave output from the SL, the optical

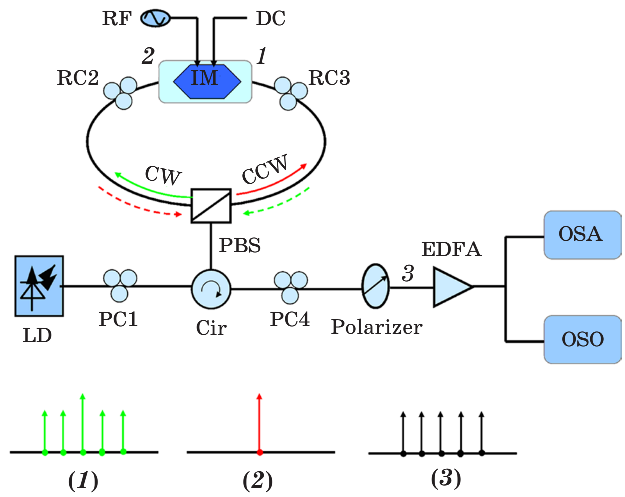


**Fig. 1.** Schematic diagram of the proposed optical frequency comb generator based on bi-directional use of an intensity modulator in a SL. LD – laser diode, PC – polarization controller, Cir – circulator, PBS – polarization beam splitter, IM – intensity modulator, PR – polarization rotation, OSA – optical spectrum analyzer, OSO – optical sampling oscilloscope, CW – clockwise, CCW – counter-clockwise. (*1–3*) Spectra of the signals at different locations of the system.

carrier can be significantly suppressed at a polarizer and then an optical frequency comb can be generated.

The optical field of the laser diode (LD) is defined as $E_{\text{in}}(t) = E_{\text{in}}\cos(\omega_c t)$, where $E_{\text{in}}$ denotes the amplitude of the optical field, and $\omega_c$ is the angular frequency of the optical carrier. The optical signals output from the two ports of the PBS can be expressed as

$$E_1(t) = E_2(t) = E_{\text{in}}(t)/\sqrt{2}. \quad (1)$$

An electrical RF driving signal $V(t) = V\sin(\omega t)$ is applied to the IM, where $V$ and $\omega$ are the corresponding the amplitude and frequency of the microwave signal. So the optical signal at the clockwise output of the modulator the can be expressed as

$$E_{\text{CW}}(t) = \frac{E_{\text{in}}}{2\sqrt{2}} \times$$

$$\times \sum_{n=-\infty}^{+\infty} \left[ J_n(m) e^{jnwt + j\varphi} + J_n(-m) e^{jnwt - j\varphi} \right], \quad (2)$$

where $J_n(\cdot)$ denotes the $n^{\text{th}}$-order Bessel function of the first kind, $m = \pi V_{\text{RF}}/V_\pi$ is the RF modulation index and $\varphi = \pi V_{\text{DC}}/V_\pi$ is the phase shift caused by the direct-current (DC) voltage, CW is clockwise. We can get the expressions for the carriers

$$E_{\text{CW},0} = \frac{E_0}{\sqrt{2}} J_0(m)\left(\exp j\varphi + \exp(-j\varphi)\right)\cos(\omega t),$$

$$E_{CW,\pm1} = \pm\frac{E_0}{\sqrt{2}} J_1(m)\times$$
$$\times(\exp j\varphi - \exp(-j\varphi))\cos[(\omega \pm \omega_m)t], \quad (3)$$

$$E_{CW,\pm2} = \pm\frac{E_0}{\sqrt{2}} J_2(m)\times$$
$$\times(\exp j\varphi + \exp(-j\varphi))\cos[(\omega \pm 2\omega_m)t].$$

The intensity of the $n^{th}$-order sideband can be expressed

$$I_{CW,n} \propto \left|E_{CW,n}\right|^2. \quad (4)$$

Solving the equation of $|I_{CW,\pm1}| = |I_{CW,\pm2}|$, we can get

$$\frac{J_1(m)}{J_2(m)} = \left|\frac{\exp j\varphi + \exp(-j\varphi)}{\exp j\varphi - \exp(-j\varphi)}\right|, \quad (5)$$

$$J_1(m)\sin(\varphi) = J_2(m)\cos(\varphi). \quad (6)$$

We can see that for any modulation index $m$, there is always a proper φ which can make Eq. (6) true. Then the 1st-order and 2nd-order sidebands would have the same amplitude and four comb lines are generated as shown in Fig. 1a. We can see the amplitude of the optical carrier is little higher than other sidebands too.

Due to the velocity mismatch of the IM, the modulation of the counterclockwise light wave in the SL is very little which can be ignored. So the optical signal at the counterclockwise output of the IM is shown in Fig. 1b and can be written as

$$E_{CCW}(t) = \frac{1}{\sqrt{2}} E_{in}(t). \quad (7)$$

Then, the clockwise and counterclockwise (CCW) light waves are combined again at the PBS and they are orthogonal at the output of the PBS. Before injected to a polarizer, the combined light wave is polarization controlled by PC4. By adjusting PC4, the principal axis of the polarizer is aligned at an angle of α to one principal axis of the PBS, and a phase difference of φ is introduced between the clockwise and counterclockwise light waves. So we can get the optical signal at the output of the PBS

$$E_{out}(t) = E_{CW}(t)\cos(\alpha) + E_{CCW}(t)\sin(\alpha)\exp(j\varphi) = (E_{CW,0} + E_{CW,\pm1} + E_{CW,\pm2})\cos(\alpha) +$$
$$+\frac{1}{\sqrt{2}} E_{in}(t)\sin(\alpha)\exp(j\varphi) \propto \left\{\begin{aligned} &[J_0(m)(\exp j\varphi + \exp(-j\varphi))\cos(\alpha) + \sin(\alpha)\exp(j\varphi)]\cos(\omega t) \\ &+J_1(m)(\exp j\varphi - \exp(-j\varphi))\cos[(\omega \pm \omega_m)t]\cos(\alpha) \\ &-J_{-1}(m)(\exp j\varphi - \exp(-j\varphi))\cos[(\omega \pm \omega_m)t]\cos(\alpha) \\ &+J_2(m)(\exp j\varphi + \exp(-j\varphi))\cos[(\omega \pm 2\omega_m)t]\cos(\alpha) \\ &+J_{-2}(m)(\exp j\varphi + \exp(-j\varphi))\cos[(\omega \pm 2\omega_m)t]\cos(\alpha) \end{aligned}\right\}. \quad (8)$$

In order to make the amplitudes of the optical carrier and the other sidebands (the 1st-order and 2nd-order sidebands) equal, we must let

$$|2J_0(m)\sin(\varphi)\cos(\alpha) + \sin(\alpha)\exp(j\varphi)| =$$
$$= |2J_2(m)\sin(\varphi)\cos(\alpha)|. \quad (9)$$

Obviously, when $\varphi = \pi$ and $\alpha = \tan^{-1}[2(J_0 - J_2)\sin\varphi]$, Eq. (9) can be satisfied. In this case, we can a 5-line OFC with a good flatness, which is shown in Fig. 1c. As it described in Ref. [11], the frequency spacing $\Delta f$ between adjacent spectral lines determines the pulse repetition period $T = 1/\Delta f$, and the rectangular bandwidth $N\Delta f$ ($N$ is the number of lines) defines the zero-crossing pulse duration $\tau_p = 2/(N\Delta f)$.

### 3. Simulation results and discussions

Computer simulations by Virtual Photonics Inc. (VPI) software package have been performed to study the performance of our proposed optical frequency comb generation. A CW laser with a linewidth of 10 MHz at a frequency of 193.1 THz is injected to PBS though an OC. The two orthogonally polarized sidebands after the PBS are fed into the SL, with one sideband sent to the IM along the clockwise direction and the other to the IM along the counter-clockwise direction. The modulation frequency $f$ of the IM is set to 20 GHz. As analysis above, the RF modulation index $m$ is 0.85 and the phase shift φ caused by the DC bias is 0.216.

An optical frequency comb with four equal tones, and 20 GHz frequency spacing can be generated as shown in Fig. 2a. At the output of the SL, the two light waves are recombined at the PBS. After polarization controlled by PC4, the combined light wave is injected into a polarizer. By properly adjusting the polarization of the light output from the SL, the optical carrier can be appropriately suppressed at a polarizer and an OFC with $N = 5$ spectral components, a frequency

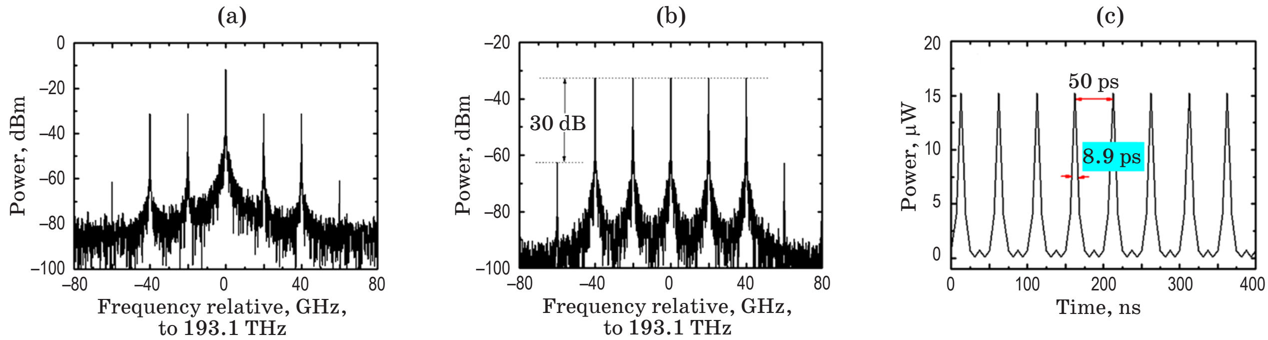


**Fig. 2.** Simulated output spectrum of the clockwise light wave after efficient modulation (a) and the polarizer (b) when the frequency of RF signal is 20 GHz. (c) Time waveform of the generated Nyquist pulses.

spacing $\Delta f$ = 20 GHz and a bandwidth of 100 GHz can be generated as shown in Fig. 2b. The intensity of the $3^{rd}$-order sideband is 30 dB lower than that of the lower order sidebands, demonstrating a quasi-rectangular spectral shape, which can be utilized in the generation of Nyquist pulses. Figure 2c presents the simulated waveform of the five-tone OFC. The sinc pulse has a zero-crossing duration of $\tau_p$ = 20 ps (FWHM duration of 8.9 ps) and a repetition period of $T$ = 50 ps. The pulse width and repetition rate can be changed by simply tuning the frequency comb parameters.

## 4. Experiment results

The experimental setup of the proposed optical frequency comb scheme is similar to Fig. 1. The CW laser (Yokogawa AQ2200-136) with a center wavelength of 1550 nm has a linewidth less than 2 MHz. By adjusting PC1, the optical signals at the two ports of the PBS are set to be identical in power. Then, the lightwave is fed to a SL with the single optical carrier that is traveling along the counter-clockwise direction, which is modulated by an RF signal at the IM. The half-wave voltage of the intensity modulator (Sumitomo) is both 3.2 V and the 3 dB band-width is 25 GHz. A 20-GHz sinusoidal signal from a microwave signal source is applied to the IM. The optical signal output from the SL is polarization controlled and injected into a polarizer. After amplified by an erbium-doped fiber amplifier, the optical signal is measured with an optical spectrum analyzer.

By properly adjusting the polarization controller before the polarizer to appropriately suppress the optical carrier. Figures 3a and 3b show the experimentally generated spectrum and waveform. As can be seen in Fig. 3a, the flatness is measured to be 0.6 dB and the intensity of a $3^{rd}$-order sideband is 24.8 dB lower than that of the lower order sidebands. The experimental results are in agreement with the theoretical analysis. The measured sinc Nyquist pulse has a zero-crossing duration of $\tau_p$ = 20 ps (FWHM duration of 8.9 ps) and a repetition period of $T$ = 50 ps, as depicted in Fig. 3b.

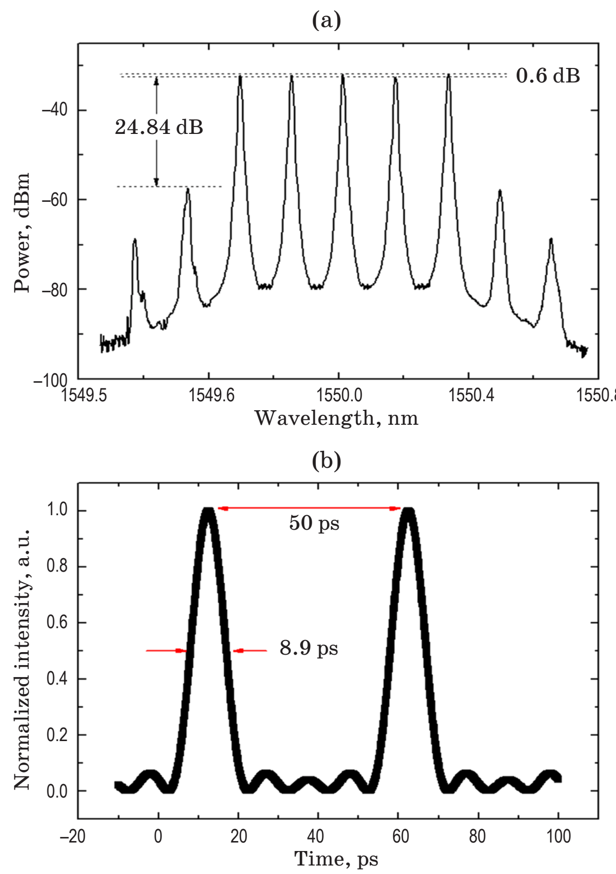


**Fig. 3.** (a) Spectrum and (b) waveform of the generated OFC with 20 GHz frequency spacing at the center wavelength of 1550 nm experimentally.

## 5. Conclusion

In conclusion we demonstrate a cost-effective and flexible generator for optical Nyquist pulse and rectangular-shaped OFC generation. A quasi-rectangular-shaped OFC with five tones and 0.6 dB flatness is experimentally achieved based on bidirectional use of an IM in a SL without waveshaping filter. And more comb lines can be obtained by cascading with another intensity modulator.

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