Comparison analysis of optical frequency comb generation with nonlinear effects in highly nonlinear fibers

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Abstract: We compare several schemes for broadband optical frequency comb (OFC) generation based on several nonlinear effects in highly nonlinear fiber (HNLF). Cascaded four wave mixing (CFWM) and self-phase modulation (SPM) processes in HNLF are proved to be effective ways for spectrum broadening. We investigate some parameters affecting the performance of the output OFC in detail. When only CFWM occurs in the HNLF, broadband OFC can be generated with poor power flatness. When only SPM occurs in the HNLF, we obtain a 10 GHz OFC of 10^3 comb lines within 5-dB power deviation. When both CFWM and SPM simultaneously occur in the HNLF, we obtain a 10 GHz OFC of 143 comb lines within 4.5-dB power deviation. All the OFC generation schemes have the advantages of tunability of central wavelength and repetition frequency.

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References and links

1. Introduction

Optical frequency comb (OFC) is a spectrum that consists of a set of evenly spaced frequency components with a coherent and stable phase relationship [1]. With the rapid development of optical communication technology, the generation of OFC is attracting lots of interests recently due to its wide applications, such as optical arbitrary waveform generation (OAWG) [2–4], multi-wavelength ultra-short pulse generation [5] and dense wavelength division multiplexing (DWDM) [6]. In such applications especially for OAWG, the number of comb lines, spectral flatness and optical tone-to-noise ratio (OTNR) represent key considerations. To date, there are various methods have been demonstrated to generate an OFC. A typical method is applying a strong sinusoidal phase modulation to a continuous wave (CW) laser. This is a relatively simple and robust method since the frequency spacing is tunable. However, employing one phase modulator (PM) generates OFCs that are not flat [7], limiting the use of these comb lines.

Recently, it has been reported that there were several improved schemes to flatten and broaden OFC, utilizing cascaded modulators [7–10], recirculating frequency shifter (RFS) architecture [11–14] or cascaded four wave mixing (CFWM) [15–19]. For example, driving a PM with dual-sine-wave could generate an OFC of 11 comb lines within 1.9-dB spectral power variation [7]. An OFC of 61 comb lines with a power deviation less than 8-dB was obtained using two cascaded PMs and a chirped Bragg grating [8]. 38 comb lines were obtained by cascading intensity modulators (IMs) and a PM, which was driven by specially tailored radio frequency (RF) waveforms [9]. Among the aforementioned schemes, the number of the generated comb lines was mostly limited due to the inherent amplitude limitation of the driven RF signals. Besides, RFS loops based on a single-side-band (SSB) modulator and two cascaded PMs have been demonstrated to generate more than 100 comb lines [11]. However, the characteristics of the OFC strictly depended on the modulation states, thus too many physical parameters of the modulators were required to be precisely optimized, making the system possibly costly and unstable. Additionally, CFWM in highly nonlinear fiber (HNLF) was proved to be an effective method to obtain broadband OFC [18]. But it was difficult to generate very flat OFCs.

In this paper, we compare and analyze several OFC generator (OFCG) schemes based on several nonlinear effects in the HNLF. Experimental results prove that the number of spectral lines can be increased as well as the OFC flatness can be improved utilizing CFWM together
with self-phase modulation (SPM) processes. We have investigated some important parameters that affect the performance of the output spectrum in detail by comparing several different OFCG schemes. When only strong SPM occurs in the HNLF, we obtain a 10 GHz OFC of 103 comb lines within 5-dB power deviation. When both CFWM and SPM are employed in the HNLF, we obtain a 10 GHz OFC of 143 comb lines within 4.5-dB power deviation. All these OFCG schemes have the advantages of tunability of central wavelength and repetition frequency.

2. OFC generation by CFWM based scheme

Scheme 1: CFWM in HNLF

Four wave mixing (FWM) in HNLF is a parametric process involving four different waves. For a degenerate FWM configuration, two idle waves at frequencies of \( \omega_3 = \omega_1 - (\omega_2 - \omega_3) \) and \( \omega_4 = \omega_2 + (\omega_2 - \omega_1) \) are generated when two single frequency pump waves with frequencies of \( \omega_1 \) and \( \omega_2 \) (assume \( \omega_1 < \omega_2 \)) are injected into HNLF [16]. In FWM process, the energy and momentum must be conserved, which is referred to as phase matching. This phase matching condition is met when the net wave vector mismatch \( \kappa = 0 \), where \( \kappa \) can be written as [21],

\[
\kappa = \Delta \kappa + \Delta \kappa_{NL} = 0
\]

where \( \Delta \kappa \) and \( \Delta \kappa_{NL} \) represent the wave vectors mismatch related to dispersion and nonlinear effects, respectively. For a degenerate FWM, \( \Delta \kappa_{NL} = \gamma (P_1 + P_2) \), where \( \gamma \) is the nonlinear coefficient of HNLF, \( P_1 \) and \( P_2 \) are the incident power of \( \omega_1 \) and \( \omega_2 \), respectively. To obtain the phase matching, the pump wavelength should exceed the zero dispersion wavelength (ZDW) of HNLF (namely \( \Delta \kappa < 0 \)), so that the net wave vector mismatch \( \kappa = 0 \). When the wavelength of \( \omega_1 \) is larger than the ZDW, \( \Delta \kappa_{NL} \) can be adjusted to achieve the phase matching by changing the pump power [20, 21]. Therefore when the pump wavelength lies in anomalous dispersion region near the ZDW, phase matching condition is relatively easy to be satisfied. Additionally, the newly formed waves by FWM can in turn interact with each other or with the primary pump waves to further generate new ones, involving a cascaded process known as CFWM. Therefore, CFWM can be considered as an effective way to obtain a broadband OFC with exact frequency spacing of \( (\omega_2 - \omega_1) \).

According to the CFWM process in HNLF, we present a scheme (marked as Scheme 1) to generate OFC, as shown in Fig. 1. The configuration consists of a tunable laser source (TLS), a polarization controller (PC), a PM to produce multi-sidebands which can act as pump seeds for HNLF, a high power erbium-doped fiber amplifier (HP-EDFA) used to provide a high pump power for HNLF, 1-km length HNLF with the nonlinear coefficient of 10 W\(^{-1}\) km\(^{-1}\), the ZDW of 1550 nm and the dispersion slope of 0.030 ps/nm\(^2\)/km at 1550 nm, which is used to induce CFWM effect for creating broadband OFC. The generated OFC is then recorded by an optical spectrum analyzer (OSA, AQ6370B) with a resolution of 0.02 nm. It should be noted that as the multi-sidebands are produced by the PM, the stimulated Brillouin scattering (SBS) in the HNLF will be suppressed significantly. Here, a spectral line with power suppression ratio larger than 10 dB is counted as an available spectral line, which may have the potential
applications in the multi-carriers coherent communication system. As illustrated in Fig. 2(b), power suppression ratio is defined as power ratio between the peak of a spectral line and the average of the two valleys adjacent to the peak. The number of available spectral lines obtained in Scheme 1 is experimentally investigated in detail, which is varied as the output pump power of HP-EDFA, central wavelength of the TLS and repetition rate of RF signal applied on PM are changed.

![Fig. 2](image)

Fig. 2. (a) Output spectrum of the TLS, and (b) output spectrum of the PM.

Firstly, we investigate the impact of output pump power of HP-EDFA on the available spectral lines. The central wavelength of TLS is fixed at 1560.2 nm with an optical power of 10 dBm, as shown in Fig. 2(a). And the PM is driven by a 20 GHz sinusoidal RF signal. In order to obtain multi-sidebands, an RF amplifier is employed to amplify the RF signal. Thus, the continuous wave (CW) will experience a large phase modulation (with modulation depth of \(-1.28\pi\)), producing 14 available spectral lines, as shown in Fig. 2(b). Then the output signal of the PM is amplified by HP-EDFA to provide high pump power for the HNLF. Since the output waveform of the PM is a CW, it is CFWM but no SPM effect that occurs in the HNLF. The CFWM effect will lead to more spectral lines. Figure 3 shows the number of available spectral lines as a function of the output power of HP-EDFA. The insets are the output spectra of the HNLF using different pump powers. One can see that, the available spectral lines increase as the pump power increases, which suggests that the CFWM effect can be improved with a large pump power.

![Fig. 3](image)

Fig. 3. Available spectral lines versus the output pump power of HP-EDFA.

Figure 4(a) shows the impact of central wavelength of the TLS on the available spectral lines. The output pump power of the EDFA is fixed at 450 mW and 800 mW, respectively. Note that, the wavelength range of measurement is from 1540.50 nm to 1564.50 nm but no further measurement is shown beyond 1565 nm, this is because our measurement is limited by the TLS tuning range (1540.00~1565.49 nm) and the gain spectral range of the HP-EDFA (1526~1566 nm). One can see that, more available spectral lines will be obtained when the central wavelength is around 1560 nm, the anomalous dispersion region of the HNLF, because phase matching condition is relatively easy to be satisfied in anomalous dispersion.
region near ZDW. Then, we investigate the number of available spectral lines at different repetition rate of RF signal, as shown in Fig. 4(b). The central wavelength of TLS is fixed at 1560.2 nm and the output pump power of HP-EDFA is 850 mW. From Fig. 4(b) one can see that the generated spectral lines have a small variation when changing the repetition rate of the RF signals. Therefore, in our case, the CFWM efficiency is mainly dependent on the launched pump power of the HNLF and laser wavelength, but not the frequency span of multi-carriers, especially when the driven signal on the PM is in the microwave frequency region.

![Fig. 4.](image)

(a) Available spectral lines versus the central wavelength of TLS (red square: output pump power is set at 450 mW, blue dot: output pump power is set at 800 mW). (b) Available spectral lines versus the repetition frequency of RF signal applied on the PM.

**Scheme 2: Enhanced CFWM in HNLF**

To further enhance the CFWM efficiency in the HNLF, we can supplement a part of single mode fiber (SMF) to compensate the chirp induced by the PM. Thus we can achieve a pulse train with very short pulse-width after the SMF. The short pulse train is then amplified by the HP-EDFA. Hence we can get a pump signal with higher peak power, which can enhance the CFWM effect in the HNLF. In such a case, the SPM occurs simultaneously due to the optical pulse injection. Figure 5 shows the experimental setup for the modified OFCG, marked as Scheme 2.

![Fig. 5.](image)

![Scheme2](image)

**Fig. 5.** Experimental setup of the modified CFWM based OFCG.

![Fig. 6.](image)

**Fig. 6.** FWHM of the short pulse obtained after SMF versus the length of SMF.

In order to obtain a higher peak power of the pulse train, the SMF length needs to be optimized so that the SMF dispersion can totally compensate the chirp of the PM’s output...
signals. Figure 6 shows the full width at half maximums (FWHMs) of the generated short pulses after different lengths of SMF when 20 GHz RF signal is applied on the PM. In this paper, all the temporal waveforms are measured by an ultrahigh optical sampling oscilloscope (OSO) (Alnair Labs, Eye-1000C) with 500-GHz bandwidth and a temporal resolution of 1 ps. One can see that the FWHM decreases first and then increases as the SMF length is increasing. The optimal length of the SMF is about 1 km. And a minimum FWHM of 6.48 ps is obtained, as shown in the inset of Fig. 6. It should be noted that even the shortest pulse is generated with a 1 km SMF, the generated pulse has a strong direct current (DC) floor before it is normalized. Thus the SPM effect may be deteriorated in the HNLF.

![Figure 6](image)

Fig. 6. Available spectral lines versus the output pump power of the HP-EDFA when fixing the central wavelength of TLS as 1560 nm and the repetition frequency of RF signal applied on PM as 20 GHz.

![Figure 7](image)

Fig. 7. Available spectral lines versus the output pump power of the HP-EDFA when fixing the central wavelength of TLS as 1560.2 nm and the repetition frequency of RF signal applied on PM as 20 GHz.

![Figure 8](image)

Fig. 8. Available spectral lines versus the central wavelength of the TLS with fixing the repetition frequency of RF signal applied on PM as 20 GHz. (red square: when output pump power of HP-EDFA is set as 450 mW, blue dot: when output pump power of HP-EDFA is set as 750 mW).

Now, the SMF length is fixed at 1 km, the output power of HP-EDFA and central wavelength of the TLS are varied. Figure 7 shows the spectral lines at different pump power of HP-EDFA. One can see that for higher pump power launching, more available spectral lines are obtained. Compared to Fig. 3, more spectral lines are generated with the 1 km SMF assistance. Therefore the chirp compensation of the SMF is very useful to obtain a broadband OFC, which can enhance the CFWM effect. Figure 8 shows the available spectral lines as a function of the laser wavelength. Similarly to Fig. 4(a), more available spectral lines are obtained when the central wavelength is in anomalous dispersion region than in normal dispersion region, since phase matching condition is relatively easy to be satisfied in
anomalous dispersion region near ZDW. Now, the laser wavelength is fixed at 1560.2 nm, the output power of HP-EDFA is fixed at 900 mW and the PM is modulated at 20 GHz. Figure 9 shows the output spectra of Scheme 1 and Scheme 2. As can be observed, the number of comb lines, spectral flatness and OTNR are all significantly improved using Scheme 2. Since the short pulse injection has a much higher peak power compared to the CW injection, the CFWM efficiency can be improved, at the same time, the SPM has the contribution for spectral broadening as well. However, both Scheme 1 and Scheme 2 have some issues, such as poor flatness of the OFC.

![Fig. 9. Output spectra of Scheme 1 and Scheme 2.](image)

**Scheme 3: CFWM and SPM assisted in HNLF**

If we inject a DC-floor-free optical pulse into the HNLF, the performance of the OFCG could be further improved. On the basis of Scheme 2, we demonstrate an improved scheme as shown in Fig. 10, marked as Scheme 3. The central wavelength of the TLS is still 1560.2 nm with an optical power of 10 dBm. The 10 GHz RF signal is applied on both a Mach-Zehnder modulator (MZM) and a PM. The additional MZM is used to cut the pulse to offer a better pulse source. By adjusting the DC bias voltage of the MZM to below the quadrature point [22] a return-to-zero (RZ) pulse with a small duty cycle can be obtained, as shown in Fig. 11(a). Figure 11(b) shows the corresponding spectrum of the RZ pulses. Subsequently, an erbium-doped fiber amplifier (EDFA) is used to compensate the loss induced by the MZM, while the optical tunable delay line (OTDL) is used to synchronize the driving RF signal applied on MZM and PM. The PM is still used to induce large chirp and produce multi-sidebands with a modulation depth of ~1.28π. Similarly, the following SMF (SMF1) is used to compensate the chirp of the PM. In this case, we find that the optimal length of SMF1 is 5-km, which is enough to compensate the chirp induced by PM. The optimal waveform and spectrum after SMF1 is measured in Fig. 11(c) and Fig. 11(d), respectively. Here, the output waveform after SMF1 is a DC-floor-free pulse with a FWHM of 15.17 ps. This pulse is then amplified by the HP-EDFA. Thus both CFWM and SPM will be enhanced in the HNLF compared to Scheme 2.

![Fig. 10. Experimental setup of the further improved OFCG.](image)

Figure 12(a) shows the final output spectrum of Scheme 3 when the output pump power of HP-EDFA is ~1.09 W. Compared with the spectra shown in Fig. 9, one can see that the spectral flatness is greatly improved except some imperfection in the central part. To further flatten the OFC, a filter element is employed to optimize the central portion of the spectrum.
Then we obtain a flat and broadband OFC with 143 spectral lines. The power deviation is no more than 4.5-dB and the OTNR is larger than 12-dB, as shown in Fig. 12(b).

The generated OFC is highly coherent, so our scheme can be used for ultrashort pulse generation as well. When the output pump power of HP-EDFA is 271.5 mW, the output spectrum of the HNLF is shown in Fig. 13(a). Then another SMF (SMF2) is used to compensate chirp induced by the HNLF. When the SMF length is optimized at 100 m, an ultra-short pulse with a FWHM of 2.27 ps is obtained, as shown in Fig. 13(b). This ultrashort pulse train is very useful for high speed optical time division multiplexing (OTDM) system [23].

Fig. 11. (a) and (b) are the output waveform and spectrum of the MZM, respectively, (c) and (d) are the output waveform and spectrum after SMF1, respectively.

Fig. 12. (a) Output spectrum of Scheme 3 when the output power of HP-EDFA is ~1.09 W, (b) flat OFC after a wavelength selective element.
3. OFCG by SPM in the HNLF (Scheme 4)

In fiber optic system, SPM induced frequency chirps can make the spectrum broadened or compressed, dependent on the incident pulse chirp. If the incident pulse is unchirped, SPM always leads to spectrum broadening. SPM effect in the HNLF is proved to be an effective way to generate broadband OFC, since it can broaden the spectrum of optical pulse. In this section, we only analyze the SPM contribution to the broadband OFCG. To do so, we use another HNLF whose ZDW is 1600 nm. Therefore, the phase matching condition is not satisfied around 1550 nm. The HNLF length is 1 km long with a nonlinear coefficient of 10 W-1km-1, and the dispersion slope at 1550 nm is 0.030 ps/nm2/km. Therefore, this HNLF only induces SPM effect but not CFWM for OFCG. Figure 14 shows the experimental scheme (marked as Scheme 4) of OFCG using SPM only. A 10 GHz RF signal is applied on the PM and the modulation depth of PM is still ~1.28π. A segment of SMF of 5-km length is used to compensate the chirp induced by the PM. An MZM is used to cut the pulse to generate a better pulse source with free DC floor. As the SPM is insensitive to the laser wavelength, we fix the laser wavelength at 1560.2 nm. The parameters are set as same as Scheme 3 except the employed HNLF. Therefore, the output waveforms and spectra after MZM and SMF1 are as same as those of Fig. 11. To enhance the SPM in the HNLF, the pulse generated after SMF1 is then amplified to a high power by HP-EDFA.

![Scheme 4](image)

Fig. 14. Experimental setup of the SPM based OFCG.
Figure 15(a) shows the output spectrum of the OFCG when the pump power is set at ~970 mW. One can see a very flat OFC is obtained. We use an optical bandpass filter (OBPF) with bandwidth of ~8 nm to tailor the flat comb lines, as shown in dash line of Fig. 15(a). The tailored spectrum is shown in Fig. 15(b). The output spectrum has a flat OFC of 91 lines with power deviation less than 5-dB and OTNR larger than 17-dB. We further tune the output power of HP-EDFA to ~1.5 W, a wider spectrum is obtained as shown in Fig. 15(c). And using another OBPF with a bandwidth of ~10 nm, we obtain another 10GHz OFC of 103 comb lines with power deviation less than 5-dB and OTNR larger than 16-dB, as shown in Fig. 15(d). To achieve ultra-short pulse generation, we use another 200 m SMF (SMF2) to compensate the chirp induced by HNLF. When the pump power is 970 mW, we observe an ultra-short pulse with a FWHM of 2.50 ps, as shown in Fig. 16. Compared with the aforementioned schemes, this scheme can generate flat and broadband OFC without using any special filter element.
4. OFCG by hybrid nonlinear effects (Scheme 5)

To further broaden the OFC, we can employ the hybrid nonlinear effects by cascading two HNLFs with different ZDWs. Figure 17 shows the experimental setup, marked as Scheme 5. The experimental setup is as same as the configuration of Fig. 14 except that the second HNLF (HNLF2) with a ZDW of 1550 nm follows the first HNLF (HNLF1) with a ZDW of 1600 nm. Only strong SPM effect occurs in HNLF1 to produce multi-sideband components. These frequency components with relatively high power then are launched into HNLF2. Since the chirp induced by HNLF1 is not compensated, the output waveform of HNLF1 is not a short pulse. Thus CFWM effect accompanied with weak SPM may occur in HNLF2, which can further broaden the spectrum of the OFC. When output pump power of HP-EDFA is 970.8 mW, the output spectrum is as shown in Fig. 18(a). One can see that the number of available spectral lines is 259, which is greatly increased compared to the aforementioned schemes. But the flat spectral region only spans 7 nm. Then an OBPF with a bandwidth of 7.5 nm is used to filter out the central flat spectrum, we obtain a flat OFC with 86 spectrum lines, as shown in Fig. 18(b). Then a 200 m SMF (SMF2) is used to compress the chirps of the HNLF2, and the measured temporal waveform is shown in Fig. 19, which suggests a short pulse with FWHM of 2.25 ps.

![Scheme 5](image)

Fig. 17. Experimental setup of modified hybrid OFCG.

![Fig. 18](image)

Fig. 18. (a) The wide spectrum obtained after HNLF2 (solid line) and the filter shape of the OBPF (dash line) and (b) the flat OFC generated after the OBPF, when the input optical power of HNLF1 is 970.8 mW.
Fig. 19. Ultra-short pulse generated after SMF2 in Scheme 5.

We have demonstrated five different schemes to generate broadband OFC. Scheme 1 is a very simple approach to generating OFC where only CFWM in HNLF is used. The number of available spectral lines is 60. However the OFC flatness is very poor. Scheme 2 and Scheme 3 are improved schemes to reshape the CW source to a pulsed source. So the peak power launched into the HNLF is greatly increased. Thus the CFWM effect is enhanced along with the SPM effect. Especially in Scheme 3, the number of available spectral lines is 179 and 143 come lines with power deviation less than 4.5-dB is obtained. Scheme 4 has demonstrated 197 available spectral lines using SPM only in the HNLF. And 91 comb lines with power deviation less than 5-dB are obtained. Finally Scheme 5 is a hybrid scheme using two HNLFs with different ZDWs. Since both SPM and CFWM are employed using different HNLFs, the available spectral lines are measured at 259, the best one of all these schemes. Table 1 shows the performance comparison of all these schemes, where the repetition rate of RF signal applied on the PM is 10 GHz, the laser wavelength is set at 1560.2 nm, and the output pump power of HP-EDFA is set around 970 mW.

Table 1. Comparison analysis of several OFCG schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Involved nonlinear effect</th>
<th>Comb lines within 5-dB flatness@10 GHz</th>
<th>OTNR</th>
<th>Available spectrum lines @10 GHz</th>
<th>FWHM</th>
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<td>259</td>
<td>2.25 ps</td>
</tr>
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</table>

6. Conclusions

We have compared several OFCG schemes based on different nonlinear effects in the HNLF. Some important parameters affecting the performance of the OFCG are investigated in detail, such as the launched pump power of the HNLF, laser central wavelength and repetition rate of driving RF signal. Experimental results show that the number of spectral lines and the spectral flatness can be increased utilizing strong CFWM and SPM processes in HNLF. When only CFWM occurs in the HNLF, broadband OFC can be achieved with poor spectral flatness. Based on Scheme 3 where both CFWM and SPM occur simultaneously in the same HNLF, we have obtained a 10 GHz flat OFC of 143 comb lines. In Scheme 4, when only SPM occurs in the HNLF, the available spectral lines are 197. In Scheme 5, when two cascaded HNLFs with different ZDWs are used, the available spectral lines are 259, which is the best one of all these schemes. Moreover, all the proposed schemes have the advantages of variability on the central frequency and frequency span of the OFC.
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