Ultra-flat optical frequency comb generation based on electro-optic intensity modulator with digital driving signal

Yu Liu
Shanghai University
Shibao Wu (wushibao@shu.edu.cn)
Shanghai University https://orcid.org/0000-0002-3378-7589
Xianmin Shen
Shanghai University

Research Article

Keywords: Optical frequency comb, Intensity modulation, Digital driving signal, Band-stop filter

Posted Date: May 11th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1137183/v1

Ultra-flat optical frequency comb generation based on electro-optic intensity modulator with digital driving signal

Yu Liu, Shibao Wu*, Xianmin Shen

Key laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University, Baoshan District, Shanghai 200444, China

***Corresponding author**

E-mail address: **wushibao@shu.edu.cn**

Abstract: We propose a new scheme to generate flat optical frequency combs (OFCs) by the electro-optic modulation method. A digital signal is used instead of the usual RF signal to drive an electro-optic intensity modulator (IM), a band-stop filter is employed to flatten the comb lines. When suitable filter bandwidth is found, the ultra-flat optical frequency comb will be generated. The scheme can generate a large number of comb lines, the number of lines is selective, and the flatness of the comb lines is less than 0.4 dB. The comb spacing of OFCs can be adjusted by controlling the bit rate of the digital signal which is simple and easy to operate. The theoretical model of the scheme is established. Two kinds of band-stop filters (Butterworth and Gaussian) are used for comparison.

Keywords: Optical frequency comb; Intensity modulation; Digital driving signal; Band-stop filter

1. Introduction

Optical frequency comb has become the focus of research in recent years, and has been applied to the fields of Optical communication, photonic microwave signal processing, precise optical metrology, arbitrary waveform generation and so on[1]-[3]. In high-speed optical transmission system, flat optical frequency comb can be used as a multi wavelength light source for communication, and the flatness is an important index of the optical frequency combs in this case. At present, there are many methods to generate optical frequency comb, such as mode-locked laser method, nonlinear effect method of nonlinear medium, micro resonant cavity method and the method based on electro-optic modulator[4]-[8]. Among them, the method based on electro-optic modulator is widely used because it is easy to realize[9]. Common methods for generating optical frequency combs based on electro-optic modulators include recirculation frequency shift and direct modulation[10]-[13]. Recirculation frequency shift includes unidirectional recirculation frequency shift and bidirectional recirculation frequency shift, the seed light source of the loop can be single seed source or multiple seed source. The main disadvantage is that with the increase of the number of cycles, the noise in the system will accumulate. The direct modulation can use intensity modulator, phase modulator, polarization modulator and Mach-Zehnder modulator, and the modulators can be connected in parallel or cascaded. By changing the drive signal and direct current (DC) bias of the modulator, the comb spacing, the number of comb lines and the flatness of the generated optical frequency comb can be controlled effectively. Yan mentioned that using digital signals instead of radio frequency signals to drive modulators, and using simulated annealing algorithms to select and design the input pseudo random data sequences[14]. However, this method is fully programmed, the selected algorithm is complex. When the number of comb lines increases or the comb spacing becomes larger, the comb lines will become more and more uneven.

Therefore, in this paper, we report an implementation scheme of an ultra-flat optical frequency comb generator based on the digital signal-driven intensity modulator (IM) and band-stop optical filter. It is more flexible and simpler compared with previous methods based on the radio frequency driven IM. After IM modulation, a uniform but uneven optical frequency comb can be generated, then we use a band-stop filter to adjust the amplitude of comb lines. Not only can the comb spacing be tuned in a large range, which is suitable for the optical transmission system, but also can generate lots of comb lines. The proposed scheme is simple in structure and easy to implement, and the generated optical frequency comb is very flat, the flatness is less than 0.4dB under the condition of appropriate filter bandwidth. Finally, we compared the performance of the two kinds of band-stop filters in the system.

2. Principle and theoretical analysis

Here we present a proof-of-concept device based on IM for generating ultra-flat optical frequency combs. The device is mainly composed of pulse generator, continuous-wave seed laser, intensity modulator, band-stop filter, band-pass filter, as shown in the Fig.1.

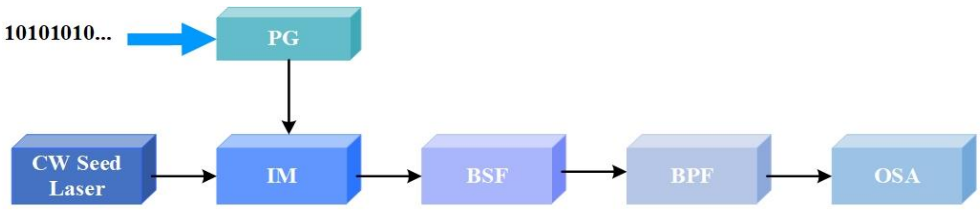


Fig. 1 Proof-of-concept setup for generating the OFC of high quality based on IM

PG: pulse generator; CW: continuous-wave; IM: intensity modulator; BSF: Band-stop filter; BPF: Band-pass filter; OSA: optical spectrum analyzer

In the time domain, a waveform generator controlled by a simple binary sequence 101010… generates a periodic square-wave signal with duty ratio of 0.5.

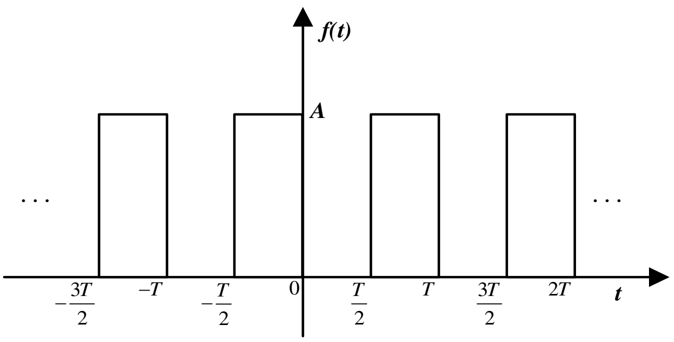


Fig. 2 Periodic square-wave signal waveform

Fig. 2 is a waveform diagram of a periodic square-wave signal. In one period

$$f(t)=\begin{cases} A & -\dfrac{T}{2}\le t<0 \\ 0 & 0\le t<\dfrac{T}{2} \end{cases} \tag{1}$$

Expanding $f(t)$ with the Fourier series of the trigonometric function:

$$\begin{aligned} f(t) &= \frac{2A}{\pi}\sin\omega_0 t+\frac{2A}{3\pi}\sin 3\omega_0 t+\frac{2A}{5\pi}\sin 5\omega_0 t+\ldots+\frac{2A}{n\pi}\sin n\omega_0 t+\ldots \\ &= a_0+\sum_{n=-\infty}^{+\infty} a_n \sin(n\omega_0 t) \end{aligned} \tag{2}$$

Where $\omega_0=\dfrac{2\pi}{T}$, and T is the period of the square-wave signal. $a_0=0$, n is an odd integer, $n=\pm1,\pm3,\pm5\ldots$ and $f(t)$ in the frequency domain is:

$$f(\omega)=\sum_{n=-\infty}^{+\infty} c_n\cdot 2\pi\delta(\omega-n\omega_0) \tag{3}$$

The amplitude value of each spectral line in the complex spectrum is $|c_n| = a_n / 2 = A / |n|\pi$, the spectral line interval is $2/T$.

The input optical signal of the IM can be expressed in frequency domain as $E_{in}(\omega)=2\pi \cdot \mathrm{E}_0 \cdot \delta(\omega-\omega_c)$, where $\omega_c = 2\pi f_c$, f_c is central frequency of the seed light from the CW laser, and E_0 is the electric field amplitude of the optical signal.

The output of the intensity modulator in the frequency domain can be expressed as:

$$\begin{aligned} E_{IM\_out}(\omega) &= \frac{1}{2\pi} E_{in}(\omega) * f(\omega) \\ &= E_{in}(\omega) * \sum_{n=-\infty}^{+\infty} c_n \cdot \delta(\omega - n\omega_0) \\ &= \sum_{n=-\infty}^{+\infty} c_n \cdot E_{in}(\omega - n\omega_0) \\ &= \sum_{n=-\infty}^{+\infty} \frac{2A\cdot \mathrm{E}_0}{n} \cdot \delta(\omega-\omega_c-n\omega_0) \quad ,n=\pm1,\pm3,\pm5... \end{aligned} \tag{4}$$

In order to obtain flat optical frequency combs, we use a band-stop filter to shape the uneven comb lines. Two kinds of band-stop filters, Gaussian filter and Butterworth filter, will be used for comparative analysis.

First, we consider using Gaussian band-stop filter. The normalized power transfer function of a linear time-invariant Gaussian band-stop filter can be expressed as:

$$H_G(\omega) = 1 - exp\left[-\frac{ln\,2\cdot(\omega-\omega_c)^{2k}}{2\omega_f{}^2}\right] \tag{5}$$

Where $\omega_c = 2\pi f_c$, f_c is central frequency of this filter. And $\frac{\omega_f}{2\pi}$ is the 3dB bandwidth of the filter, k is the order of the Gaussian band-stop filter.

Thus, the final output power spectrum of the experimental device is obtained:

$$\begin{aligned} P_{G\_out}(\omega) &= \left|E_{IM\_out}(\omega)\right|^2 \cdot H_G(\omega) \\ &= \sum_{n=-\infty}^{+\infty} \left|2\pi\cdot \mathrm{E}_0 \cdot c_n\right|^2 \delta(\omega-\omega_c-n\omega_0)\cdot\left\{1-\exp\left[-\frac{\ln 2\cdot(\omega-\omega_c)^{2k}}{2\omega_f{}^2}\right]\right\} \\ &= \sum_{n=-\infty}^{+\infty} \left|\frac{2A\cdot \mathrm{E}_0}{n}\right|^2 \cdot \left\{1-\exp\left[-\frac{\ln 2\cdot(n\omega_0)^{2k}}{2\omega_f{}^2}\right]\right\} \quad ,n=\pm1,\pm3,\pm5... \end{aligned} \tag{6}$$

The same analysis can be carried out for the Butterworth band-stop filter, whose power transmission function as follows:

$$H_B(\omega) = 1 - \frac{1}{1+(\frac{\omega-\omega_c}{\omega_f})^{2k}} \tag{7}$$

Thus, the final output is:

$$P_{B\_out}(\omega) = \left|E_{IM\_out}(\omega)\right|^2 \cdot H_B(\omega)$$

$$= \sum_{n=-\infty}^{+\infty} \left|2\pi \cdot \mathrm{E}_0 \cdot c_n\right|^2 \delta(\omega - \omega_c - n\omega_0) \cdot \left\{1 - \frac{1}{1 + (\frac{\omega - \omega_c}{\omega_f})^{2k}}\right\} \tag{8}$$

$$= \sum_{n=-\infty}^{+\infty} \left|\frac{2A \cdot \mathrm{E}_0}{n}\right|^2 \cdot \left\{1 - \frac{1}{1 + (\frac{n\omega_0}{\omega_f})^{2k}}\right\} \quad , n = \pm1, \pm3, \pm5 \ldots$$

It can be seen from the equation(6) and equation(8) that when both n and ω_0 are determined, the magnitude of each spectral line is only related to ω_f, the bandwidth of the filter can be changed to adjust the flatness of the OFC.

3. Experimental simulation and results analysis

In this section, we discuss the generation of ultra-flat optical frequency comb based on the digital signal-driven IM and band-stop optical filter. In order to verify the feasibility of our proposed scheme, we use VPI TransmissionMaker commercial software to make a simulation, and analyze the performance of the scheme. As shown in Fig.1, one continuous-wave (CW) seed laser is used as the light source with output power of $10mW$, center frequency at $193.1THz$ and linewidth at $100KHz$. The MZM modulator with $40GHz$ bandwidth is in push-pull mode to act as an intensity modulator. In this case, we set the half-wave voltage of the MZM to $3.5V$, the extinction ratio to $35dB$, the insertion less to $6dB$ and the DC bias is $0.5V_\pi$. The binary sequence is 101010... with duty cycle of 0.5. The center frequency of the band-stop filter is $193.1THz$ which is the same as the seed laser. The comb spacing of the generated optical frequency comb can be changed by controlling the bit rate of square-wave signal.

Fig. 3 shows the output spectrum of the intensity modulator, the spectrum is a 64-line optical frequency comb with the comb spacing of 6.25GHz. It is obvious that the comb is not flat and also contains the carrier, and the comb spacing is not uniform. Therefore, a filter is added after the intensity modulator to adjust the amplitude of comb lines to generate ultra-flat optical frequency combs. The following analysis is based on the Gaussian filter.

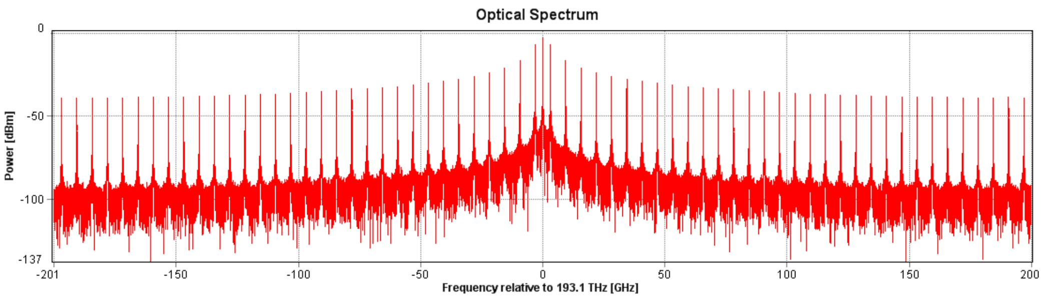
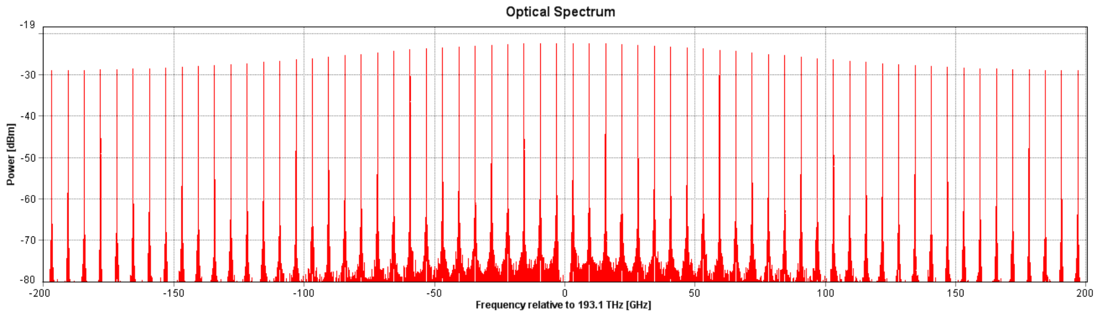
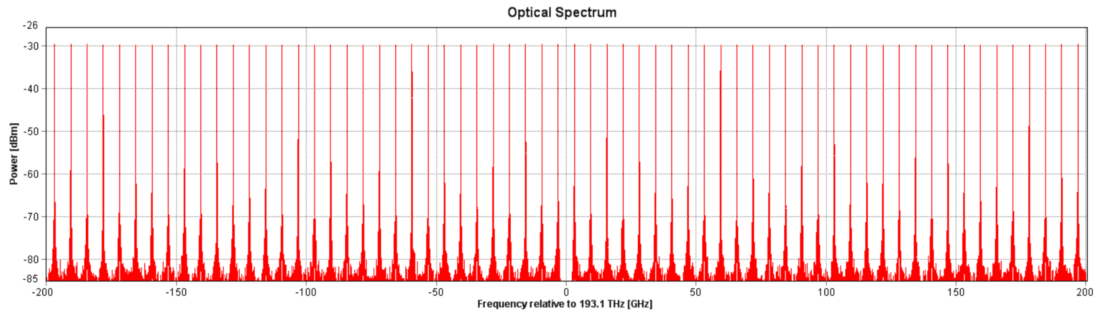


Fig. 3 The output 64-line optical comb of the IM with the comb spacing of 6.25GHz

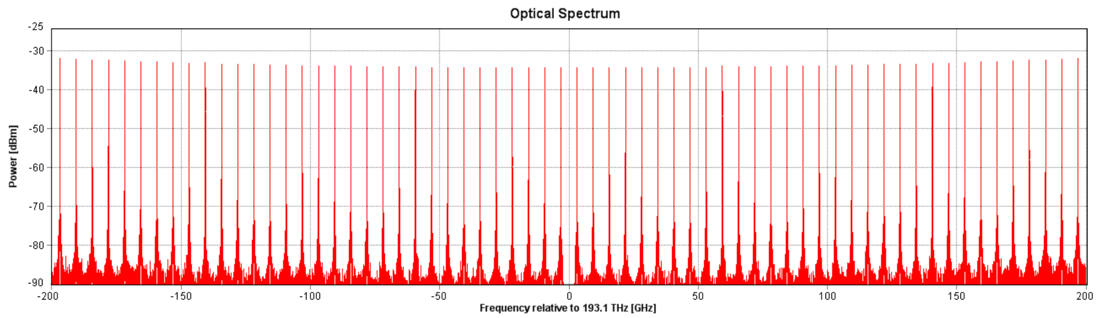
According to the above analysis in the section 2, changing the filter bandwidth will change the flatness of the comb. Therefore, in order to study the influence of filter bandwidth on the flatness of optical frequency combs, different filter bandwidths will be set for the research. Figure 4 shows the flatness of the 64-line optical frequency comb with 6.25GHz comb spacing at different filter bandwidths after the Gaussian band-stop filter. When the filter bandwidth is set to 100GHz, 232.24GHz and 400GHz, the measured flatness of the generated optical frequency comb is 5.7dB, 0.25dB and 1.8dB respectively, as shown in Fig.4 (a-c). It can be seen that there is an optimal filter bandwidth of 232.24GHz with which the generated optical frequency comb is the flattest.



(a)



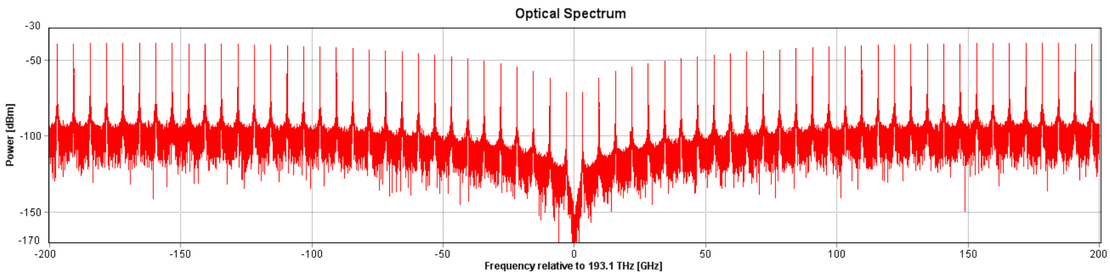
(b)



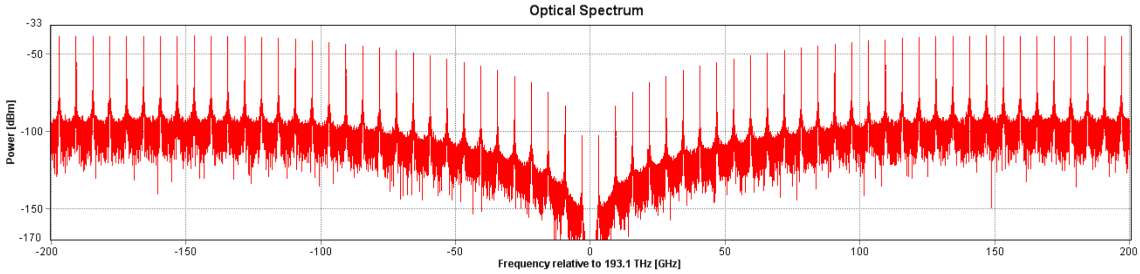
(c)

Fig. 4 The flatness of comb lines varies with the bandwidth of Gaussian band-stop filter (a) 100 GHz, (b) 232.24 GHz, (c) 400GHz

In the above research, the filters are all set to the first order. It can be analyzed from equation (5) and equation (6) that different order of the filter will generate different output power distribution. In order to study the effect of the filter order on the filter output, different orders were set for Gaussian filter. The flattest 64-line optical frequency combs generated with different filter orders are shown in Fig. 5, the spectral line interval is 6.25GHz. As can be seen from the Fig.5, when the order is greater than 1, there will be a middle sag, which makes it impossible to form a continuous flat optical frequency comb near the center frequency. Therefore, the first order filter is selected in our research.



(a)



(b)

Fig. 5 The flattest 64-line optical frequency combs generated with the Gaussian band-stop filter of (a) the 2nd-order, (b) the 3rd-order

In order to obtain the most suitable 3dB bandwidth for generating flat optical frequency combs, we further study the relationship between the flatness and the bandwidth of the optical frequency combs with different comb lines, the comb spacing is 6.25GHz. It can be seen from the figure 6 that when more flat comb lines need to be generated, the required filter bandwidth will increase.

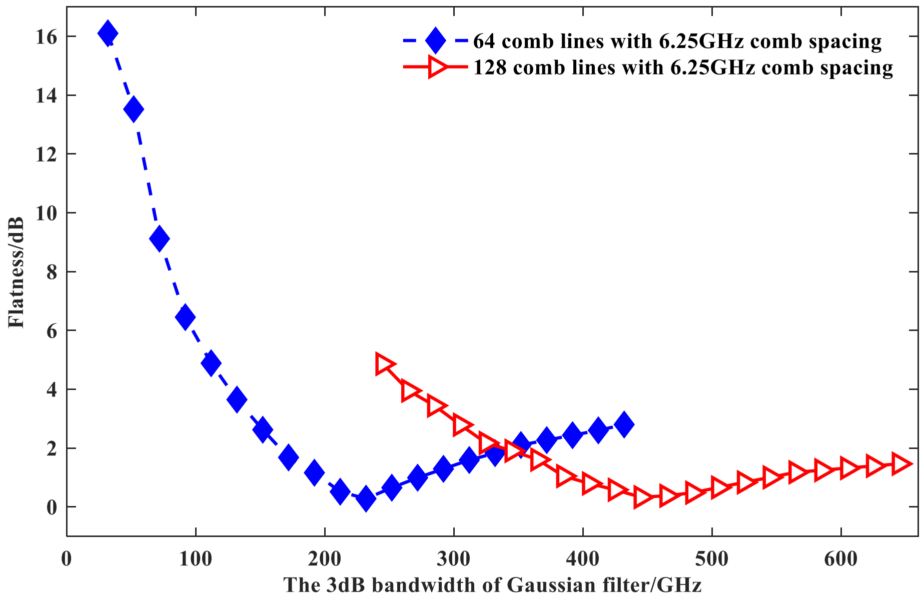


Fig. 6 The comb flatness at different filter bandwidths after Gaussian band-stop filter

Butterworth filter and the Gaussian filter have similar transmission characteristics, but there are still some differences. The two kinds of filters, Gaussian and Butterworth, will be compared and analyzed below. The following analysis is based on the first order filters.

Fig. 7 shows the relationship between the comb flatness and the bandwidth of two kinds of filters when the generated optical frequency combs with 128 lines and 6.25GHz comb spacing. In the case of the same number of comb lines and the same comb spacing. Gaussian filter requires smaller 3dB bandwidth to achieve flattest comb that of Butterworth filter.

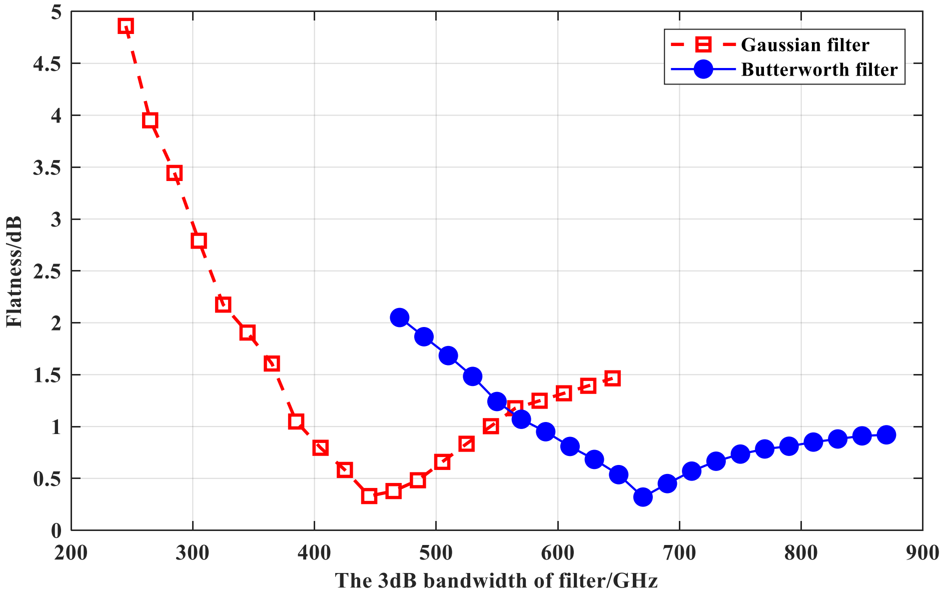


Fig. 7 The comb flatness at different filter bandwidths for the two types of filters

Figure 8 is the flatness of the generated flattest optical frequency combs with 6.25GHz comb spacing and different comb line numbers, respectively. As long as the appropriate filter bandwidth is selected, the comb spacing has little or no affection on the flatness of the optical frequency combs.

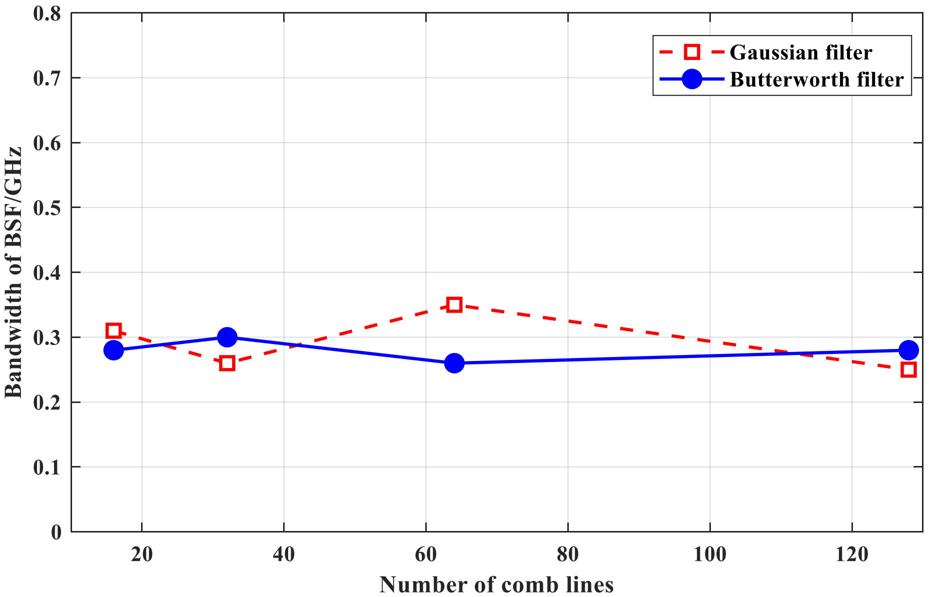


Fig. 8 The combs flatness at different comb line numbers under two types of filters

When the power of the seed carrier is determined, the average power will decrease as the number of comb lines increases. Figure 9 shows the average power of the output comb lines when the flattest combs are generated with different comb line numbers. It can be seen that the average comb line power by Gaussian filter is larger than by Butterworth filter.

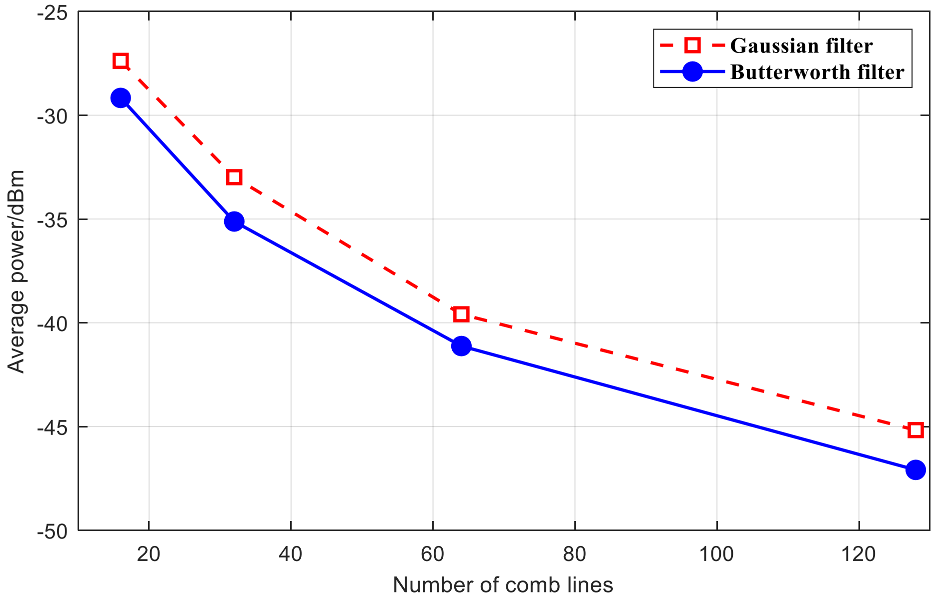


Fig. 9 Average comb line powers at different comb lines with 6.25GHz comb spacing

In fact, we can add a band-pass filter to select the needed number of comb lines. Figure 10 shows 100 comb lines selected from an optical frequency comb with 128 comb lines and 2.5GHz comb spacing.

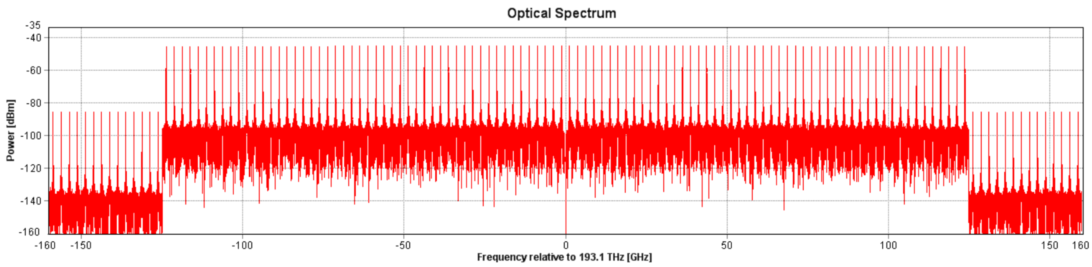


Fig. 10 100 comb lines selected from an optical frequency comb with 128 comb lines

4. Conclusion

We propose a new scheme to generate flat optical frequency combs based on the digital signal-driven intensity modulator and band-stop optical filter. By theory analysis and experiment simulation to verify the feasibility of the proposed scheme. The scheme is more flexible and simpler compared with previous methods based on the radio frequency driven IM. The generated optical frequency combs have the characteristics such as a large number of comb lines, selectable number of comb lines and adjustable comb spacing. When a proper filter bandwidth is chosen, ultra-flat optical frequency combs can be generated. In addition, Gaussian filter and Butterworth filter have similar effect on the generation of the optical frequency combs, using Gaussian filter is relatively better.

Statements & Declarations

This work was supported by National Natural Science Foundation of China (Project No. 61601279, 61601277), Shanghai Science and Technology Development Funds (Project No. 17010500400, 18511103400).

The authors declare that there is no relevant financial or non-financial interests to disclose.

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

[1] Yao J.: Microwave Photonics, Journal of Lightwave Technology, 27(3), 314-335 (2009)

[2] Cundiff S T, Weiner A M.: Optical arbitrary waveform generation, Nature Photonics, 4(11), 760-766 (2010)

[3] Zhi J, Leaird D E, Huang C B, et al.: Spectral Line-by-Line Pulse Shaping on an Optical Frequency Comb Generator, IEEE Journal of Quantum Electronics, 43(12), 1163-1174 (2007)

[4] Cundiff S T, Ye J T.: Colloquium: Femtosecond optical frequency combs, Rev. mod. Phys, 75(1), 325-342 (2003)

[5] Yang T, Dong J, Liao S, et al.: Comparison analysis of optical frequency comb generation with nonlinear effects in highly nonlinear fibers, Optics Express, 21(7), 8508-8520 (2013)

[6] Imai K, Kourogi M.: 30-THz span optical frequency comb generation by self-phase modulation in an optical fiber, IEEE J Quantum Electron, 34(1), 54-60 (1998)

[7] Kippenberg T J, Holzwarth R, Diddams S A.: Microresonator-based optical frequency combs, Science, 332(6029), 555-559 (2011)

[8] Wu R, Supradeepa V R, Long C M, et al.: Generation of very flat optical frequency combs from continuous-wave lasers using cascaded intensity and phase modulators driven by tailored radio frequency waveforms, Optics Letters, 35(19), 3234-3236 (2010)

[9] Chang, William SC: RF photonic technology in optical fiber links, Cambridge University Press (2002)

[10] Li J, Zhang X, Tian F, et al.: Generation of stable and high-quality multicarrier source based on re-circulating frequency shifter for Tb/s optical transmission, Optical Fiber Communication Conference, Optical Society of America, OWE4 (2011)

[11] Li D, Wu S, Liu Y, et al.: Flat optical frequency comb generation based on a dual-parallel Mach–Zehnder modulator and a single recirculation frequency shift loop, Applied optics, 59(7), 1916-1923 (2020)

[12] Zhang J, Yu J, Chi N, et al.: Stable optical frequency-locked multicarriers generation by double recirculating frequency shifter loops for Tb/s communication, Journal of Lightwave Technology, 30(24), 3938-3945 (2012)

[13] Skehan J C, Naveau C, Schroder J, et al.: Widely tunable, low linewidth, and high power laser source using an electro-optic comb and injection-locked slave laser array, Optics Express, 29(11), 17077-17086 (2021)

[14] Yan X, Zou X, Pan W, et al.: Fully digital programmable optical frequency comb generation and application, Optics letters, 43(2), 283-286 (2018)