0.18-dB Ultra-flat Optical Frequency Comb Generation Using Cascaded Modulators with Low Driving RF Power

Xu Xiao, Kan Wu,* and Jianping Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
kanwu@sjtu.edu.cn

Abstract: An improved modulation scheme is proposed for ultra-flat optical frequency comb generation. A comb with 15 lines and only 0.18 dB spectral power variation is demonstrated near 1550nm by using only two modulators.
OCIS codes: (060.0060) Fiber optics and optical communications; (060.5060) Phase modulation; (060.5625) Radio frequency photonics.

1. Introduction

Optical frequency comb (OFC) generation has wide applications in ultrashort pulse generation, microwave photonic processing and optical communication. For microwave photonic application, OFC generation using cascaded modulators have been paid special attention for its flexible tunability of frequency spacing, high stability and simple scheme [1-4]. The flatness of the generated comb plays an important role in many spectrum-processing related applications. For example, microwave synthesis by filtering and beating two comb lines requires equal power of two comb lines to maximize the beating efficiency. Arbitrary waveform generation by attenuating power and tuning phase of each comb line also requires flat comb lines to reduce power penalty and increase signal-to-noise ratio. Moreover, generating flat OFC with less modulators and lower driving radio-frequency (RF) power is always desired from the view of better stability, lower power consumption and lower cost.

In this paper, we demonstrate an improved scheme to generate ultra-flat OFC using two cascaded Mach-Zehnder modulator (MZM) and phase modulator (PM). By combining fundamental modulation frequency and its x2 and x5 harmonic frequencies, and precisely balancing their power, an OFC with only 0.18 dB power variation and 15 comb lines has been generated. Moreover, the total driving RF power is only 19.8 dBm noting that most reported works requiring an RF power more than 25 dBm.

2. Experiment and Results

The setup to generate ultra-flat OFC is shown in Fig. 1(a). It is consisted of a continuous wave (CW) laser at 1549.6 nm, a $LiNbO_3$ MZM and a $LiNbO_3$ PM. There are two key designs to improve the OFC flatness. The first is the usage of f_m (2.5 GHz) and $2f_m$ (5 GHz) RF modulation frequencies to drive the MZM. Each frequency generates two nearly equal comb lines on the two sides of the center wavelength. By carefully tuning the power and relative phase of two frequencies using electrical variable amplifiers (VAs) and phase shifter (PS), and the bias point of the MZM using a DC supply, an OFC with 5 lines and 0.09 dB power variation can be obtained, shown in Fig. 1(b). To obtain a wide and flat OFC, a simple approach is to shift this 5-line OFC to a lower center frequency of $-5f_m$ and a higher center frequency of $+5f_m$. Therefore, the spectrum can be filled by 15 equally spaced lines, i.e., a flat 15-line OFC. Based on this analysis, the second key design is to use a $5f_m$ (12.5 GHz) RF modulation frequency to drive the PM. The output spectrum of the PM is shown in Fig.1(c) and the central 15 lines are shown in Fig. 1(d). It can be seen that the power variation is only 0.18 dB.

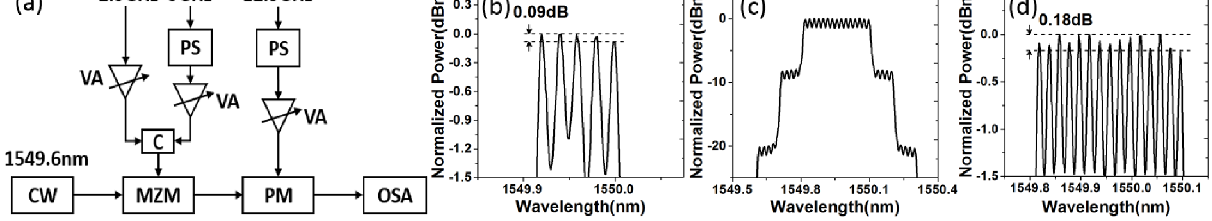

Fig.1. (a) Configuration of the ultra-flat OFC generator, (b) output spectrum of MZM, (c) output spectrum of PM, (d) zoomed view of central 15 flat lines of output spectrum of PM

Another attractive advantage of this scheme is the usage of commercial standard modulators and low input RF power. In previous reported works, modulators with very low Vpi and very high RF power were usually used to obtain a higher modulation index. However, in our scheme, each modulation frequency only contributes to the generation of first two sidebands. Therefore, the requirement on the Vpi of modulators and the applied RF power is very low. In the experiment, we use commercial MZM with Vpi of 5.5V and PM with Vpi of 4.5V. The RF powers of 2.5GHz, 5GHz and 12.5GHz are 10.6 dBm, 11.3 dBm and 19.6 dBm, respectively. The total applied RF power is ~19.8 dBm. In the following table, OFC specifications are compared in the number of lines, flatness and injected RF power for the reported schemes with no more than two modulators. It can be seen that our scheme has significantly improved the flatness of the OFC and reduced the required RF power.

Table.1. Comparison on the OFC specifications in different schemes

Configuration	ours	one dual-arm MZM [1]	MZM+PM [2]	PM+PolM [3]	PolM+PolM [4]
Lines	15	11	15	13	25
Flatness(dB)	0.18	0.5	1.0	2.1	0.92
Injected RF power (dBm)	19.8	32.1	29.0	27.8	26.2

To further investigate the influence of the modulation frequency applied to the PM, we also use 5.0 GHz, 7.5 GHz and 10.0 GHz RF signals to drive the PM. OFCs with high flatness can also be obtained but the number of comb lines is reduced. The experiment results are shown in Fig. 2. Fig. 2(a)-(c) shows the optical spectra when different frequencies are applied and Fig. 2(d) summarizes the performance of four frequencies (including 12.5 GHz). When 5.0 GHz RF frequency is applied to the PM, OFC with 7 lines and 0.07 dB flatness is obtained. When 7.5 GHz is applied, OFC with 9 lines and 0.15 dB flatness is obtained. When 10 GHz is applied, OFC with 11 lines and 0.22 dB flatness is obtained. It is consistent with the previous analysis that $5f_m$ has the best performance.

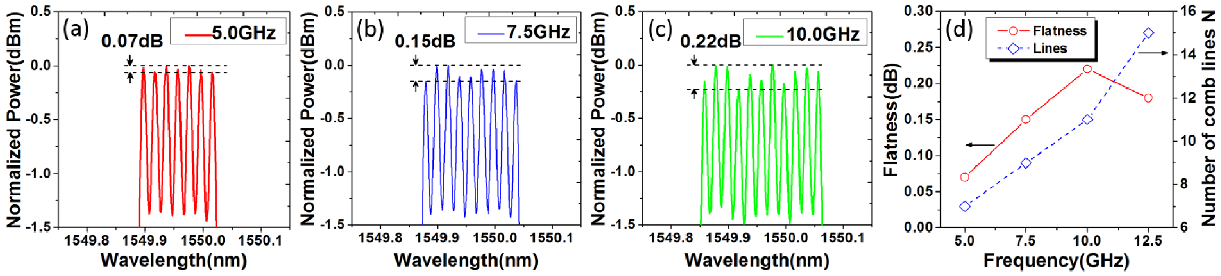

Fig.2. Experimental OFC spectra of different RF frequencies injected to PM: (a) 5 GHz (b) 7.5 GHz (c) 10 GHz, (d) comparison of four different RF frequencies

3. Conclusion

We propose and demonstrate an ultra-flat OFC by simply using two cascaded MZM and PM. The OFC has 15 lines with power variation of only 0.18 dB. Moreover, our scheme has very low requirement on the Vpi of modulators and applied RF power. In the experiment, commercial modulators with Vpi of 4-5V and only 19.8 dBm RF power is applied. It is believed that this high-quality OFC generation scheme with low power consumption and cost can benefit the application of OFC in microwave photonics and optical communications.

References

[1] N. Yokota, K. Abe, S. Mieda, and H. Yasaka, “Harmonic superposition for tailored optical frequency comb generation by a Mach–Zehnder modulator,” Opt. Lett. 41, 1026–1029, (2016).

[2] Y. J. Dou, H. M. Zhang, and M. Y. Yao, “Improvement of flatness of optical frequency comb based on nonlinear effect of intensity modulator,” Opt. Lett. 36, 2749, (2011).

[3] C. Chen, C. He, D. Zhu, R. Guo, F. Zhang, and S. Pan, “Generation of a flat optical frequency comb based on a cascaded polarization modulator and phase modulator,” Opt. Lett. 38, 3137–3139 (2013).

[4] C. He, S. Pan, R. Guo, Y. Zhao, and M. Pan, “Ultraflat optical frequency comb generated based on cascaded polarization modulators,” Opt. Lett. 37, 3834 (2012).