Generation of Seven-Line Optical Frequency Comb Based on a Single Polarization Modulator

Article *in* IEEE Photonics Technology Letters · November 2013

DOI: 10.1109/LPT.2013.2282404

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Generation of Seven-Line Optical Frequency Comb Based on a Single Polarization Modulator

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***Abstract*— A flat and tunable optical frequency comb generation scheme based on a single polarization modulator (PolM) is proposed and experimentally demonstrated. In the proposed scheme, the even- and odd-order optical sidebands of the polarization-modulated signal are split by a polarization beam splitter (PBS) into two paths, respectively. The signal with lower power is amplified and then combined with the other path by a polarization beam combiner. By carefully controlling the power of the radio frequency signal to the PolM, the polarization states of the signal before the PBS and the gain of the erbium doped fiber amplifier, seven flat comb lines can be generated. An experiment is performed. Seven comb lines within 1.8-dB spectral power variation are obtained.**

***Index Terms*— Optical frequency comb, polarization modulation, microwave photonics.**

I. INTRODUCTION

OPTICAL frequency comb (OFC) generation has excited great interests due to its widespread applications in photonic microwave signal processing [1], [2], optical arbitrary waveform generation [3], [4], high-precision photonic sensors [5], and materials characterization [6]. A variety of schemes have been developed for OFC generation, which are usually realized by laser mode-locking [7], [8], fiber nonlinearities [9]–[12], or external modulation [13]–[17]. The method based on laser mode-locking requires sophisticated feedback controls to attain stable operation, and the comb line spacing is hard to be tuned. Fiber nonlinearity, such as four-wave-mixing (FWM) effect, is also used for OFC generation. This method needs high power amplifiers and complicated system designed to achieve high FWM efficiency. In contrast, generation of OFC by external modulation of a continuous wave (CW) light using electro-optic modulators (EOMs) offers advantages of low complexity, high stability and good frequency tunability. Pioneering work on this subject typically uses phase modulation method via a single phase modulator (PM), which has a simple configuration but suffers from poor spectral flatness [3]. To generate a flat OFC using a PM, the PM could be driven by two RF sine waves with different amplitudes and different multiple frequencies [13]. An asymmetrically dual-driven Mach-Zehnder modulator (MZM) can also be used to generate the flat OFC, where the two driving RF signals have different amplitudes [14], [15], or different frequencies [16]. The above techniques utilize only one single EOM, but they require two synchronized RF signal sources, of which the amplitudes and/or frequencies need to be precisely controlled. Moreover, when a MZM is involved, a DC bias control is preferred for better stability. Besides the single EOM structure, cascaded EOMs are also proposed to generate flat OFCs [3], [4], [17]. This method can produce wideband OFC with more comb lines, but the system cost and complexity are increased at the same time.

In this letter, we propose and experimentally demonstrate a flat and tunable OFC generation scheme based on a single polarization modulator (PolM). After polarization-modulation, the even- and odd-order optical sidebands are separated by a polarization beam splitter (PBS) together with a polarization controller (PC). The separated branch with lower power is amplified and recombined with the other branch through a polarization beam combiner (PBC). By appropriately setting the RF power to the PolM, the polarization states before the PBS, and the gain of the optical amplifier, a flat seven-line OFC can be obtained. The scheme uses only one RF signal source, and requires no DC bias to the modulator. The comb line spacing can be easily tuned by changing the RF frequency. In the experiment, flat seven-line OFCs with spectral power variations less than 1.8 dB, and frequency spacing of 3, 5, 7.5, and 10 GHz are successfully generated.

II. OPERATION PRINCIPLE

Fig. 1 shows the operation principle of the proposed scheme. A CW light from a tunable laser source (TLS) is coupled into a PolM via a PC (PC1). The polarization state of the CW light is adjusted to have an angle of 45 degree to one principal axis of the PolM. The PolM is driven by a RF signal with tunable frequency and amplitude. After the PolM, a pair of complementary phase-modulated signals are generated along

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Manuscript received June 23, 2013; revised August 26, 2013; accepted September 2, 2013. Date of publication September 18, 2013; date of current version October 16, 2013. This work was supported in part by the National Basic Research Program of China under Grant 2012CB315705, in part by the National Natural Science Foundation of China under Grant 61107063, in part by the Natural Science Foundation of Jiangsu Province under Grant BK2012031, in part by the Fundamental Research Funds for the Central Universities under Grant NE2012002 and Grant NP2013101, in part by the Natural Science Foundation Plan Project of Fujian Province under Grant 2012D143, and in part by a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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Digital Object Identifier 10.1109/LPT.2013.2282404

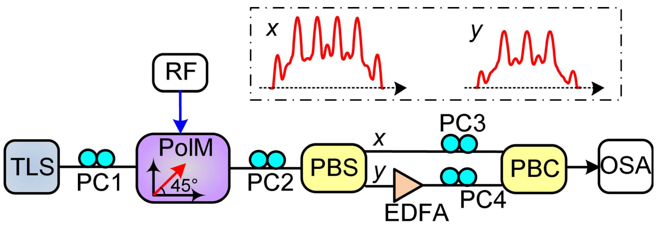

Fig. 1. Schematic diagram of the proposed OFC generation scheme. TLS: tunable laser source; PolM: polarization modulator; PC: polarization controller; PBS: polarization beam splitter; PBC: polarization beam combiner; EDFA: Erbium doped fiber amplifier; RF: radio frequency; OSA: optical spectrum analyzer. (Inset: optical spectra of channel x and y at the outputs of the PBS.)

the two principal axes (x_0 and y_0) [18]. The normalized optical field at the output of the PolM is given by

$$\begin{bmatrix} E_{x0}(t) \\ E_{y0}(t) \end{bmatrix} \propto \frac{\sqrt{2}}{2} \begin{bmatrix} \exp(j\omega_c t + j\beta\cos\omega_m t + j\phi) \\ \exp(j\omega_c t - j\beta\cos\omega_m t) \end{bmatrix} \tag{1}$$

where ω_c and ω_m are the angular frequencies of the lightwave and the driving RF signal, respectively, β is the phase modulation index denoted as $\beta = \pi V_\mathrm{m}/V_\pi$, where V_π is the half-wave voltage, ϕ is the static phase difference between E_{x_0} and E_{y_0}. The polarization-modulated signal is sent to a PBS after its polarization state is properly adjusted by another PC (PC2). After the PBS, the optical signal is split into two orthogonal polarizations. Based on the Jacobi-Anger expansions, the optical fields at the two PBS outputs (x and y) are written as

$$\begin{aligned} E_x &\propto \exp(j\omega_c t)\big[\exp(j\beta\cos\omega_m t + j\phi)\cos\alpha \\ &\qquad - \exp(-j\beta\cos\omega_m t)\sin\alpha\big] \\ &= \exp(j\omega_c t)\sum_{n=-\infty}^{\infty}\big\{j^n J_n(\beta)\cdot\exp(jn\omega_m t) \\ &\qquad \times [\exp(j\phi)\cos\alpha - (-1)^n\sin\alpha]\big\} \end{aligned} \tag{2}$$

$$\begin{aligned} E_y &\propto \exp(j\omega_c t)\big[\exp(j\beta\cos\omega_m t + j\phi)\sin\alpha \\ &\qquad + \exp(-j\beta\cos\omega_m t)\cos\alpha\big] \\ &= \exp(j\omega_c t)\sum_{n=-\infty}^{\infty}\big\{j^n J_n(\beta)\exp(jn\omega_m t) \\ &\qquad \times [\exp(j\phi)\sin\alpha + (-1)^n\cos\alpha]\big\} \end{aligned} \tag{3}$$

where J_n denotes the nth order of the Bessel function of the first kind, α is the angle between one principal axis of the PBS and the principal axis of the PolM. By tuning PC2, both α and ϕ can be adjusted [18]. It can be obtained from Eq. (2) and (3), $\sin(2\alpha)\cos(\phi) = 1$, when $\alpha = \pi/4$ and $\phi = 0$, respectively. Under this condition, only the odd-order sidebands present in channel x and only the even-order sidebands appear in channel y. This indicates that the even- and odd-order sidebands of the polarization-modulated signal are separated by the PBS into two different paths with tuning PC2.

According to Eq. (2) and (3), the relative amplitude of the separated even- or odd-order sidebands can be tuned to the same power level, respectively. Theoretically, by choosing a proper amplitude of the RF signal to let β equal to 5.32 rad, the 0^{th}-(carrier) and $\pm$ 2^{nd}-order sidebands in channel y have the nearly same amplitude, as can be seen from the simulation results in Fig. 2(a) (blue solid line). At the same time, the $\pm 1^{\mathrm{st}}$- and $\pm 3^{\mathrm{rd}}$-order sidebands in channel x achieve very close amplitude, which is also shown in Fig. 2(a) (red dashed line). With the lower power channel (channel y) amplified by an Erbium doped fiber amplifier (EDFA), the two channels are recombined through a PBC. At the output of the PBC, we get

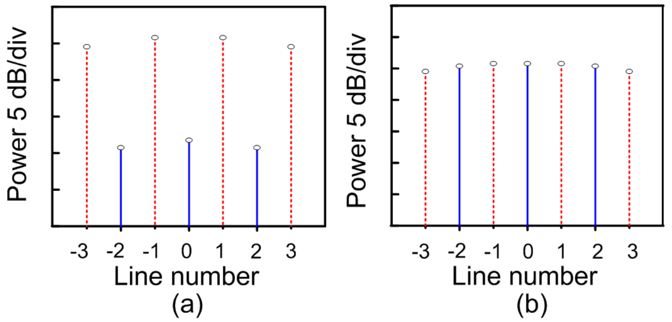

Fig. 2. Simulation results of the relative power distributions. (a) Channel x (odd-order sidebands with red dashed line) and channel y (even-order sidebands with blue solid line) at the two output ports of the PBS, (b) the recombined 7 flat comb lines at the PBC output.

$$|E_{out}|^2 = |E_x|^2 + G\cdot\left|E_y\right|^2 \tag{4}$$

where G is the gain of the EDFA. After properly setting the value of G, the spectral power of the two channels could have nearly the same amplitude, and seven flat comb lines with a flatness of 1.4 dB can be generated, as shown in Fig. 2(b). Besides amplifying the lower power channel, attenuating the optical power of the other channel (channel x) using an optical attenuator can also achieve a flat OFC. Since the basic comb line spacing is determined by the frequency of the RF signal, it can be easily tuned by changing the frequency of the RF signal.

III. EXPERIMENTAL RESULTS AND DISCUSSION

An experiment is carried out based on the setup shown in Fig. 1. The CW light from a TLS (SANTUR TL-2020-C) has a maximum power of 20 mW. The PolM (Versawave Inc.) has a V_π of 3.5 V at 1GHz and a 3-dB bandwidth of 40 GHz, which is driven by a tunable RF signal from a vector signal generator (Agilent E8267D). The PBS has a polarization extinction ratio of more than 35 dB, and the PBC is realized by another PBS. PC3 and PC4 are used to adjust the polarization states of the two channels before the PBC. The spectral properties of the obtained OFC are monitored by an optical spectrum analyzer (Yokogawa AQ6370C) with a resolution of 0.02 nm.

Fig. 3 shows the optical spectra of the generated OFCs when the optical carrier wavelength is 1553.3 nm. With the frequency of the RF signals set to be 3, 5, 7.5 and 10 GHz, and the RF power set to be 25.94, 26.05, 26.19 and 26.32 dBm, respectively, four seven-line OFCs are obtained. The side mode suppression ratio (SMSR) of the combs in Fig. 3(a)–(d) is 6.75, 9.11, 7.76 and 9.04 dB, respectively. The corresponding spectral power variation is 1.63, 1.47, 1.78 and 1.66 dB, respectively, which confirms the good flatness of the seven-line combs. The basic comb line spacing of the combs

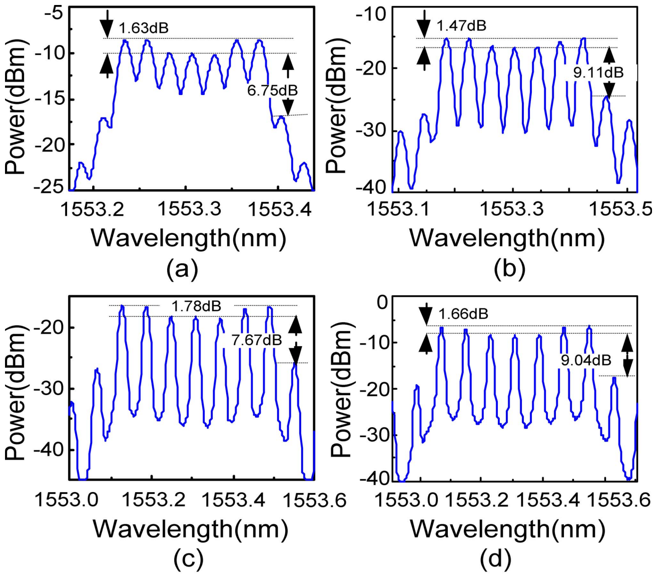

Fig. 3. Optical spectra of the experimentally generated seven-line OFCs with a frequency spacing of (a) 3 GHz, (b) 5 GHz, (c) 7.5 GHz and (d) 10 GHz.

in Fig. 3(a)–(d) is 3, 5, 7.5, and 10 GHz, respectively, which is exactly the same frequency as those of the driving RF signals. When the RF frequency is tuned to other values, the basic line spacing of the obtained OFC is changed accordingly. This verifies the convenient frequency tunability of the scheme. It is worthy noting that, V_π of the PolM is dependent on the frequency of the driving RF signal. Thus, when the frequency of the driving RF signal is changed, the RF signal power needs to be slightly adjusted to ensure the comb flatness. The optical carrier wavelength tunability of our scheme is also investigated by continuously tuning the carrier wavelength from 1548.5 nm to 1561 nm. It is found that the flatness of the obtained OFCs keeps within 0.2 dB. Besides, the generated OFCs have an invariable spectral shape during a 40-min observation.

The above results show that seven flat comb lines with tunable comb line spacing and power variation less than 1.8 dB are successfully generated utilizing one single PolM. The experimental result is very close to the simulation result, and the slight difference is due to the imperfection of the devices we used.

IV. CONCLUSION

In summary, we have proposed a novel method for generating a flat seven-line OFC exploiting a single PolM and a single-frequency driving RF signal. The odd- and even-order optical spectrum can be separated by a PBS together with a PC. Optical frequency comb lines are obtained after recombining the odd-order signal and the amplified even-order signal. Feasibility of the proposed scheme is verified by an experiment. Seven flat comb lines with power deviation within 1.8 dB, and basic line spacing of 3, 5, 7.5 and 10 GHz are successfully generated. The good flatness and easy frequency tunability are confirmed by the experimental results.

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