Ultraflat optical frequency comb generated based on cascaded polarization modulators

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A novel approach to generating an ultraflat and stable optical frequency comb with tunable frequency spacing is proposed and experimentally demonstrated. The proposed generator consists of a polarization modulator (PolM) and a polarizer. The joint operation of a PolM and a polarizer is equivalent to intensity modulation, but with a third controllable parameter in addition to the two controllable parameters in conventional intensity modulation. By tuning the three parameters, an ultraflat optical frequency comb with five comb lines is generated. By cascading the PolM with a second PolM, an ultra-flat optical frequency comb with 25 lines is generated. An experiment using two cascaded PolMs is performed. A 25- line frequency comb with the comb flatness within 1 dB is generated. © 2012 Optical Society of America

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Optical arbitrary waveform generation [1], precise optical metrology [2], high accuracy optical sensor [3], ultrafast optical signal processing [4], and photonic microwave signal processing [5] demand a flat optical frequency comb with a large number of comb lines. Although the amplified fiber loop based optical frequency comb generator can generate thousands of comb lines [6], the phase between these lines is not locked, which is not suitable for the above applications. To generate the frequency comb with a fixed phase relationship between the comb lines, one can apply mode-locked lasers followed by supercontinuum generation in nonlinear optical fibers [7], but this approach always needs a sophisticated scheme to guarantee stable operation. In addition, it is very hard to tune the center wavelength and the frequency spacing of the generated comb in a wide range. An optical frequency comb can also be generated by externally modulating a single laser source with microwave signals [8–11]. Advantages of this method include the simple configuration, stable operation, adjustable wavelength, and precise comb spacing. However, the number of the comb lines is usually limited or the flatness is poor. For example, nine spectral lines within 2 dB power variation were obtained by two cascaded intensity modulators (IMs) [8], and eleven comb lines within 1.9 dB power variation were generated based on a phase modulator (PM) driven by two sinusoidal microwave signals [9]. With the cascaded IM and PM, 15 lines within 1 dB power variation or 17 lines within 3 dB power variation were reported [10]. Although more than 60 comb lines were reported by using two PMs and chirped fiber Bragg grating, the power variation among these lines is larger than 7 dB [11]. The cascaded IMs and PMs in [12] resulted in 38 comb lines with 1 dB flatness, but four modulators must be employed and a very complex setting of the microwave signals was applied.

In this Letter, we propose a novel method to generate an ultraflat optical frequency comb by using cascaded polarization modulators (PolMs). Twenty-five spacing-tunable comb lines within 1 dB power variation are experimentally generated by adjusting the electrical powers to the two PolMs and the polarization states of the optical signals.

The schematic diagram of the proposed optical frequency comb generator is shown in Fig. 1, which consists of a laser diode (LD), two PolMs, three polarization controllers (PCs), a polarizer, and two RF sources (RF1 and RF2).

A linearly polarized lightwave from the LD is aligned by PC1 to have an angle of 45° to one principal axis of the PolM. In the PolM, a pair of complementary phase-modulated signals are generated along the two principal axes [13]. The normalized optical field at the output of the PolM can be expressed as

$$\begin{bmatrix} E_{x1}(t) \\ E_{y1}(t) \end{bmatrix} \propto \begin{bmatrix} \exp(j\beta_1 \sin \omega_{m1} t) \\ \exp(-j\beta_1 \sin \omega_{m1} t) \end{bmatrix}, \tag{1}$$

where ω_{m1} is the angular frequency of the drive RF signal, β_1 is the phase modulation index which is defined as $\pi A_1 / V_{\pi 1}$, where A_1 is the amplitude of the RF signal, and $V_{\pi 1}$ is the half-wave voltage of the PolM. If the polarization-modulated signal is sent to a polarizer, polarization-modulation to intensity-modulation conversion would be performed. The optical field after the polarizer can be written as

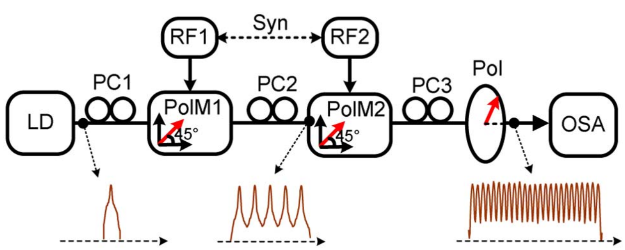

Fig. 1. (Color online) Schematic diagram of the proposed optical frequency comb generator based on cascaded polarization modulators. LD: laser diode; PC: polarization controller; PolM: polarization modulator; RF: radio frequency; Pol: polarizer; OSA: optical spectrum analyzer; and Syn: synchronization.

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$$E_o \propto [\exp(j\beta_1 \sin \omega_{m1} t) \cos \alpha_1 + \exp(j\phi_1 - j\beta_1 \sin \omega_{m1} t) \sin \alpha_1], \quad (2)$$

where ϕ_1 is a static phase term and α_1 is the angle between one principal axis of the PolM and the principal axis of the polarizer. Both ϕ_1 and α_1 can be adjusted by placing a PC before the polarizer. To control ϕ_1 and α_1 separately, one can also apply a $\lambda/4$ waveplate and a $\lambda/2$ waveplate, with ϕ_1 controlled by the $\lambda/4$ waveplate and α_1 adjusted by a $\lambda/2$ waveplate.

Based on Jacobi–Anger expansion, Eq. (2) can be rewritten as

$$E_o \propto \sum_{k=-\infty}^{+\infty} J_k(\beta_1)[\cos \alpha_1 + (-1)^k \sin \alpha_1 \exp(j\phi_1)] \times \exp[jk\omega_{m1} t], \quad (3)$$

where $J_k(\beta_1)$ is the kth order of the Bessel function of the first kind. Therefore, we can get the expressions for the carrier, the ±1st and ±2nd sidebands,

$$\begin{aligned} E_{o0} &= J_0(\beta_1)[\cos \alpha_1 + \sin \alpha_1 \exp(j\phi_1)], \\ E_{o1} &= -E_{o-1} \\ &= \exp(\pm j\omega_{m1} t) J_1(\beta_1) \\ &\quad \times [\cos \alpha_1 - \sin \alpha_1 \exp(j\phi_1)], \\ E_{o2} &= E_{o-2} \\ &= \exp(\pm 2j\omega_{m1} t) J_2(\beta_1) \\ &\quad \times [\cos \alpha_1 + \sin \alpha_1 \exp(j\phi_1)]. \end{aligned} \quad (4)$$

If we let

$$J_0(\beta_1) = J_2(\beta_1) \quad (5)$$

and

$$\sin(2\alpha_1) \cos \phi_1 = \frac{B^2 - 1}{B^2 + 1}, \quad (6)$$

where $B = J_1(\beta_1)/J_0(\beta_1)$, we can get

$$|E_{o0}| = |E_{o1}| = |E_{o-1}| = |E_{o2}| = |E_{o-2}|. \quad (7)$$

To satisfy Eqs. (5) and (6), at least three parameters (i.e., α_1, β_1 and ϕ_1) should be adjustable. For the intensity modulation based on a conventional MZM, α_1 is fixed at $\pi/4$ due to the 50/50 splitting ratio in the Y-splitter of the MZM, and only two parameters (i.e., β_1 and ϕ_1) can be tuned, so no more than three flat spectral lines can be obtained [9]. Unlike the MZM-based intensity modulation, all the three parameters of the PolM-based intensity modulation can be changed by adjusting the electrical powers to the PolM and the polarization states of the optical signal, as shown in Eq. (2), so 5 flat spectral lines can be generated with only one PolM. For instance, Eqs. (5) and (6) are satisfied when $\beta_1 = 5.33$, $\alpha_1 = 2.34$, and $\phi_1 = 3.51$, or $\beta_2 = 5.25$, $\alpha_2 = 4.12$, and $\phi_2 = 0.37$.

Then, the optical signal with 5 spectral lines is sent to the second PolM, which is driven by the RF signal with a frequency that is five times or one fifth of that of RF1. Based on the same principle as described in Eqs. (4)–(7), each spectral line can generate another 5 spectral lines by PolM2 together with the polarizer. As a result, 25 flat comb lines are achieved with the cascaded PolMs. To ensure the phase correlation between the 25 spectral lines, the second RF signal can be generated by applying a frequency multiplier or a frequency divider to the first RF signal.

An experiment based on the setup shown in Fig. 1 is carried out. The LD used in the experiment is a tunable laser source with a maximum power of 20 mW (Santur TL-2020-C). The PolMs (Versawave Inc.) have a bandwidth of 40 GHz and a half-wave voltage of 3.5 V at 1 GHz. A polarization beam splitter (PBS) with a polarization extinction ratio of more than 35 dB is used as a polarizer. The RF signals are generated by two vector signal generators (Agilent E8267D), which are synchronized by a 10 MHz reference signal. Two RF power amplifiers (Agilent 83020A) are used to amplify the RF signals to the satisfactory power level. An optical spectrum analyzer (Yokogawa AQ6370C) with a resolution of 0.02 nm is employed to monitor the optical spectrum.

Figure 2 shows the optical spectra of the 5-line frequency comb with a spacing of 20 GHz generated by a single PolM and the 25-line frequency comb with a spacing of 4 GHz generated by the two cascaded PolMs. To generate the flat optical frequency comb, the setting of the PCs should be adjusted to satisfy (6) and the

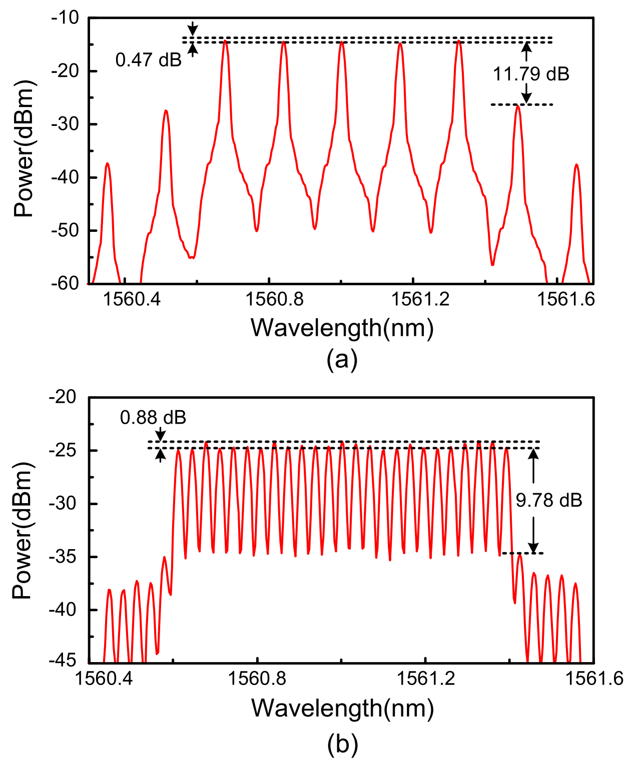

Fig. 2. (Color online) Optical spectra of (a) the five-line frequency comb with a spacing of 20 GHz generated by a single PolM and (b) the 25-line frequency comb with a spacing of 4 GHz generated by two cascaded PolMs.

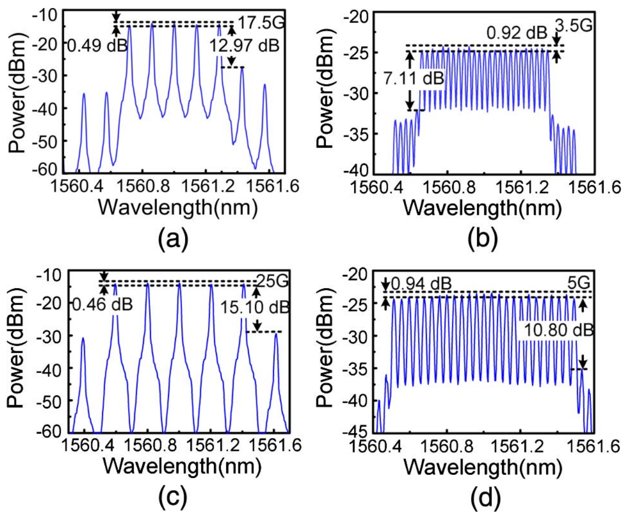

Fig. 3. (Color online) Optical spectra of the five-line frequency comb with a spacing of (a) 17.5 GHz and (c) 25 GHz generated by a single PolM, and the 25-line frequency comb with a spacing of (b) 3.5 GHz and (d) 5 GHz generated by two cascaded PolMs.

electrical powers should satisfy (5), which is implemented by setting the frequency and power of RF1 to be 20 GHz and 25.46 dBm, and those of RF2 to be 4 GHz and 22.73 dBm, respectively. When only RF1 is enabled, as can be seen in Fig. 2(a), we can get 5 flat spectral lines, which have a power variation within 0.47 dB, a wavelength spacing of 0.16 nm (or 20 GHz), and an unwanted-mode suppression ratio (UMSR) of 11.76 dB. When both RF sources are enabled, a 25-line frequency comb can be generated, as shown in Fig. 2(b). The flatness is less than 0.88 dB and the UMSR is 9.78 dB.

One key advantage of the frequency comb generator based on external modulation is its wide-range tunability of the frequency spacing of the generated comb because no wavelength filtering in the optical domain or frequency filtering in the electrical domain is used. Figures 3(a) and 3(b) show the optical spectra of the generated optical frequency combs with a frequency spacing of 17.5 and 3.5 GHz. To obtain the comb, the RF power of RF1 is 25.01 dBm and that of RF2 is 22.82 dBm. The power variations of the 5- and 25-line combs are 0.49 and 0.92 dB, respectively. When the frequency of RF signals increase, we can also obtain the optical frequency combs with a frequency spacing of 25 and 5 GHz and a flatness of 0.46 and 0.94 dB, as shown in Figs. 3(c) and 3(d). In this case, the powers of the two RF sources are 26.35 and 22.02 dBm. Because the half-wave voltages of the PolMs are frequency dependent, the RF power needed for the optical combs with different frequency spacing is different. If the frequency response of the PolMs is flattened, single-parameter tunability of the frequency spacing could be obtained. It should be noted that the UMSRs have a large difference between different figures, which is mainly because of the imperfect setting of the three parameters, i.e., α, β, and ϕ. For instance, according to Eq. (3), when $\alpha = 0.5$, $\beta = 1.8$, $\phi = 0.95$, the flatness is 0.92 dB and the UMSR is 14.47 dB. When $\alpha = 0.8$, $\beta = 5.34$, $\phi = 0.35$, the flatness is 0.88 dB and the UMSR is 2.27 dB.

In addition to the excellent frequency spacing tunability, the generated frequency comb is very stable. In the laboratory environment, the flatness of the 25-line optical frequency comb keeps almost the same for more than 1 h. We attribute this feature to the bias-drift free operation of the PolM since no DC bias is needed.

In conclusion, a novel optical frequency comb generator based on cascaded PolMs was proposed and demonstrated. By simply adjusting the electrical powers to the two PolMs and the polarization states of the optical signals, a 25-line optical frequency comb with tunable frequency spacing and 1 dB flatness was obtained. The method is simple and stable, which can find applications in microwave photonics filters, channelized receivers, wavelength-division-multiplexing systems, optics signal processing and modern instrumentations.

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