Generation of a flat optical frequency comb based on a cascaded polarization modulator and phase modulator

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A scheme to generate a flat optical frequency comb (OFC) with a fixed phase relationship between the comb lines is proposed and experimentally demonstrated based on a cascaded polarization modulator (PolM) and phase modulator. Because the PolM introduces more controllable parameters compared with the conventional intensity modulator, 9, 11, and 13 comb lines can be generated with relatively low RF powers, or 15, 17, and 19 comb lines can be obtained if high RF powers are applied. The experimentally generated 9, 11, and 13 OFCs have a flatness of 1, 1.3, and 2.1 dB, respectively. The scheme requires no DC bias to the modulators, no optical filter, and no frequency divider or multiplier, which is simple and stable.

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In the past two decades, the extensive effort devoted to flat optical frequency comb (OFC) generation has promoted the development of optical microwave signal processing [1], optical arbitrary waveform generation [2–4], high-accuracy optical sensors [5], and precise optical metrology [6]. These applications always require that the phase between the comb lines is strictly locked. Previously, many approaches have been proposed for generating flat and large-line-number OFCs with a fixed phase relationship between the comb lines. For instance, by using passively mode-locked lasers, a smooth spectral profile can be generated [7], but the repetition rate is usually low. To enlarge the wavelength spacing, methods based on cascaded electro-optical modulation have been widely adopted [8–14], which features adjustable wavelength, high stability, precise comb spacing, and low complexity. However, the number of generated comb lines is usually limited for a given flatness, or high radio frequency (RF) power must be fed to the modulators. In [3], a 9-line OFC with a 2 dB flatness was generated based on two cascaded intensity modulators (IMs), and a 25-line OFC with a 1 dB flatness was achieved by using two cascaded polarization modulators (PolMs) [9]. However, two different microwave sources with a fixed frequency relationship are needed to drive the two modulators. In [10], Healy *et al.* generated 11 comb lines with a flatness of 2 dB using two cascaded amplitude modulators, but the applied RF signals were greater than $3.5V_\pi$. Fifteen lines within a 1 dB power variation were achieved with a cascaded IM and phase modulator (PM) [12], but the RF signal applied to the PM should be $\sim 3V_\pi$. Although more comb lines can be achieved by using three or more cascaded modulators, the applied RF powers are typically larger than $7V_\pi$ [13,14].

In this Letter, we propose and experimentally demonstrate a simple method of generating a flat and stable OFC by using a cascaded PolM and PM. Thanks to the three adjustable parameters of the PolM, 13 comb lines can be generated with relatively low RF powers, or 19 comb lines can be obtained if high RF powers are applied. An experiment is performed. By adjusting the polarization state of the optical signal and the powers of RF signals applied to the PolM and PM, OFCs with 13, 11, and 9 lines are obtained with power variations of less than 2.1, 1.3, and 1 dB, respectively. The scheme requires no DC bias to the modulators, no optical filter, and no frequency divider or multiplier.

Figure 1 shows the schematic diagram of the proposed OFC generator, which consists of a tunable laser source (TLS), a PolM, a PM, three polarization controllers (PCs), a polarizer, an RF source, and a phase shifter. The PolM is a special PM that can support both TM and TE modes with opposite phase modulation indices [15]. By tuning PC1, the linearly polarized incident lightwave from the TLS is aligned to have an angle of 45° to one principal axis of the PolM. A pair of complementary phase-modulated signals are generated along the two principal axes of the PolM. The normalized optical field at the output of the PolM along the two principal axes can be expressed as

$$\begin{bmatrix} E_{xo} \\ E_{yo} \end{bmatrix} \propto \frac{\sqrt{2}}{2} \begin{bmatrix} \exp(j\omega_c t + j\beta_1 \cos \omega_m t) \\ \exp(j\omega_c t - j\beta_1 \cos \omega_m t) \end{bmatrix}, \quad (1)$$

where ω_m and ω_c are the angular frequencies of the driven RF signal and the optical carrier, respectively,

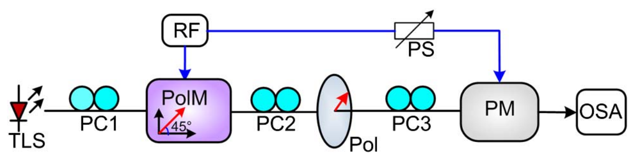

Fig. 1. Schematic diagram of the proposed OFC generator based on a cascaded PolM and PM. TLS, tunable laser source; PolM, polarization modulator; PM, phase modulator; PC, polarization controller; Pol, polarizer; OSA, optical spectrum analyzer; RF, radio frequency; PS, phase shifter.

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and β_1 is the phase modulation index of the PolM, which is defined as $\beta_1 = \pi V_P / V_\pi$, where V_P is the amplitude of the RF signal and V_π is the half-wave voltage. The polarizer with its polarization direction aligned by PC2 is incorporated to combine the two orthogonally polarized signals, so we have

$$E_{o1} \propto [\exp(j\omega_c t - j\beta_1 \cos \omega_m t) \sin \alpha + \exp(j\omega_c t + j\beta_1 \cos \omega_m t + j\phi) \cos \alpha], \quad (2)$$

where α is the angle of the polarization direction of the polarizer and one of the principal axes of the PolM, and ϕ is the phase difference of the signals along the two principal axes of the PolM. Both α and ϕ can be adjusted by tuning PC2 before the polarizer. By introducing the signal in Eq. (2) to the PM, we obtain

$$E_{o2} = E_{o1} \cdot \exp(j\beta_2 \cos \omega_m t), \quad (3)$$

where β_2 is the phase modulation index of the PM. Based on the Jacobi–Anger expansion, the signal in Eq. (3) can be expanded as

$$E_{o2} \propto \exp(j\omega_c t) \cdot \sum_{n=-\infty}^{\infty} j^n \exp(jn\omega_m t)\{J_n(\beta_2 - \beta_1) \sin \alpha + J_n(\beta_1 + \beta_2) \exp(j\phi) \cos \alpha\}, \quad (4)$$

where J_n denotes the nth order of the Bessel function of the first kind. As can be seen, four parameters, i.e., α, ϕ, β_1 and β_2, can be controlled to generate the OFC. As a comparison, the conventional OFC generator based on the cascaded IM and PM [12] has only three controllable parameters. With one additional degree of freedom, moderate comb lines can be generated by the proposed scheme with relatively lower RF powers, or more comb lines can be obtained if high RF powers are applied.

Based on Eq. (4), we can calculate the parameters for obtaining the desired number of comb lines. Table 1 shows some calculation results. As an example, Fig. 2(a) shows a contour plot for the power variation of 19 comb lines when α and ϕ are fixed at 5.53 and 5.69 rad, respectively. With β_1 and β_2 being tuned to satisfy the optimum region marked "1" in Fig. 2(a), the flatness of the output spectra can be controlled to be within 2 dB. Figure 2(b) shows a typical calculated optical spectrum, in which the power variation of the 19 comb lines is about 1.65 dB. Since no DC bias is required for both PolM and PM, the system is free from bias drift problems, ensuring stable operation. In addition, the system can be further simplified if the PolM and PM are polarization-maintaining

Table 1. Typical Parameters for OFC Generation

Comb Lines	α (rad)	ϕ (rad)	β_1 (rad)	β_2 (rad)	Flatness (dB)
9	5.47	0.58	3.60	1.76	0.50
11	3.89	2.49	3.64	1.87	1.37
13	0.64	1.08	4.93	1.82	2.29
15	0.88	0.59	1.98	5.49	2.78
17	3.88	2.52	0.42	8.0	1.80
19	5.53	5.69	0.39	9.14	1.65

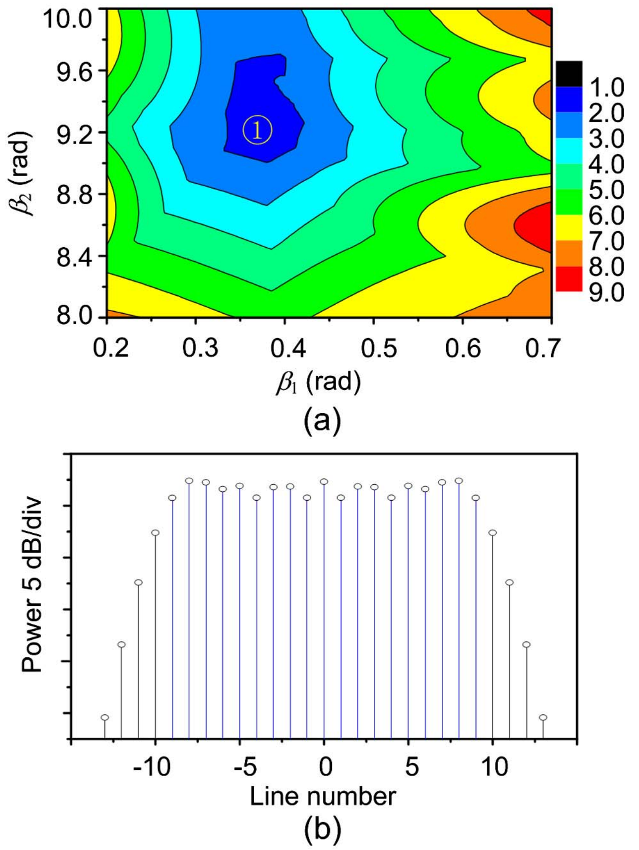

Fig. 2. Typical simulation results of the proposed OFC generator. (a) The power variation contour plot for 19 comb line generation and (b) the relative power distribution within the 19 frequency comb lines.

pigtailed and have inner polarizers at the input ports. In that case, PC1, PC3, and the polarizer can be removed from the scheme. If the polarization of the laser drifts, the power of every comb line would decrease identically, but the flatness of the comb would scarcely vary.

An experiment is carried out based on the setup shown in Fig. 1. The maximum output power of the TLS (SANTUR TL-2020-C) is 20 mW. The PolM (Versawave Inc.) has a half-wave voltage of 3.7 V (at 10 GHz) and a bandwidth of 40 GHz. The polarizer is realized by a polarization beam splitter with a polarization extinction ratio of more than 35 dB. The PM (EOSpace AZ-AV5-40) has a usable bandwidth of 40 GHz and a half-wave voltage of 5.3 V (at 10 GHz). A vector signal generator (Agilent E8267D) serves as an RF source. The frequency of the RF signal is set to be 10 GHz. A power amplifier (Agilent 83020A) and a tunable attenuator are used to adjust the power of the RF signals. The optical spectra are monitored by an optical spectrum analyzer (Yokogawa AQ6370C) with a resolution of 0.02 nm.

Figures 3 and 4 show the optical spectra of the OFC generated by the proposed scheme. With the power of the RF signal applied to the PolM and the PM set to be 26.33 and 19.17 dBm, respectively, 9 flat spectral lines within a power variation of 1.0 dB are obtained if PC2 is carefully adjusted, as shown in Fig. 3(a). When the RF powers are 26.63 and 20.61 dBm, we achieve 11 flat spectral lines with a flatness of 1.3 dB, as shown in Fig. 3(b).

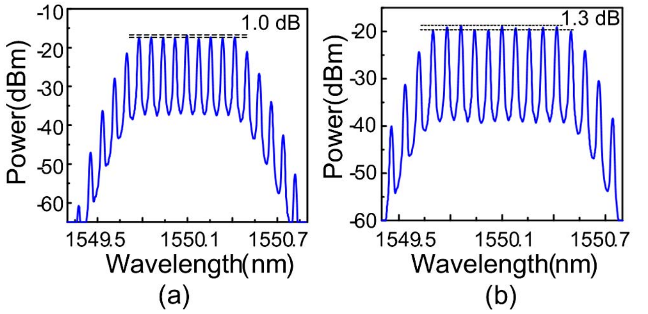

Fig. 3. Optical spectra of the OFC with a spacing of 10 GHz and (a) 9 and (b) 11 lines.

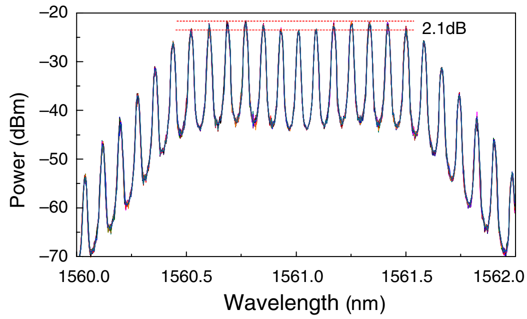

Fig. 4. Sixty superimposed traces of the 13-line OFC with a spacing of 10 GHz.

In Fig. 4, 13 flat comb spectral lines within a flatness of 2.1 dB are observed. In that case, the RF powers are 27.02 and 23.14 dBm, respectively. The 13-line OFC is observed for more than 90 min in the laboratory environment. The power distribution of the OFC generator remains almost the same, indicating that the stability of the scheme is good. Due to the limited RF power that can be undertaken by the modulators, we cannot generate more comb lines in the experiment. But according to the theoretical analysis, 15, 17, and 19 comb lines can still be generated if modulators with more tolerable RF powers are applied.

In conclusion, a novel (to our knowledge) flat OFC generator with an adjustable comb number based on a cascaded PolM and PM was proposed and demonstrated. By adjusting the polarization states of the optical signal and the RF powers applied to the modulators, OFCs with 13, 11, and 9 lines were experimentally obtained, with a flatness of 2.1, 1.3, and 1 dB, respectively. The phase modulation indices required were much lower than those used in previous approaches. Nineteen comb lines can be generated if high RF power is applied to the PM. The proposed OFC generator can find applications in channelized receivers, microwave photonics filters, high-capacity optical communication systems, and modern instrumentation.

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