Tunable optical comb generation based on carrier-suppressed intensity modulation and phase modulation

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An approach to generate a flat optical comb with tunable comb spacing and adjustable comb number is proposed. In the proposed approach, a Mach-Zehnder modulator (MZM), being biased to generate two carrier-suppressed first-order sidebands, is cascaded with a phase modulator. The two optical sidebands are then sent to the phase modulator to generate two identical, but frequency-shifted phase-modulated spectra. Thanks to the complementary nature of the two adjacent comb lines in the phase-modulated spectra, the overlapping of the two spectra would lead to the generation of a flat optical comb. Since only the phase modulation index or the microwave power is needed to be adjusted, the system is easy to be implemented with tunable comb spacing and adjustable comb number. Numerical simulations are performed, and the approach is verified by an experiment.

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Optical combs can find many applications in wavelength-division-multiplexing systems, radio over fiber systems, and modern instrumentations[1−4]. Instead of the laser array, an optical comb can also be generated from a single laser source externally modulated by a microwave signal. It not only significantly simplifies the system configuration but also has the advantages such as stable operation, adjustable operation wavelength, and precise comb spacing[2−13]. Therefore, different configurations using external modulation have been proposed to generate a flat optical comb. In general, these configurations can be classified into two categories. In the first category, a single phase modulator is used, but additional elements are needed to flatten the power spectrum, such as the nonlinear fiber[4], the line-by-line spectral shaper[5], or the chirped fiber Bragg gratings[6]. In the second category, the flatness of the power distribution is improved by using two modulators or a single dual-drive modulator[7−13]. In Refs. [7, 8], an amplitude modulator and a phase modulator driven by two identical-frequency microwave signals were cascaded. The modulation indices, the phase difference between the two microwave signals, and the direct current (DC) bias applied to the amplitude modulator have to be optimized to obtain a flat optical comb. In Refs. [9, 10], a flat optical comb was generated using an intensity modulator and a phase modulator, which were driven respectively by a fundamental microwave signal and its second-order harmonic, and the comb flatness was controlled by a joint adjustment of the modulation indices of the two modulators. A flat optical comb can also be generated using two phase modulators or one dual-drive phase modulator, to which a fundamental microwave signal and its second-[11] or third-order[12] harmonic with the powers and the phase difference of two microwave signals restricted in a selected range were applied. In Ref. [13], an approach to generate a flat optical comb by asymmetrically modulating a dual-drive Mach-Zehnder modulator (MZM) with large modulation indices was proposed, where the phase difference between the two microwave signals and the modulation index difference satisfied a driving condition described by a simple formula.

The techniques discussed above require a simultaneous control of multiple parameters, including the two microwave powers applied, the DC bias, and the microwave phase difference, to ensure a flat power distribution of the comb. The simultaneous control of multiple parameters is not expected since it is difficult to tune the comb spacing and to adjust the comb number. To simplify the operation, in this letter we propose a novel and simple approach to the generation of a flat optical comb, which only requires the control of a single parameter. In this approach, an MZM, being biased at the minimum transmission point to generate two carrier-suppressed first-order sidebands, is cascaded with a phase modulator. The microwave signal applied to the MZM has a frequency of $f_{\rm m}/2$ and the frequency spacing between the two first-order sidebands is $f_{\rm m}$. The two optical sidebands are then sent to the phase modulator to be modulated by a frequency-doubled microwave signal, which results in the generation of two identical but $f_{\rm m}$-frequency-shifted spectra. Thanks to the complementary nature of the adjacent comb lines in the phase-modulated optical spectra, the overlapping of the two generated spectra would lead to the generation of an optical comb with a flat power distribution. Compared with the previous techniques[7−11], the MZM here only functions to produce two optical carriers with a wavelength spacing of $f_{\rm m}$. Different from the techniques in Refs. [9, 10], where multiple parameters should be simultaneously controlled, in the proposed approach only the phase modulation index needs to be controlled, with the flatness, the comb number, and the comb spacing flexibly adjusted by adjusting the phase modulation index.

Generally, the key difficulty associated with the use of phase modulation for the generation of an optical comb is the poor flatness due to the oscillating nature of the phase-modulated power spectrum. Here, we may take advantage of the oscillating nature to generate a flat optical comb. As shown in Fig. 1(a), two identical phase-modulated spectra with a f_{m}-frequency shift are generated. By overlapping the two spectra, a flat optical comb would be generated, as shown in Fig. 1(b). Next we need to obtain two phase-correlated and f_{m}-spaced optical carriers and sent them to the phase modulator.

The proposed approach can be implemented using the system shown in Fig. 2. A continuous-wave (CW) light wave is intensity-modulated by a microwave signal with a frequency of $f_{\mathrm{m}}/2$ in the MZM which is biased at the minimum transmission point for carrier suppression. As a result, two first-order optical sidebands with a frequency spacing of f_{m} are obtained. The two first-order sidebands are then sent to the phase modulator driven by a microwave signal with a frequency of f_{m}, with each sideband acting as an independent optical carrier to generate a phased-modulated spectrum. Since the phase-modulated signals are coherent with nearly complementary power distributions, the overlapping of the two power spectra will generate a flat optical comb. Mathematically, the electric fields of the optical comb lines generated by the overlapping can be expressed as the sum of two Bessel functions with an identical modulation index,

$$E_{k,k+1} = \mathrm{i}^k J_k(\beta) + \mathrm{i}^{k+1} J_{k+1}(\beta), \qquad (1)$$

where β is the phase modulation index, $J_k(\cdot)$ is the kth order Bessel function of the first kind. From Eq. (1), the only parameter that determines the flatness of the power spectrum is the phase modulation index. In other words, by only changing the microwave power applied to the phase modulator, we can get a flat optical comb. Compared with the previous techniques[7−10] in which a simultaneous control of multiple parameters is needed, the proposed approach is easier to be implemented.

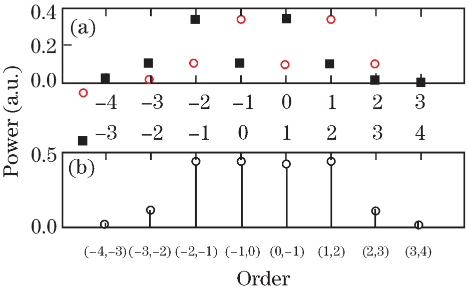

Fig. 1. Conceptual illustration of an optical comb generation by overlapping two phase-modulated power spectra. (a) Two phase-modulated spectra; (b) the overlapped spectrum.

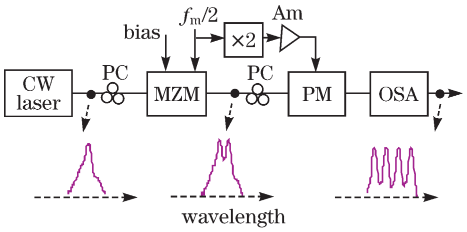

Fig. 2. Schematic diagram of the proposed optical comb generator. PC: polarization controller; Am: microwave amplifier; PM: phase modulator; OSA: optical spectrum analyzer.

The proposed approach provides a simpler and more convenient way to generate a flat optical comb with adjustable comb number and comb spacing. In Refs. [9, 10], the generation of a flat optical comb was achieved based on the convolution between the multiple optical sidebands from the intensity modulator and the phase one. Thus, a specific relationship between the two modulation indices should be satisfied and needs to be changed for different comb numbers. The two modulation indices should be adjusted jointly to reach the specific relationship if different comb numbers are expected. In the proposed approach, however, the total comb number is only associated with the phase modulation index. Therefore, for an adjustable comb number, only the microwave power applied to the phase modulator has to be adjusted. According to Eq. (1), the power distributions of optical combs generated under different modulation indices are shown in Fig. 3. When β is 1.85, 5.1, 10, or 19.8, optical combs having 4 comb lines with a power variation less than 0.2 dB, 6 comb lines with a power variation less than 1 dB, 14 comb lines with a power variation less than 3.2 dB, and 22 comb lines with a power variation less than 3.5 dB, are generated. It is clearly seen that optical combs with flat power distributions are generated under different modulation indices and an increase in the phase modulation index leads to an increase in the comb number. Note that, with the increase of the phase modulation index (or the number of the comb lines), the power variation among comb lines increases. Thus, according to the analysis above, the maximum number of the comb lines generated at one wavelength could be 22 if a maximum power variation of 3.5 dB is specified. To achieve more comb lines, multiple light waves having different wavelengths could be employed, like the work reported in Ref. [7].

In addition, it is known that the half-wave voltages of the modulators vary with the drive frequency. In Refs. [9, 10], the two microwave powers applied to the two modulators should be adjusted if a tunable comb spacing is needed, even though the specific relationship is maintained unchanged. Thus, the proposed approach provides an easy way to tune the comb spacing as well. The power flatness is independent of the microwave power applied to the MZM as long as a small signal modulation condition is ensured. As a result, only the microwave power applied to the phase modulator should be tuned when the microwave frequency is tuned, which makes the tuning of the comb spacing greatly simplified. The robustness of the optical comb depends on the stability of the modulation condition,

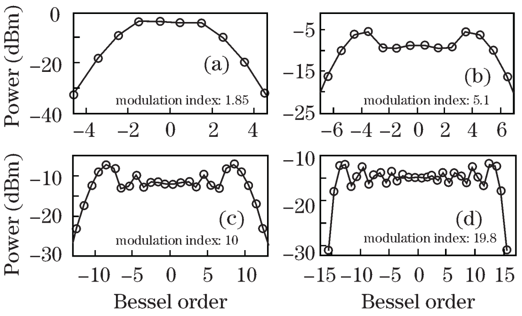

Fig. 3. Optical combs generated under different phase modulation indices.

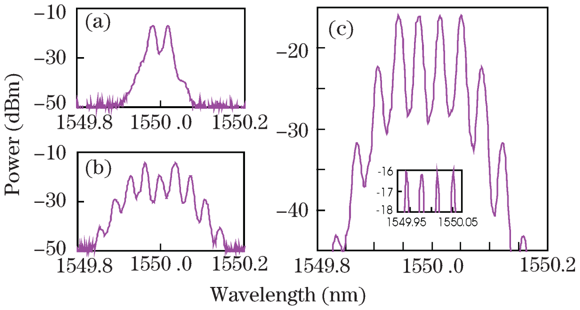

Fig. 4. Measured power spectra. (a) First-order sidebands at the output of the MZM; (b) phase-modulated spectrum with a modulation index of 1.85; (c) generated four-comb-line optical comb.

including the carrier-suppressed modulation in the MZM and the stable large-signal modulation in the phase moldulater. For practical applications, a stability-controlling setup may be needed.

To confirm the effectiveness of the proposed approach, a proof-of-concept experiment based on the setup in Fig. 2 was performed. A 2.25-GHz microwave signal was applied to the MZM biased at the minimum transmission point for carrier suppression. At the output of the MZM, two optical sidebands with a spacing of 4.5 GHz were obtained, as shown in Fig. 4(a). Then a frequency-doubled microwave signal was applied to the phase modulator. To estimate the phase modulation index, the spectrum of the phase modulation with only a single optical carrier was recorded, as shown in Fig. 4(b), with the phase modulation index estimated to be 1.85. With this modulation index, an optical comb with four comb lines was generated. As shown in Fig. 4(c), the power variation of the comb lines is less than 0.2 dB, which agrees well with the result obtained from the simulation in Fig. 3(a). Here the line width of the generated comb lines was approximate 70 kHz which was the line width of the CW laser source (Anritsu MG9638A), since the comb lines were generated by externally modulating the CW laser source using a sinusoidal drive signal.

In conclusion, a novel and simple approach to generate a flat optical comb with tunable comb spacing and adjustable comb number is proposed and experimentally demonstrated. The key to achieve a flat comb generation is the overlapping of two phase-modulated spectra. Thanks to the complementary nature of the phase-modulated spectra, the overlapping of the two spectra leads to the generation of a flat optical comb. Compared with the previous techniques, our approach is easier to be implemented, with the comb spacing and comb number adjustable by simply adjusting the phase modulation index.

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