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An Energy-Saving Optical Comb Generator by Deeply Driven MZM and Multi-Stage Phase Modulators

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Abstract: *We demonstrate a flat comb generator cascading multi-stage phase modulator to an MZM and reusing driving signals. It efficiently broadens bandwidth reducing energy consumptions because the MZM for spectral flattening also enhances the bandwidth and driving signals are reused. 37×25-GHz ultra-wideband combs are experimentally generated.*

Introduction

Optical combs with equally-spaced optical frequency components have several attractive applications, such as optical frequency measurements, optical controls/manipulations, and multiple-wavelength/ ultra-short-pulse light sources [1-6]. When such optical combs are used in practical systems, their spectra must be flat, and their bandwidth should be broader as much as possible. For practical, cost-effective and sustainable comb generation, wideband and flat combs must be efficiently generated with lower energy consumption.

It is well known that deep phase modulation using electro-optic (EO) modulators can easily generate spectrally enhanced optical combs. However, the spectra of phase-modulated lightwave are not flat, which is not suitable for practical comb generation. Previous reports demonstrated that the spectrum of a multi-stage phase-modulated light can be flattened by convoluted with that of a sinusoidally intensity-modulated lightwave generated with a Mach-Zehnder Modulator (MZM), as shown in Fig. 1(a) [2][3][6]. However, optical loss increases because the generator needs one additional EO modulator to flatten the output spectra. The larger cascade scale increases the complexity, and requests more energy for driving the modulators. On the other hand, we previously demonstrated a flat comb generation by single-stage modulation with an MZM [4][5], which significantly simplifies the comb generation saving the number of modulators. We propose in this paper an energy-saving optical comb generator that cascade a multi-stage phase modulator to an MZM. Some of the EO modulators employed in the generator are driven by reused signals. It can generate a comb with wider spectra than conventional generators with the same cascade scale because the MZM in the proposed generator plays a role of enhancing the bandwidth in addition to spectral flattening as shown in Fig. 1(b). In addition, it can further enhance the bandwidth keeping spectral flatness by simply increasing the cascade scale of phase modulators. Normally, as the cascade scale increases, the energy consumption increases; however, the proposed generator consumes less energy because some signals which drive EO modulators are reused in other modulators.

In this paper, we propose an energy-saving optical comb generator which efficiently generates a wideband flat comb. And finally, we experimentally demonstrate flat comb generation with 37×25-GHz spectral width.

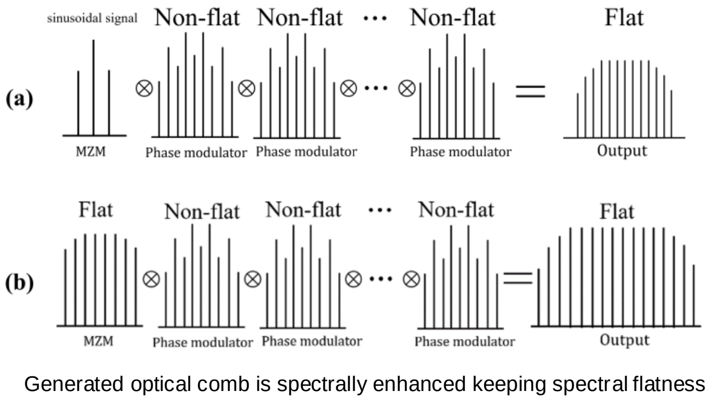


Fig. 1: comb generation by cascaded modulation (a) conventional, (b) proposed

Principles

Conditions for Flat Comb Generation Using the Proposed Comb Generator

The process to generate spectrally broadened flat comb is as follows. An optical comb is output from an MZM, and its spectrum is enhanced with multi-stage phase modulators cascaded in series. In the generator, the EO modulators cascaded in series, as shown in Fig. 1(b). These modulators are synchronously driven with in-phase sinusoidal signals at a common frequency. In general, optical combs generated by cascaded phase modulation have non-flat spectra. However, we propose, in this paper, that the spectra can be flattened if we apply the cascaded modulation on the optical comb generated from the MZM under a specific condition. We found that this can be achieved if the modulation on the MZM in the generator is operated under the following condition.

$$\Delta A \pm \Delta\theta = \frac{\pi}{2} \tag{1}$$

where ΔA is the amplitude difference normalized to induced phase shift [rad] of two signals which is input to the MZM, and $\Delta\theta$ is the bias phase difference. Note that the spectrum of the generated comb under this condition is kept flat even if cascaded phase modulation is applied many times. As shown in Fig. 1(b), no matter how many times the phase-modulator is applied, spectra of the output lightwave are kept flat.

Energy Efficient Comb Generation Reusing Driving Signals

Here we show the advantage of reusing driving signals in the proposed comb generator, considering the difference of modulation depths between with and without reusing the electrical driving signal at the same power consumption. In the case without reusing, as shown in Fig. 2(a), the modulation depth is

$$\phi_{\text{total}} = \eta A_0 \tag{2}$$

where η is modulation efficiency, A_0 is phase shift in each time of modulation. Theoretically, there is no loss in the modulator electrodes when electrical signals are reused; however in reality, there is some loss. Note that modulation depth in Fig. 2(b) is given by $A_0\alpha^n$, where α is the transmittance of each modulator electrode ($\alpha = 1$ means no loss). Thus, the sum of the modulation depth in n times is given by the following equation.

$$\phi_{\text{total}} = \sum_{k=1}^{n} \eta A_n = \eta A_0 \frac{1-\alpha^n}{1-\alpha} \tag{3}$$

Comparing equations (2) and (3), it is clear that the phase of lightwave is shifted more deeply with reusing power. When an MZM is cascaded to n-th phase modulator in Fig. 2(b) as shown Fig. 2(c), the total modulation depth becomes

$$\phi_{\text{total}} = \sum_{k=1}^{n+1} \eta A_{n+1} = \eta A_0 \frac{1-\alpha^{n+1}}{1-\alpha} \tag{4}$$

By cascading an MZM, driven with a reused signal, to the multi-stage phase modulator, it can shift the phase of the lightwave more deeply without increasing power consumption and it also can make spectra flat.

Different from conventional setup (Fig. 1 (a)), the MZM can accept driving signals with higher intensities in the proposed setup (Fig. 1(b)). Conventionally, the role of MZM was only for sinusoidal intensity modulation; thus, the driving signal could not be a high power. This corresponds to Fig. 2(b). In this case, energy efficiency is limited. In the proposed system, the MZM accepts input of higher-power driving signal; accordingly, the MZM also help broaden the generated comb. In this case, we can reuse the driving the signal for comb generation in the MZM as shown in Fig. 2(c).

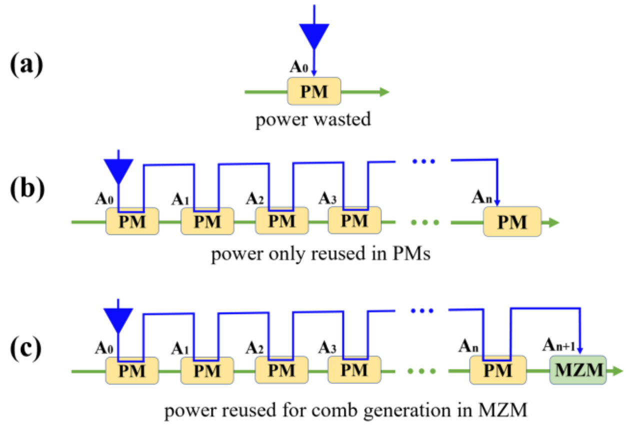


Fig. 2. Reuse of driving signals
(a): w/o reuse
(b): w/ reuse for PMs (conventional)
(c): w/ reuse for PMs + MZM (proposed)

Experiments

Fig. 3 shows the experimental setup for the comb generation. The comb generator consisted of a laser diode (LD), two phase modulators, an MZM, a frequency doubler, four bandpass filters (BPF), four amplifiers, a signal generator (SG), and three mechanical tunable delays. A continuous-wave (CW) light was generated from the LD, whose center wavelength was 1550 nm and intensity was 0.0 dBm, respectively. The CW light was introduced to the modulators in the order of an MZM, one phase modulator and another phase modulator. All modulators were driven with sinusoidal signals (Rf-a, Rf-b, Rf-c, Rf-d) at a frequency of 25 GHz. These signals were generated by the following processes. First, a sinusoidal signal whose frequency was 12.5 GHz was generated from SG. And then, this signal was divided into two signals after the frequency was doubled by the frequency doubler. Rf-a and Rf-b were the amplified signals of those. Rf-c and

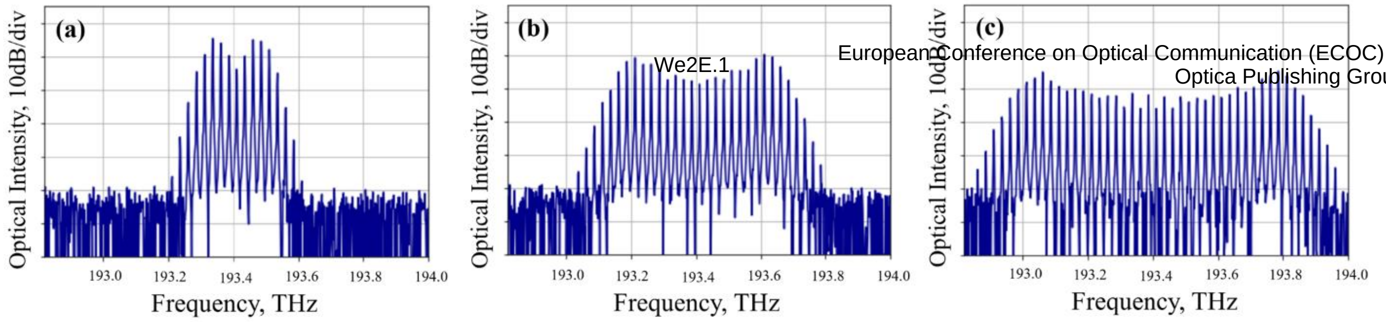


Fig. 4. Measured spectra (spectral enhancement of comb generation)

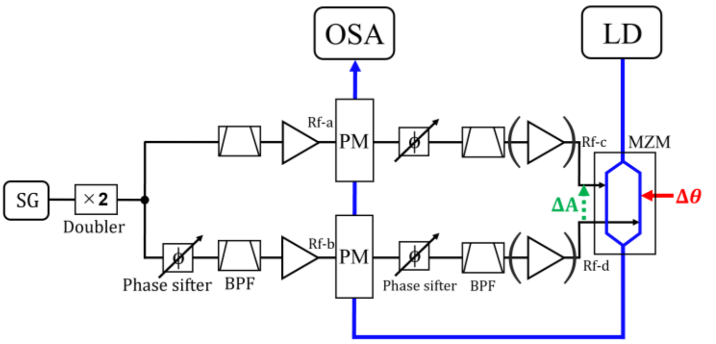
Center wavelength: 1550 nm

(a) MZM output

(b) MZM + PM output

(c) MZM + PM x 2 output

Rf-d were signals that were recycled from Rf-a and Rf-b, respectively. The power of Rf-c and Rf-d were amplified in this experiment because the intensities of Rf-a and Rf-b were too low to enhance bandwidth to drive the MZM after recycling. All the phases of Rf-a ~ Rf-d were aligned to be in-phase using mechanical tunable delays in order that the bandwidth of the optical output was as wide as possible and frequency spectrum was flat.



PM: phase modulator

BPF: bandpass filter (24~26GHz)

Fig. 3. Experimental setup

Figs. 4(a), (b) and (c) show optical frequency spectra observed at the corresponding points indicated in Fig. 3. Fig. 4(a) indicates the frequency spectrum of the lightwave modulated with the MZM. Fig. 4(b) was observed when phase modulation was applied to the MZM output. Comparing Figs. 4(a) and (b), it was found that the number of frequency components within 10-dB bandwidth increased from 11 to 21. Fig. 4(c) indicates the frequency spectrum of the optical output of this generator, which was phase-modulated to the lightwave at (b) in Fig. 3. From Fig. 4 (a) it was found that the MZM driven by the recycled signals enhanced bandwidth, spectrally flattening output lightwave. Finally, the number of frequency components within 10dB bandwidth reached 37 as shown in Fig. 4(c).

To show that the proposed comb generator that reuses the electrical signals can generate a flat comb, we have experimented comb generation without amplifiers led to the MZM in Fig. 3. Fig. 5 shows optical spectra of the output from the comb generator. This shows that a spectrally broadened flat optical comb was generated from the proposed generator even without amplifying the power of the reused signals. From the results, we can conclude that a wideband and flat comb can be generated with much low power as long as power of the driving signals for reusing are high enough.

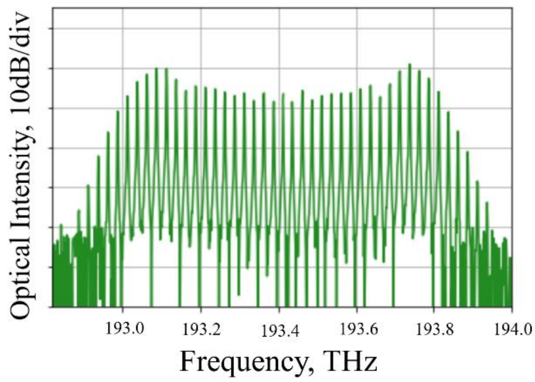


Fig. 5. Measured spectra
(comb generation without amplifiers driving the MZM)
Center wavelength: 1550 nm

Conclusions

In this paper, we have proposed and demonstrated a flat optical comb generator that cascaded a multi-stage phase modulator to an MZM and reuses electrical signals which drive EO modulators. It can efficiently broaden bandwidth because the MZM for spectral flattening also enhances the bandwidth a lot. Furthermore, it consumes lower power assisted by the reuse of signals driving EO modulators. We finally demonstrated a spectrally flattened ultra-wideband optical comb generation with a 37×25-GHz spectral width.

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