1 THz-Bandwidth Optical Comb Generation using Mach-Zehnder-Modulator-Based Flat Comb Generator with Optical Feedback Loop

Isao Morohashi[1], Takahide Sakamoto[1], Naokatsu Yamamoto[1], Hideyuki Sotobayashi[1,2], Tetsuya Kawanishi[1], Iwao Hosako[1]

[1]National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan
[2]College of Science and Engineering, Aoyama Gakuin University, 5-10-1-L218 Fuchinobe, Sagamihara-shi, Kanagawa 229-8558, Japan
Author e-mail address: morohashi@nict.go.jp

Abstract: We demonstrated broadband comb generation using a Mach-Zehnder-modulator-based flat comb generator with an optical feedback loop. A 1 THz-width comb signal was successfully generated by increment of the modulation depth.

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1. Introduction

Wideband multi-wavelength continuous-wave (cw) sources are important for dense wavelength division multiplexing (DWDM) and orthogonally frequency division multiplexing (OFDM) systems. Optical frequency combs are good candidate for such multi-wavelength sources. Furthermore, the comb sources can be used for frequency metrology and radio over fiber (RoF) system. For these purposes, high coherence, high stability, low noise, high efficiency, low cost and simplicity are key issues. In addition, high flatness in spectral intensity is also important. Conventional optical comb sources such as mode-locked lasers [1, 2] have drawbacks in stability, because a long-length cavity is influenced by the environmental conditions. Furthermore, the comb spacing is almost fixed, because that is decided by the cavity length. On the other hand, optical comb sources based on optical modulators are good candidates for a flexible and stable source [3,4]. These sources have no cavity configuration: thus, they can operate stably.

An optical comb generator using a dual-drive-type Mach-Zehnder modulator (MZM) can generate comb signals with good flatness [5]. The benefits of this comb generator are high stability, low jitter, and independent control of the comb spacing and the center wavelength. In addition, this system can operate with alignment-free and turn-key starting. The comb spacing and the bandwidth can be varied by the frequency and the power of an rf signal driving the MZM, respectively. This comb generator has been applied to arbitrary waveform generation [6], and a widely spaced comb generation (40 GHz or more) have been demonstrated by employing this configuration [7].

In general, the obtainable bandwidth of comb signals directly from the comb generator is few hundred gigahertz. To obtain broadband comb signals, nonlinear fibers such as a dispersion-decreasing fiber [8] and a comblike wavelength dispersion profiled fiber [9] are typically used. In order to broaden the bandwidth using these fibers, the high optical power is required to induce nonlinear effect in the fibers. Some broadband comb sources using an optical modulator are also proposed. A comb generator using a $LiNbO_3$ phase modulator installed in a Fabry-Perot cavity was proposed [10]. This source is required a cavity control system to stabilize the operation. On the other hand, comb generators with a feedback configuration are attractive methods. Comb generators, in which a single-sideband (SSB) modulator [11] or a phase modulator [12, 13] was inserted in a feedback loop, were proposed. Comb signals generated by feedback-type comb generator have Gaussian-like shape.

In this paper, we propose a MZM-based flat comb generator (MZ-FCG) with an optical feedback loop as a broadband comb generator. In our technique, the bandwidth of comb signals is broadened with good stability and high flatness.

2. MZ-FCG

In the MZ-FCG, a dual-drive-type MZM is used, which is fabricated on a $LiNbO_3$ crystal. The MZM device is driven by two large-amplitude rf sinusoidal signals with slightly different amplitudes. A continuous-wave (cw) light led to the MZM undergoes electro-optic modulation, which produces multiple side-bands with even spectral spacing on both sides of the fundamental component. The spectral spacing is directly related to the rf frequency, and the number of sideband components is decided by the rf power. Thus, the bandwidth of the optical comb signal is decided by the frequency and the power of the rf signal. Although the amplitudes of each component of the optical comb signal are governed by the Bessel function, they are flattened out when the condition of

$$\Delta A \pm \Delta\theta = \pi / 2, \qquad (1)$$

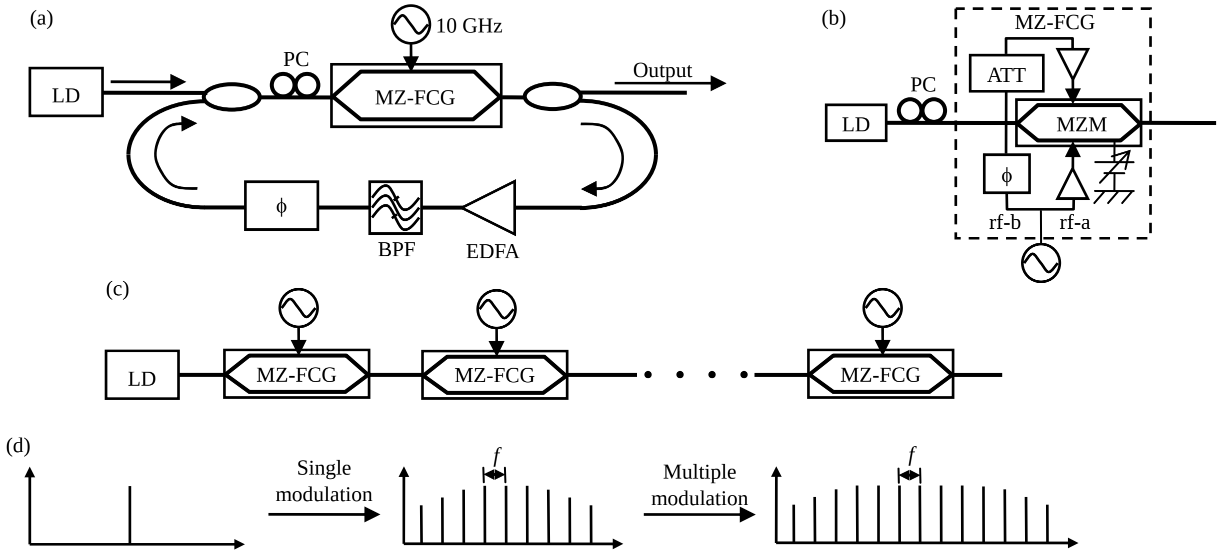

Fig. 1. The MZ-FCG with the optical feedback loop: (a) the system configuration, (b) the setup for the MZ-FCG, (c) the modeled system of the optical feedback loop in a cascaded MZ-FCG system, (d) the sequence of broadband comb generation.

is satisfied (comb flattening condition), where ΔA is half the difference between the amplitudes of the rf signals, and $\Delta\theta$ is half the optical phase difference between the two arms of the MZM [14].

3. Broadband comb generation

Figure 1(a) shows a configuration of the broadband comb generator using a MZ-FCG with an optical feedback loop. Two optical couplers are placed at both sides of the MZ-FCG, and a feedback loop is constructed among the MZ-FCG and the optical couplers. In the feedback loop, an Er-doped fiber amplifier (EDFA), an optical bandpass filter (BPF), and an optical delay line are inserted. A cw light from a LD is launched into the MZ-FCG via one of the couplers. A comb signal generated by the MZ-FCG is split into two components by the other coupler; one is conducted to the feedback loop, and the other is to be the output signal. The comb signal in the feedback loop is amplified by the EDFA to compensate the loss of the feedback loop, and the ASE noise of the EDFA was eliminated by the BPF. After the amplification, the comb signal is fed back to the input side of the MZ-FCG.

This feedback loop can be modeled in a cascaded modulation system as shown in Fig. 1(c), in which a series of the MZ-FCGs successively modulate an input light. Because the cascaded MZ-FCGs increase the modulation depth

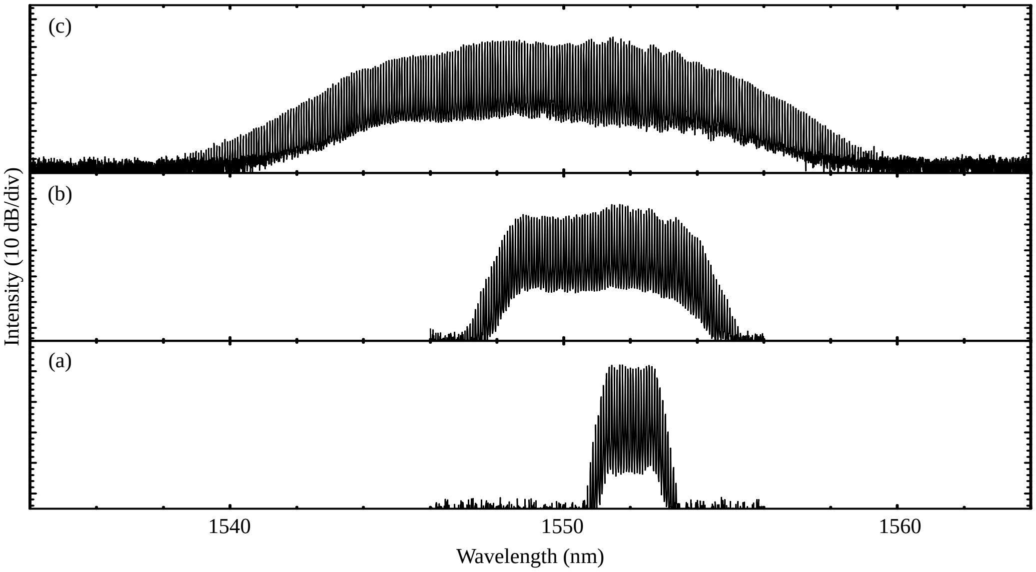

Fig. 2. Spectra of generated comb signals; (a) single-pass configuration, (b) the feedback loop with the 4 nm-width BPF, and (c) with the 10 nm-width BPF

as compared with the single-path MZ-FCG, the bandwidth of the comb signal is broadened, as shown in Fig. 1(d). By setting the driving condition of the MZ-FCG to the comb flattening condition given by Eq. 1, the comb signal in the feedback loop is flatly broadened.

The experimental setup of the MZ-FCG is shown in Fig. 1(b) [15]. An rf signal with the frequency of 10 GHz and the power of 16 dBm was generated by a synthesizer, and split into halves (rf-a and rf-b). The rf-a signal was amplified to 29 dBm, and applied to one arm of the MZM. The rf-b signal was adjusted to be in-phase with the rf-a signal using a mechanical delay line, amplified to 28 dBm, and input to the other arm of the MZM. Flat optical comb signals were obtained by adjusting a bias voltage to satisfy the comb flattening condition given by Eq. 1. A cw light from a distributed feedback (DFB) laser diode (LD) with a wavelength of 1552 nm and the power of 7 dBm was led into the MZ-FCG and was converted to a flat optical comb signal. Figure 2(a) shows a spectrum of a generated comb signal. 34 modes were clearly observed, and the 10 dB-reduction bandwidth of the comb signal was 220 GHz (23 modes).

In the feedback loop, the maximum output power of the EDFA was 20 dBm, and two types of the BPF (the pass-bandwidth of 4.2 and 10 nm) were used. The optical power fed back to the MZ-FCG was set to 10 dBm. Figure 2(b) and (c) show a spectrum of a comb signal generated by the MZ-FCG with the feedback loop. By constructing the feedback loop, broadband comb signals were successfully broadened. In this system, the bandwidth of generated comb signals depends on the bandwidth of the BPF. Figure 2(b) shows a spectrum of a comb signal when a 4.2 nm-width BPF was used. A comb signal with the 10 dB-reduction bandwidth of 680 GHz (69 modes) was observed. When a 10 nm-width BPF was used, the bandwidth of the comb signal was more broadened. A broadband comb signal with the 10 dB-reduction bandwidth of 1.22 THz (122 modes) was successfully generated. Note that the center wavelength of the broadened comb signal was also decided by those of the BPF.

4. Conclusions

We demonstrated broadband comb generation using the MZ-FCG with the optical feedback loop. By constructing the optical feedback loop around the MZ-FCG, the modulation depth was increased, and a comb signal was flatly broadened as compared with the single-path MZ-FCG. A broadband comb signal with the 10-dB reduction bandwidth of 1.22 THz was successfully generated.

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