Broadband Optical Comb Generation using Mach-Zehnder-Modulator-Based Flat Comb Generator with Feedback Loop

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Abstract *We demonstrated broadband comb generation using a Mach-Zehnder-modulator-based flat comb generator with a feedback loop. By constructing the feedback loop, the modulation depth was increased. A generated comb signal was broadened as compared with single-path configuration.*

Introduction

Optical frequency combs can be applied to several attractive applications, for example, wideband multi-wavelength continuous-wave (cw) sources for wavelength division multiplexing systems, ultrashort optical pulse generator for time division multiplexing systems and optical frequency reference. For these purposes, high coherence, high stability, low noise, high efficiency, low cost and simplicity are key issue. In addition, it is important to generate comb signals with good spectral flatness, namely, each spectral component should have save intensity. Conventional optical comb sources are based on mode-locking techniques. Mode-locked semiconductor lasers[1] and Er-doped fiber lasers[2] have been developed. However, such lasers have drawbacks in stability because a long-length cavity is influenced by the conditions of the environment. 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.

Recently, an ultra-flat optical comb generator has been proposed and demonstrated[5]. The comb generator was based on an optical modulation technique using a Mach-Zehnder modulator (MZM). The benefits of this system 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 gigahertzes. 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.

In this paper, we propose a 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.

Flat comb generation

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

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

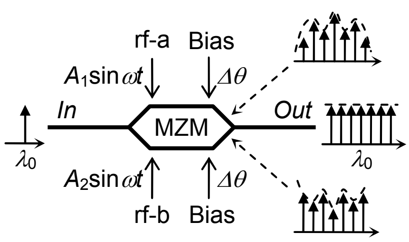

Fig. 1: The mechanism of the MZ-FCG

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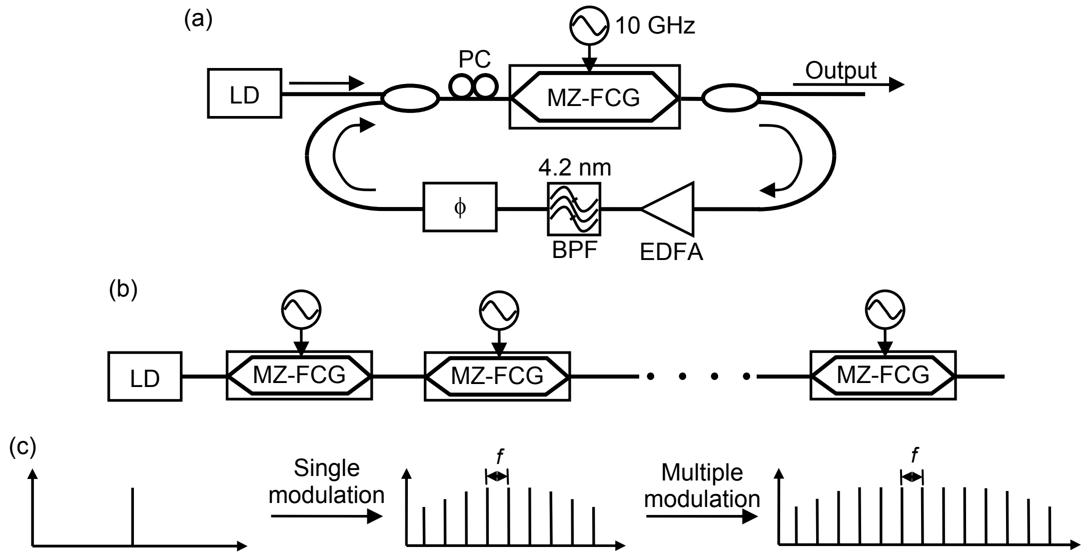

Fig. 2: The MZ-FCG with optical feedback loop: (a) the configuration, (b) the model of the comb generator by a cascaded modulation system, (c) the sequence of comb broadening.

is satisfied (comb flattening condition), where ΔA is half the difference between the amplitudes of the rf signals, and $\Delta\theta$ is half that between the optical phases of both arms of the MZM[10].

MZ-FCG with feedback loop

Figure 2 shows the concept of broadband comb generation by a MZ-FCG with an optical feedback loop. Figure 2(a) shows a configuration of the comb generator. 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 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 modelled by a cascaded modulation system as shown in Fig. 2(b), in which a series of the MZ-FCGs successively modulate an input light. Because the cascaded MZ-FCGs increase the modulation depth as compared with the single-path MZ-FCG, the bandwidth of the comb signal is broadened, as shown in Fig. 2(c). 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.

Broadband comb generation

The experimental setup of the MZ-FCG is shown in Fig. 3. 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 formed into a flat optical comb signal. Figure 4(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 MZ-FCG with the feedback loop, an EDFA with the maximum output power of about 20 dBm was used, and the bandwidth of the

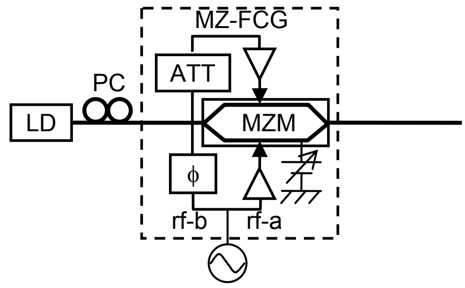

Fig. 3: The setup for the MZ-FCG. ATT: attenuator, ϕ: phase shifter, PC: polarization controller.

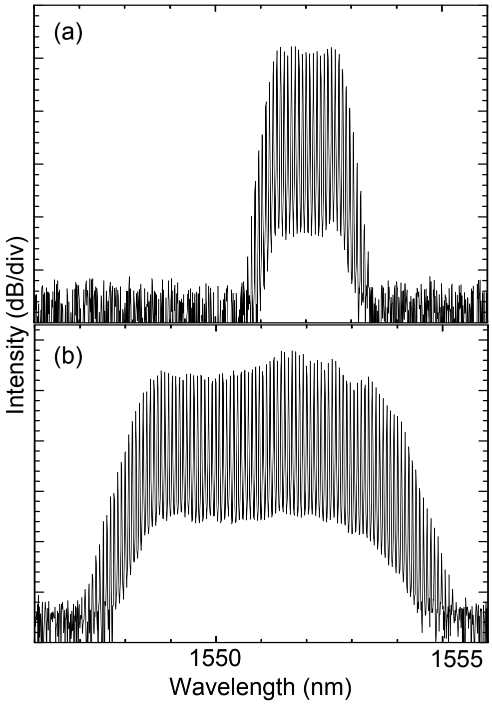

Fig. 4: Spectra of generated comb signal; (a) without the feedback loop, (b) with the feedback loop.

BPF was 4.2 nm. The optical power fed back to the MZ-FCG was about 10 dBm. Figure 3(b) shows a spectrum of a comb signal generated by the MZ-FCG with the feedback loop. The comb signal generated by the MZ-FCG without the feedback loop was successfully broadened. As a result, a broadband comb signal, where 100 modes were clearly observed, was generated. The 10 dB-reduction bandwidth was 680 GHz (69 modes). The bandwidth and the center wavelength of the broadened comb signal were decided by those of the BPF. It is expected that more broadened comb signal can be generated by optimizing the bandwidth of the BPF.

Conclusions

We demonstrated broadband comb generation using the MZ-FCG with the feedback loop. By constructing the feedback loop around the MZ-FCG, the modulation depth was increased, and a comb signal was flatly broadened as compared with single-path MZ-FCG. A broadband comb signal with the 10-dB reduction bandwidth of 680 GHz was successfully generated.

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