Generation of 10-GHz 2-ps optical pulse train over the C band based on an optical comb generator and its application to 160-Gbit/s OTDM systems

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Abstract

We demonstrate stable generation of a 10-GHz 2-ps optical pulse train from 1530 to 1555 nm based on an optical comb generator. Such pulse train is multiplexable to 160 Gbit/s.

Introduction

Optically time-division multiplexing (OTDM) enables the ultra-fast photonic network at the bit rate over 100 Gbit/s. The most crucial issue for OTDM systems is to develop a simple and stable technique for generating ultra-short (<3 ps), widely-tunable optical pulse trains with high extinction ratio and low timing jitter.

The actively mode-locked fiber laser is the most common technique to generate the high-quality pulse train applicable to OTDM systems; however, it is usually difficult to maintain the mode-locked state over a long period because of the long fiber cavity and DC bias drift of a modulator. Although a regenerative AM mode-locking scheme [1] and an FM mode-locking scheme free from modulator-bias adjustment [2] dramatically improve the long-term stability of the mode-locked state, their rather complicated configurations are not suitable to practical systems.

Another approach is external intensity modulation of a CW light. This scheme is high stable and reliable; however, the pulse width is too wide to directly apply to OTDM systems due to bandwidth limitation of the EO conversion. Although additional pulse compression and/or pulse reshaping based on fiber nonlinearity have been reported [3,4], such configuration that requires high power EDFAs is not a cost-effective solution to real system applications.

In this paper, we propose a much simpler configuration for stable pulse generation using Fabry-Perot electro-optics (FP-EO) phase modulation [5-7] and subsequent optical filtering. The operation principle of FP-EO modulation is similar to that of FM mode locking. A set of a down-chirped pulse train and an up-chirped pulse train is generated from an FP-EO phase modulator, and subsequent external filtering selects one of the pulse trains. Based on our proposed scheme, we demonstrate 10-GHz 2-ps pulse train generation tunable from 1530 to 1555 nm. The pulse train is multiplexable to 160 Gbit/s, and power penalties of all 10-Gbit/s tributaries are less than 5 dB measured from the back-to-back result.

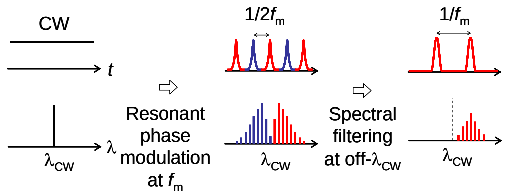

Fig. 1: Operation principle of our pulse generator.

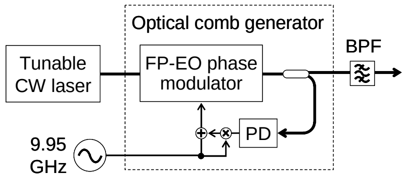

Fig. 2: Configuration of our pulse generator.

Operation principle

Figure 1 shows operation principle of our proposed pulse generator. A CW light with a wavelength of λ_{CW} is resonantly phase-modulated at a frequency of f_m by an FP-EO phase modulator, where a phase modulator is inserted in a FP cavity. While the light makes multiple round trips inside the phase modulator, higher-order sidebands, which is called optical comb (OC), are generated efficiently. It should be noted that the broadband OC consists of a set of two pulse trains at the repetition rate of f_m interleaved in the time domain [6]. The spectrum of one pulse train covers the longer wavelength side of OC with respect to λ_{CW}, while the other does the shorter wavelength side. Therefore, extracting the longer or shorter wavelength side of OC, we can easily obtain a high-quality pulse train at f_m.

This operation principle of the FP-EO phase modulation is similar to that of the FM mode-locking scheme. The FP-EO phase modulator generates a set of down-chirped and up-chirped pulse trains. In our scheme, external optical filtering selects one of the pulse trains, whereas precise control of intra-cavity dispersive and nonlinear effects is indispensable for avoiding competition between the two pulse trains in an FM mode-locked laser [2].

Configuration of pulse generator

Figure 2 shows configuration of our pulse generator, consisting of a tunable CW light source, a FP-EO phase modulator, which is called an optical comb generator (OCG) [7], and an optical bandpass filter (BPF). The bandwidth of BPF was 3 nm, and the center wavelength was shifted by 6 nm from λ_{CW}.

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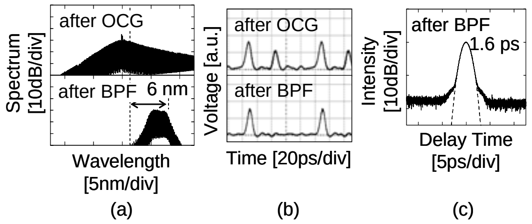

Fig. 3: (a) Optical spectra and (b) intensity waveforms after OCG and BPF. (c) Autocorrelation trace after BPF.

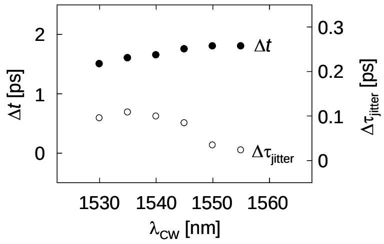

Fig. 4: Pulse width Δt and additional timing jitter $\Delta\tau_{\text{jitter}}$ as a function of the wavelength of λ_{CW}.

All fiber parts in our pulse generator were polarization-maintaining.

The OCG was composed of a waveguide-type LiNbO_3 (LN) phase modulator inserted in a FP cavity. The FSR of the cavity was equal to 9.953 GHz (SONET/SDH standard). In addition, our OCG includes an automatic servo-locking scheme, which controls the cavity length so that one of the wavelengths of the cavity modes is equal to λ_{CW} [7]. Therefore, we can easily tune the center wavelength of the optical pulse train.

Characteristics of the generated pulse train

Figures 3 (a) and (b) respectively show optical spectra and intensity waveforms after OCG and BPF when $\lambda_{\text{CW}} = 1535$ nm. We find that a set of two 10-GHz pulse trains is generated from OCG when the OC spectrum is broadened over 10 nm. We can see that one 10-GHz pulse train is selected by filtering out a longer wavelength part of OC. The corresponding autocorrelation traces after BPF are shown in Fig. 3(c). The dashed line represents Gaussian fit to the experimental result, and the 3-dB bandwidth Δt is calculated to be 1.6 ps.

Figure 4 is the λ_{CW}-dependence of Δt and the additional timing jitter $\Delta\tau_{\text{jitter}}$ induced from our pulse generator, which is calculated by the measured single-sideband phase noise spectra of the pulse train after BPF and the 10-GHz clock. From 1530 to 1555 nm, Δt is maintained below 2 ps and $\Delta\tau_{\text{jitter}}$ is less than 100 fs.

Application of our pulse generator to 160-Gbit/s OTDM systems

We evaluate the applicability of our pulse generator to a 160-Gbit/s OTDM transmitter as follows. We prepared a 160-Gbit/s OTDM signal by intensity-modulating the pulse train by a pseudo-random data pattern at 10 Gbit/s followed by an optical delay-line-based multiplexer. The 160-Gbit/s signal was demultiplexed into optical 40-Gbit/s tributaries by cascaded LN Mach-Zehnder modulators sinusoidally driven at 40 GHz. After optical 40-Gbit/s tributaries were preamplified and photo-detected, an electrical demultiplexer separated the 40-Gbit/s tributaries into electrical 10-Gbit/s tributaries. We evaluated bit error rates (BERs) of all 10-Gbit/s tributaries while changing the power P_{in} of the optical 40-Gbit/s tributaries before preamplification.

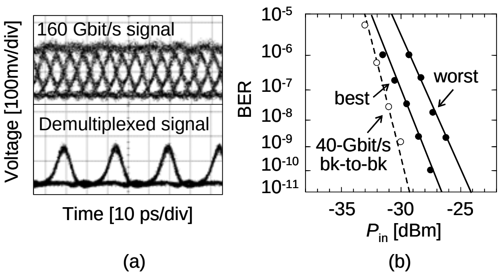

Fig. 5: (a) Eye patterns of the 160-Gbit/s optical signal and the demultiplexed 40-Gbit/s signal. (b) BERs of the best and worst 10-Gbit/s triburaries.

Figure 5(a) represents eye patterns of the 160-Gbit/s optical signal and one of the demultiplexed 40-Gbit/s tributaries, which are measured by an 80-GHz sampling oscilloscope. We find clear eye opening both before and after demultiplexing.

Dots in Fig. 5(b) show BERs of the 10-Gbit/s tributaries in the best and worst cases. Open circles indicate the back-to-back measurement result when a 40-Gbit/s optical signal is directly incident on the pre-amplifier. Dashed line is the theoretical result determined from the ASE-signal beat noise. We find the error-free operation of all tributaries, and the power penalty of the worst tributary from the dashed line is 5 dB.

Conclusions

We have proposed a simple pulse generator composed of an OCG and a BPF. A set of up-chirped and down-chirped pulse trains is generated from OCG, and the external BPF selects one of the pulse trains. Using our proposed scheme, we demonstrate stable generation of 10-GHz 2-ps pulse trains in the spectral range from 1530 nm to 1555 nm. We also perform 160-Gbit/s time-division multiplexing/demultiplexing experiments, where power penalties of all 10-Gbit/s tributaries from the back-to-back result are below 5 dB.

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