Fully Passive Integrated-optic Chromatic Dispersion Compensator and its Use to PAM4 Signal Compensation

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Abstract: We report an integrated-optic chromatic dispersion compensator without any adjustment parts. The compensator comprises two arrayed-waveguide gratings and 100 fixed delay lines and was used to compensate for 80 Gbit/s pulse amplitude modulation signal distortion.

1. Introduction

Optical communication, which implements key signal processing in the electrical domain [1], is widely utilized and being vigorously developed. While on the other hand, optical-domain signal processing is significant in view of future high-speed and low-power-consumption all-optical networks [2]. Simple and easy-to-operate optical signal processing including optical fiber chromatic dispersion compensation is desirable when transmitting high-speed intensity-modulated optical signals such as pulse amplitude modulation (PAM) signals over a short distance. Although a dispersion-compensation fiber [3] has superior characteristics including low loss and wide bandwidth, it is unsatisfactory on several counts. Its size is large, and it has an appreciable effect on the signal delay.

In this paper, we report on a silica waveguide-based chromatic dispersion compensator that consists of an array of 100 fixed delay lines sandwiched between a pair of arrayed-waveguide grating (AWG)-based wavelength filters [4]. The AWGs function as multi/demultiplexers of 100 wavelength components, and the delay lines were employed to assign specific delay time to each wavelength component. The compensator is composed of broadly used and reliable material and components, and is fully passive, that is, it does not utilize any phase shifters. We first demonstrate the configuration and operating principle relating to the compensator. We then show its transmission and delay characteristics, and its application to dispersion compensation for a 40 Gbaud PAM4 signal.

2. Configuration and operating principle of compensator

Figures 1 (a) indicates the whole schematic configuration of our integrated-optic chromatic dispersion compensator. We fabricated the compensator with silica waveguide technology [4], [5], whose relative index difference Δ was 2.3%. We monolithically integrated two AWGs 1 and 2, and 100 fixed delay lines. The compensator size was 50 mm x 50 mm. The channel spacing, 3 dB-down channel bandwidth, and free spectral range relating to each AWG were designed to be 24.9 GHz, 24.2 GHz, and 4,778 GHz, respectively. The AWG1 output ports were connected to the AWG2 input ports through the delay lines. Each wavelength component demultiplexed at the AWG1 is assigned with specified delay and is again multiplexed at the AWG2. We emplaced the two AWGs close to each other so that they have the same wavelength characteristics. Figure 1 (b) shows the schematic configuration to explain a delay line pattern we adopted. We put ten delay lines into one unit and set the delay in each unit so that it decreases versus a wavelength. In each unit, the delay difference between the adjacent waveguides was set at 10.0 ps, and the maximum delay difference was 90.0 ps. We arranged ten units as shown in Fig. 1 (a). Thus, the compensator in Fig. 1 (a) has anomalous dispersion with a cycle of about 2.0 nm, which is applicable to the wavelength division multiplexing communication. In view of crosstalk from adjacent and other channels, we set out each AWG so that

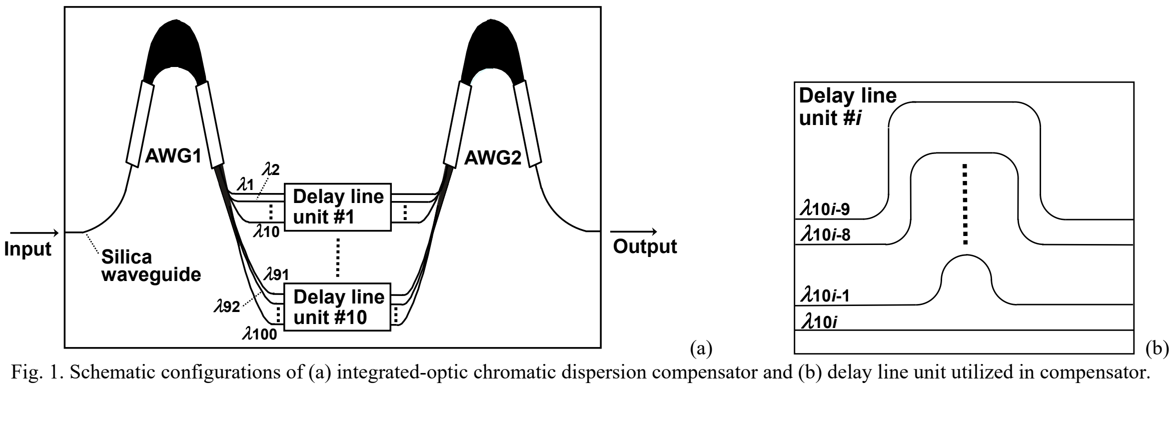

Fig. 1. Schematic configurations of (a) integrated-optic chromatic dispersion compensator and (b) delay line unit utilized in compensator.

the channel bandwidth was nearly equal to the channel spacing and the flat transmittance could be obtained through the lightwave interference. In addition, the length difference between adjacent delay lines was designed to be the integral multiple of the average value of the two main wavelengths in the delay lines for the same purpose.

3. Experimental results

Figure 2 shows transmittance of the AWG1 in Fig. 1 (a), which was measured with an amplified spontaneous emission (ASE) light source. The characteristics of 102 input ports were evaluated by inputting the light into an output monitor port. The fiber-to-fiber loss and loss deviation between the channel center wavelengths were 5.3 dB and 0.7 dB, respectively. We confirmed that the channel bandwidth surely gave close agreement with the channel spacing. Figures 3 (a) and (b) show measured transmittance and relative delay time of the compensator shown in Fig. 1 (a), respectively. The transmittance and delay were evaluated with the ASE light source and a modulation phase shift method (modulation frequency: 3 GHz) [6], respectively. The fiber-to-fiber loss was 11.1 dB, and the loss variation within the channel bandwidth was 2.9 dB on average. The loss variation mainly resulted from the non-ideal interference between lightwaves in the adjacent delay lines at the multiplexing AWG2, which was caused by the length difference deviation between the adjacent delay lines from the ideal value. The intersections between the waveguides due to the densely integrated delay lines were also the cause of the loss variation. As observed for Fig. 3 (b), the delay characteristics repeat themselves about every 2.0 nm as designed, and the obtained average dispersion and bandwidth of all ten channels were -53 ps/nm and 1.6 nm, respectively. The delay characteristics discontinuity between channels (CHs) 2 and 3 occurred since the used method reset the measurement every 2π phase shift [6].

As shown in Fig. 4, we carried out dispersion equalization experiments of a 40 Gbaud PAM4 signal using CH5 in Fig. 3 (b). The lightwave (wavelength: 1548.95 nm) from a tunable laser diode was modulated with an intensity modulator. The bit rate and pseudo-random bit sequence of the optical on-off keying (OOK) signal were 40 Gbit/s and 2^7-1, respectively. The OOK signal was input into an integrated-optic PAM signal emulator consisting of a tunable asymmetric Mach-Zehnder interferometer to produce a 40 Gbaud (80 Gbit/s) optical pseudo-PAM4 signal [7]. The produced PAM4 signal was introduced into a 5 km-long single-mode fiber (SMF, dispersion at 1.55 μm: 86 ps/nm) and the compensator (CH5 dispersion: -50 ps/nm). We evaluated an optical signal after an optical amplifier using an optical sampling oscilloscope with bandwidth of 65 GHz. Figure 5 (a) shows bit error rates (BERs) of a back-to-back signal and a signal after the compensator. The errors showed floors at optical intensity of more than

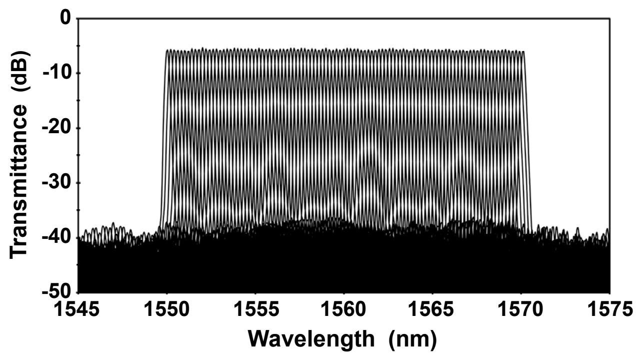

Fig. 2. Measured transmittance of AWG1 in Fig. 1 (a).

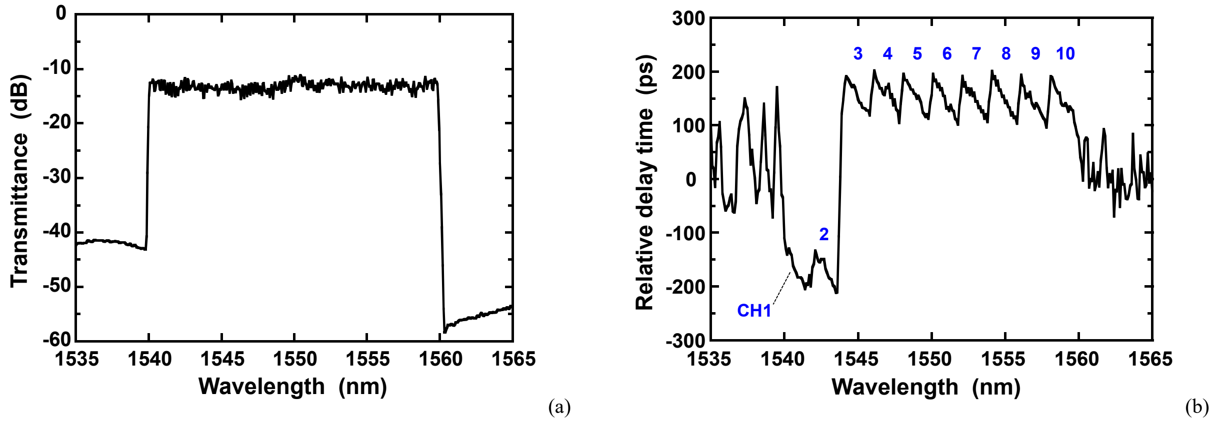

Fig. 3. Measured (a) transmittance and (b) delay time characteristics of chromatic dispersion compensator shown in Fig. 1 (a).

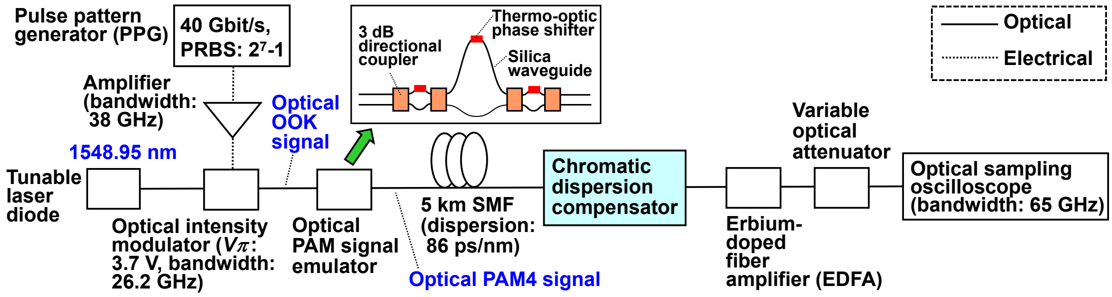

Fig. 4. Experimental set-up of dispersion compensation for 40 Gbaud PAM4 signal.

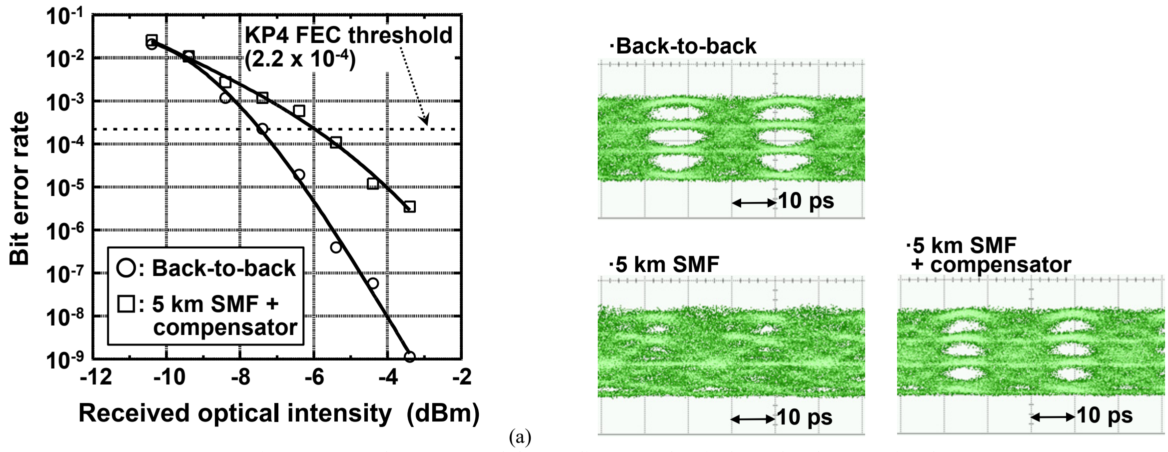

Fig. 5. Measured (a) BERs and (b) eye diagrams of optical 40 Gbaud PAM4 signals.

-3.4 dBm. Figure 5 (b) indicates eye diagrams of the signals at various points. The eye of the back-to-back or compensated signal was measured when the BER in Fig. 5 (a) was at a minimum. We estimated BERs with off-line processing of numerical data acquired with the oscilloscope. We assumed that each sampled level value had a Gaussian probability density function. Each threshold value was optimized to minimize the BER [7], [8]. We could not estimate the BER of the signal after the SMF. The eye of the compensated signal was clearly open, and the distorted signal after the SMF was recovered with the compensator although it did not completely equalize the SMF dispersion and had some characteristics imperfectness. The BER of the compensated signal showed the minimum value of 3.5×10^{-6} (below the KP4 forward error correction (FEC) threshold 2.2×10^{-4} [9]). The BERs of 40 Gbaud PAM4 signals compensated with other nine channels ranged 5.7×10^{-8} to 6.9×10^{-5}, which were also below the FEC threshold. The BERs tended to increase with increasing wavelength due to the impact of the SMF dispersion slope.

4. Summary

We demonstrated a fully passive integrated-optic chromatic dispersion compensator that comprised 100 fixed delay lines sandwiched between two arrayed-waveguide gratings. The compensator showed dispersion compensation values of about -53 ps/nm in all ten channels at intervals of about 2.0 nm. The compensator could equalize a distorted 40 Gbaud PAM4 signal passing through a 5 km-long single-mode fiber (dispersion: 86 ps/nm) at 1.55 μm.

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5. References

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