Wideband Tunable Dispersion Compensator Using a 25-Stage PLC-MZI

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ABSTRACT In high-bit-rate optical transmission systems that are being introduced into commercial applications, such as those with 40-Gbps bit-rate, there is a need for tunable dispersion compensators (TDCs) that enable adaptive compensation for dispersion fluctuations due to temperature changes and the like in the transmission lines, and accordingly, a variety of TDCs based on different principles have been reported. In particular, the cascaded Mach-Zehnder interferometer (MZI) type TDC using a lattice type filter based on the silica-based planar lightwave circuit (PLC) technology is promising because of its ease of control and large achievable dispersion. However, the usable bandwidths of this type of TDCs reported to date are thought to be insufficient for their practical application to the 40-Gbps systems. We have demonstrated here, therefore, a TDC using a 25-stage PLC-MZI that combines a usable bandwidth of 60 GHz or higher and a tunable dispersion range of ±300 ps/nm or more. Its superior characteristics will be reported in this paper.

1. INTRODUCTION

In high-bit-rate optical transmission systems that are being introduced into commercial applications, such as those with 40-Gbps bit-rate, there is a need for tunable dispersion compensators (TDCs) in order to additively compensate for chromatic dispersion (CD) fluctuations due to temperature changes and the like in the transmission lines. Accordingly, a variety of TDCs based on different principles have been reported so far [1)~7)]. In particular, the cascaded Mach-Zehnder interferometer (MZI) type TDC using a lattice type filter based on the silica-based planar lightwave circuit (PLC) technology is promising because of its ease of control and large achievable dispersion [5)~7)].

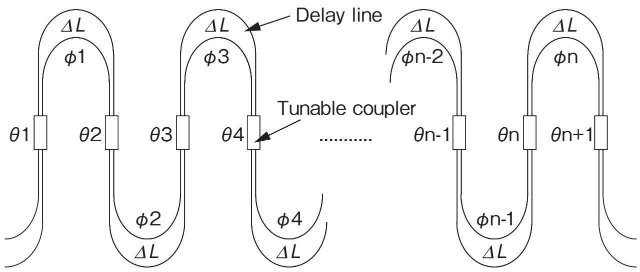

Figure 1 Configuration of cascaded PLC-MZI type TDC.

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Figure 1 shows the basic configuration of cascaded PLC-MZI type TDC. Basically this TDC is a finite impulse response (FIR) filter of lattice filter type, consisting of multiple PLC-based MZIs that are cascaded via tunable couplers, in which, by tuning the phase of each delay line and the coupling ratio between delay lines, the filter response shown in Equation (1) can be obtained.

$$T(f)=\sum_{i=1}^{n+1} a_i \left\{\exp\left(j\,\frac{2\pi}{c}\,n_{eff} f \Delta L\right)\right\}^{-i+1} \qquad (1)$$

where, a_i is the Fourier coefficient, j is the imaginary unit, n_{eff} is the effective refractive index, f is the optical frequency, and c is the light velocity in vacuum.

In this circuit, the degree of freedom of the filter characteristics is determined by the number of stages n in the MZI, so that arbitrary filter characteristics can be obtained according to the value of n. And, since periodical waveforms are obtained per every free spectral range (FSR) depending on ΔL, this circuit can be used in simultaneous compensation for wavelength multiplexed signals or as a colorless device. However, in order to obtain desired filter characteristics by using such a general FIR filter, all the phases of delay lines and all the coupling coefficients must be tuned, and this makes it problematic in terms of practicality.

On the other hand, other types of cascaded PLC-MZI TDCs have been proposed, in which the delay lines on the first and last stages have optical path difference of ΔL, while the rest delay lines have that of $2\Delta L$, and every tunable coupler is driven in parallel by the same power source [6), 7)].

Figure 2 shows the schematic configuration of this type of TDC. Even though its usable bandwidth is limited to about half the FSR, this type allows for "single knob control" of tunable couplers, where, by precisely trimming the optical path difference on each delay line to ΔL or $2\Delta L$ in advance, every coupler can be driven in parallel, at the time of practical usage, either to the plus or minus direction, using a single current source. This improved the practicality in terms of controllability and power consumption. Moreover, by adjusting the ratio of driving power on the first and last tunable couplers over that on the rest, the linearity and flatness of group delay spectrum and transmittance spectrum can be controlled. Furthermore, by using a quarter waveplate combined with a reflection mirror or Faraday rotator mirror, compensation for polarization dependence can be provided simultaneously with doubling of tunable dispersion range which results from double pass configuration. Thus several demonstrations have been reported including a TDC with a tunable dispersion range of about ±500 ps/nm based on 8-stage MZI [7)].

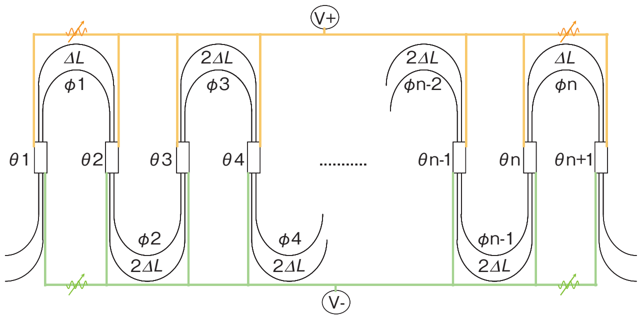

Figure 2 Configuration of cascaded PLC-MZI type TDC with single knob control.

With these TDCs reported, in order to obtain a tunable dispersion range of about ±300 ps/nm or more that is required in the 40-Gbps systems, it is necessary to set the FSR to 100 GHz and the usable bandwidth to about 40 GHz. However, this bandwidth might be insufficient for practical application in the 40-Gbps systems. Usable bandwidth of this type of TDC can be expanded by expansion of the FSR, but since there is a tradeoff relationship between the usable bandwidth being proportional to the FSR and the tunable dispersion range being inversely proportional to the square of FSR, it is difficult to make them compatible with each other. On the other hand, the maximum tunable dispersion range achievable is approximately proportional to the number of stages. Thus, by expanding the FSR and simultaneously increasing the number of stages, there is the possibility of making the usable bandwidth compatible with the tunable dispersion range at a high level.

Here, we have accordingly studied designs to satisfy both of these characteristics, i.e., usable bandwidth of higher than 60 GHz and tunable dispersion range of larger than ±300 ps/nm, which are sufficient for 40-Gbps transmission. Based on the design, we have further fabricated a cascaded PLC-MZI TDC with single knob control, and carried out dispersion compensation experiments on a 40-Gbps return-to-zero (RZ) on-off keying (OOK) signal.

2. CONFIGURATION

To design a TDC suitable for 40-Gbps transmission as mentioned before, we aimed at assuring a usable bandwidth of higher than 60 GHz and a tunable dispersion range larger than ±300 ps/nm. First, the FSR was set to 200 GHz in order to deal with WDM optical transmission on the ITU grid while assuring a usable bandwidth higher than 60 GHz. Next, the relationship between the number of stages and tunable dispersion range at an FSR of 200 GHz was calculated by simulation. Figure 3 shows the relationship between the maximum dispersion and number of stages, which is obtained from the calculation results of group delay spectrum with the dispersion maximized for each number of stages. In this calculation, the driving power ratio of the first and n-th tunable couplers over the rest was set at 1:1.8.

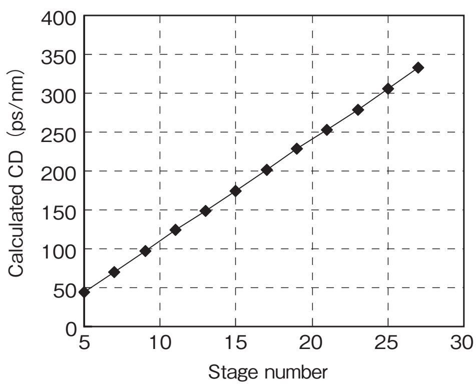

Figure 3 Calculated maximum dispersion vs. number of stages.

It can be seen from Figure 3 that the tunable dispersion range increases approximately in proportion to the number of stages, reaching ±300 ps/nm at 25 stages.

Next, setting the number of stages at 25, the group delay and transmittance spectra were calculated at the plus and minus maxima of dispersion and at zero dispersion, and the results are shown in Figure 4.

From Figure 4, the tunable dispersion range is seen to be 60 GHz (0.48 nm) or more under any conditions. Thus it was decided to adopt the 25-stage configuration.

Figure 5 shows the schematic configuration of 25-stage MZI-TDC. This circuit, basically equivalent to the cascaded PLC-MZI TDC with single knob control shown in Figure 2, consists of cascaded 25-stage MZIs, comprising two MZIs with an FSR of 200 GHz at both ends and 23 intermediate MZIs with an FSR of 100 GHz in between. Each MZI is connected by a tunable coupler having an initial coupling ratio of 0%, which consists of an MZI having a phase difference of π and a thin-film heater on its arm.

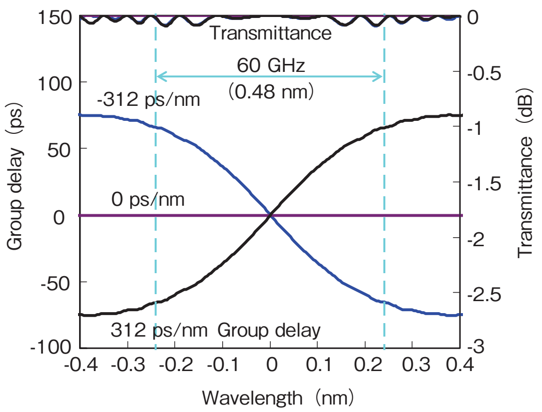

Figure 4 Calculated spectra of 25-stage TDC.

The MZIs at both ends are connected to the input and output waveguides by means of a Y junction, rather than a 2x2 structured coupler, thereby assuring 1:1 branch coupling. Moreover, in order to reduce polarization dependence, a polarization diversity scheme is implemented by connecting a polarization beam splitter (PBS) circulator via a polarization maintaining fiber.

With this TDC, tunable dispersion characteristics can be obtained by providing in parallel the heaters on each tunable coupler with either plus or minus dispersion driving power, thereby changing the coupling coefficient within the range of 0% ～ ±50%.

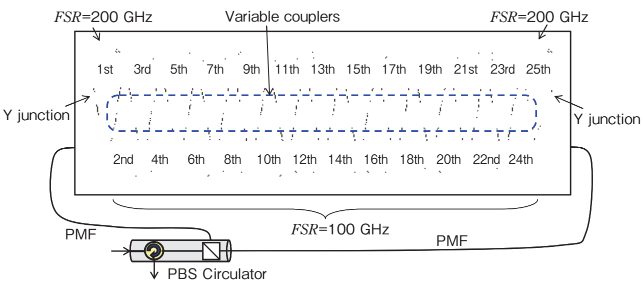

Figure 5 Schematic configuration of 25-stage MZI-TDC with polarization diversity.

Meanwhile, each MZI has a thin-film heater on its delay lines, so that phase errors due to fabrication variation can be permanently compensated for by local heating-based phase trimming [8].

But, in fabricating a 25-stage MZI of such a structure as a practical PLC circuit, it was found that however much downsizing is strived for by inverse disposing the curvature of MZIs alternately as shown in Figure 5, the resulting circuit size becomes excessively large, making implementation difficult. Accordingly, a folded arrangement shown in the circuit layout in Figure 6 was newly adopted here to make the circuit size more compact. In this structure, the circuit is folded at the delay line on the 13th MZI, the center of the 25-stage MZI, so that the (13+n)th delay line (n is integer, 1≦n<13) is laid along the (13-n)th delay line. This allows for higher-density arrangement of delay lines than that shown in Figure 5, thus reducing the chip area. Furthermore, at the time of folding back the 13th delay line, the two delay lines were made to cross with each other in order to make the optical connection between adjacent delay lines identical to that in Figure 5. This makes the control method for the folded structure identical to that for the circuit arrangement shown in Figure 5. Meanwhile, the delay lines are arranged to cross with an angle of 90° in order to suppress loss increase due to crossing. By devising such a layout, the circuit area has been reduced by about 20% compared with the layout shown in Figure 5.

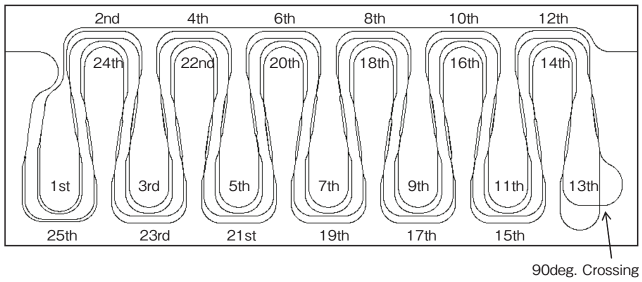

Figure 6 Waveguide layout of compact 25-stage MZI-TDC with folded arrangement.

3. FABRICATION

Based on the design described above, the MZI-TDC chip was fabricated using usual silica PLC fabricating technologies. Then, a polarization maintaining fiber is connected to the input and output waveguide ends, and subsequently the PBS circulator is connected thus implementing polarization diversity. After that, while evaluating the interference characteristics of each delay line using a temperature-controlled stage, phase trimming was carried out using the thin-film heaters on the delay lines.

Figures 7 and 8 show the fabricated MZI-chip and optical module, respectively. As shown in Figure 7, despite its multi-stage structure including as many as 25 stages, the chip has a compact size of 25 mm x 70 mm. The optical module measures 130 mm x 100 mm x 16 mm.

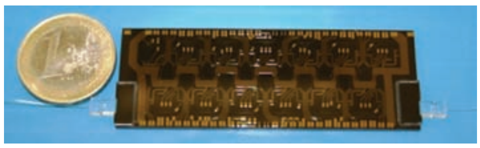

Figure 7 Photo of 25-stage MZI-TDC chip.

Figure 8 Photo of 25-stage MZI-TDC module.

4. EVALUATION RESULTS OF OPTICAL CHARACTERISTICS

With a single power source connected to drive the heaters on the tunable couplers, the group delay, transmittance and polarization mode dispersion (PMD) were measured. On this occasion, the driving power ratio over the tunable couplers was set at 1:1.8.

Figure 9 shows the measurement results, as the control voltage is changed, of the group delay and transmittance spectra, as well as polarization-dependent loss (PDL) and PMD at CD values of +336 ps/nm and −320 ps/nm. It has been confirmed from Figure 9 that, as has been targeted at, CD of ±300 ps/nm or more is achieved with a usable bandwidth of about 60 GHz (0.48 nm). The insertion loss is about 7 dB at the center wavelength in the passband, and the loss fluctuation was not more than 1.5 dB within the 60-GHz band under every driving condition. The insertion loss comprises about 4.8 dB from circuit loss, about 1 dB from two fiber connections, and about 1.2 dB from PBS circulator and connectors. It has also been confirmed that, thanks to the polarization diversity using PBS circulator, PDL and PMD were 0.3 dB or less and 0.3 ps or less, respectively, for the whole passband.

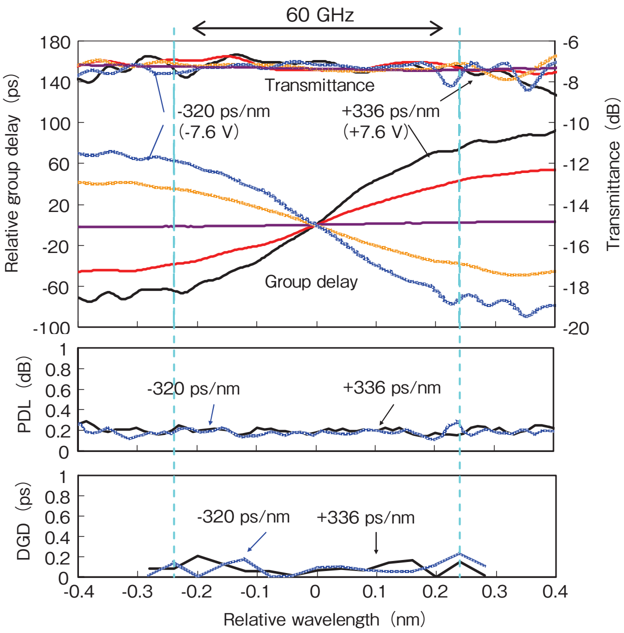

Figure 9 Measured transmittance, group delay, PDL, and PMD.

5. DISPERSION COMPENSATION EXPERIMENTS ON 40-GBPS RZ-OOK SIGNAL

In order to validate the effectiveness of the TDC developed here in high-bit-rate optical communication systems, dispersion compensation experiments on a 40-Gbps RZ-OOK signal was carried out using the fabricated TDC module. Figure 10 shows the experimental setup. In the experiment, CW light of 1561.0 nm in wavelength from a distribution feedback laser diode (DFB-LD) array was modulated, using a $LiNbO_3$ modulator (LN1), by 40-Gbps nonreturn-to-zero (NRZ) pseudorandom bit sequence of 10^7-1 in signal length, subsequently was modulated using LN2 by 40-Gbps RZ pulses, to obtain 40-Gbps RZ-OOK signals. After amplification using an erbium-doped fiber amplifier (EDFA), the signal was transmitted over dispersion compensated fibers (DCFs) each having CD of −125, −250, and −330 ps/nm, dispersion compensated at the TDC, and was received for eye pattern observation and bit error rate (BER) measurement. Figure 11 shows the signal spectra for the back-to-back and −330 ps/nm transmissions. It can be seen from Figure 11 that good RZ signal spectrum has been generated and that, due to the wide passband of the TDC, practically no spectral narrowing has occurred. Figure 12 shows eye pattern comparisons of the zero, −250, and −330 ps/nm transmission line dispersions, with and without TDC. From Figure 12 it can

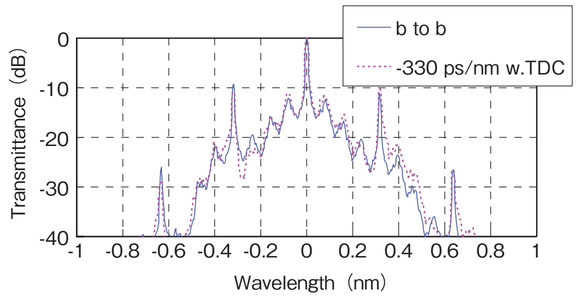

Figure 11 Measured optical spectra.

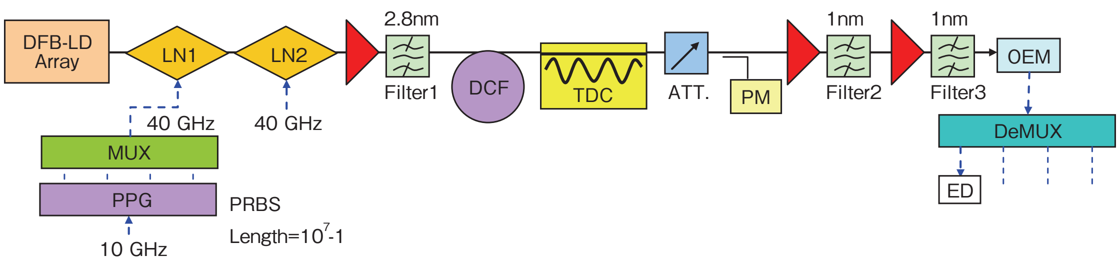

Figure 10 Experimental setup for dispersion compensation of 40-Gbps RZ signal.

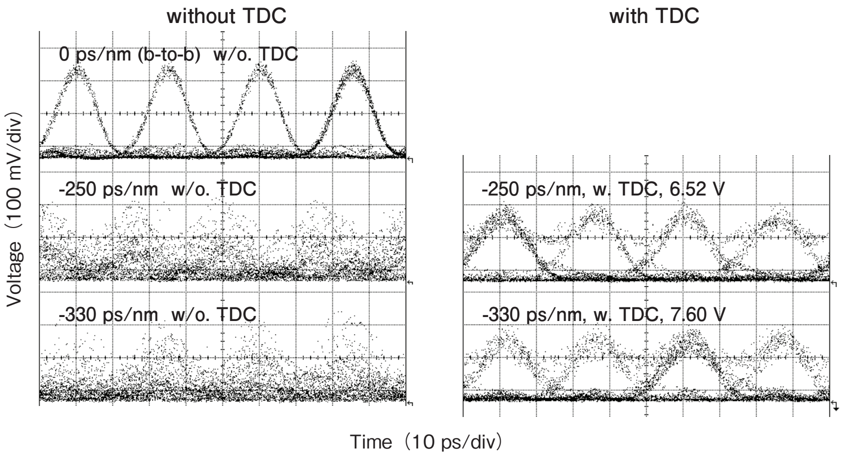

Figure 12 Eye opening of 40-Gbps RZ signal with/without TDC.

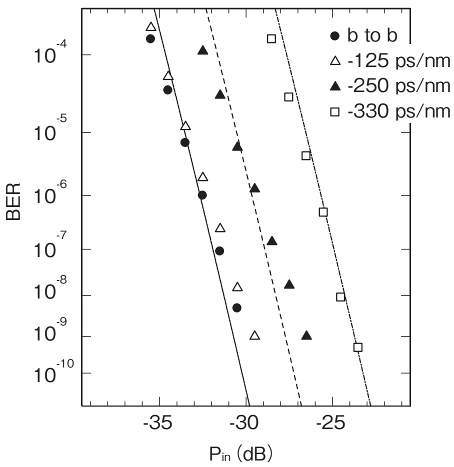

Figure 13 BER measurement results.

be seen that, in contrast to the fact that, without TDC, the eye pattern is completely closed at −250 ps/nm, it is open, with TDC, not suffering significant degradation up to -330 ps/nm, thus confirming substantial effectiveness of dispersion compensation. Figure 13 shows the measurement results of BER. From Figure 13, it has been confirmed that, despite power penalty of several dB included, transmission with a BER of approximately 10^{-9} is possible by using this TDC. As described above, the TDC developed here has been confirmed to be effective for tunable dispersion compensation in 40-Gbps systems.

6. CONCLUSIONS

We have developed a PLC-MZI tunable dispersion compensator with broad bandwidth targeted at 40-Gbps high-bit-rate optical transmission systems.

To satisfy both the wide bandwidth and large tunable dispersion required for 40-Gbps systems, the free spectrum range was designed to be as broad as 200 GHz, and cascaded MZI of as many as 25 stages was adopted. A folded circuit configuration was used to densely arrange the waveguides, thereby succeeding in accommodating the very large-scale circuit of 25-stage MZI in a compact chip size of as small as 70 mm x 25 mm. Moreover, polarization diversity was implemented using a polarization splitter/circulator module in order to reduce polarization dependence.

As the result, the fabricated TDC showed good characteristics including: insertion loss of about 7 dB, bandwidth of about 60 GHz, tunable dispersion range of ±300 ps/nm or more, PDL of 0.3 dB or less, and PMD of 0.3 ps or less.

Furthermore, using this TDC, we conducted dispersion compensation experiments on 40-Gbps RZ on-off keying signal, and demonstrated that dispersion compensation up to -330 ps/nm is possible, thus confirming the applicability of this TDC to 40-Gbps optical transmission systems.

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