Time caliper method with enhanced accuracy using an arbitrary waveform generator and time demultiplexer with fine clock offset

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An improved time caliper method has been proposed for measuring a small relative delay of two signals transmitted on different channels. This is achieved by using a new method to generate two periodic pulse trains that have much smaller period difference, over 1000 times smaller than that in the prior scheme. The two pulse trains, with a period difference of 0.1 ps, are generated by an arbitrary waveform generator and a time demultiplexer, with a fine clock offset. The average and maximum measurement errors obtained are 0.68 and 1.67 ps, respectively.

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Multiplexing is used to increase the capacity of optical transmission systems and can be realized by various schemes, such as multiplexing of subchannels in time-, wavelength-, polarization-, or space-division. Measurement of the relative delay of two signals on different channels is essential for many applications to characterize transmission channel characteristics [1,2]. For instance, chromatic dispersion of a fiber can be obtained from the relative delay of two signals of different wavelengths transmitted through the fiber. Differential mode group delay of few-mode fibers can be measured by the relative delay of two signals propagating through two spatial modes. Polarization mode dispersion (PMD) can also be measured by the relative delay between two polarizations. Measurement of the dispersion or propagation delays enables dispersion compensation and channel characterization for various network functions like link setup and performance monitoring. Time caliper method (TCM) has been proposed to measure the relative delay of two signals by calculating the time alignment shifting of two pulse trains with slightly different period in time [3]. It enables the measurement of small relative delay of two signals while using lower-bandwidth measurement pulses. The measurement of chromatic dispersion using TCM has been successfully demonstrated for various types of fibers with different dispersion coefficients and a measurement error of less than 0.2 ps/(km $*$ nm) in single-mode fiber has been achieved [3]. For PMD measurement, various measurement methods, including the time-of-flight method, interferometric method, and derivation of Jones Matrix using polarizer, have been proposed [4–8]. In order to measure small chromatic dispersion, the relative propagation delay between the two signals at two wavelengths can be increased by increasing the wavelength separation of the two signals. Thus a large delay can be induced even for fibers of short length. However, for PMD measurement, the two polarizations are of the same wavelength, thus the same technique cannot be applied. Due to lack of wavelength selection freedom, measurement of PMD using TCM requires an implementation with fine time resolution. It was shown that the accuracy of TCM was proportional to the relative period difference of the two measurement pulse trains. The finest period difference that could be obtained in the original setup was 100 ps. In this Letter, we propose a new method to reduce the period difference of the TCM by 1000 times, with the help of an additional time demultiplexer module and a properly adjusted clock offset. The period difference of the two pulse trains is significantly reduced to 0.1 ps. The average and maximum measurement errors obtained are 0.68 and 1.67 ps, respectively.

We will first describe the principle and the system setup, as shown in Fig. 1, for the proposed TCM. PMD measurement is used as a demonstration only. PMD is caused by fiber birefringence that results in the propagation speed differences between two orthogonal polarizations in fibers. Using a polarization maintaining coupler (PMC), the output of the laser source is first split into two

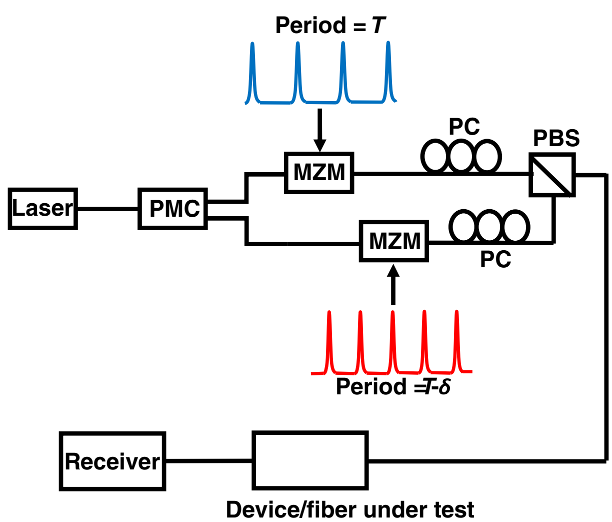

Fig. 1. Schematic diagram of the proposed measurement system. PMC, polarization maintaining coupler; MZM, Mach–Zehnder modulator; PBS, polarization beam splitter; δ, period difference of the two pulse trains; PC, polarization controller.

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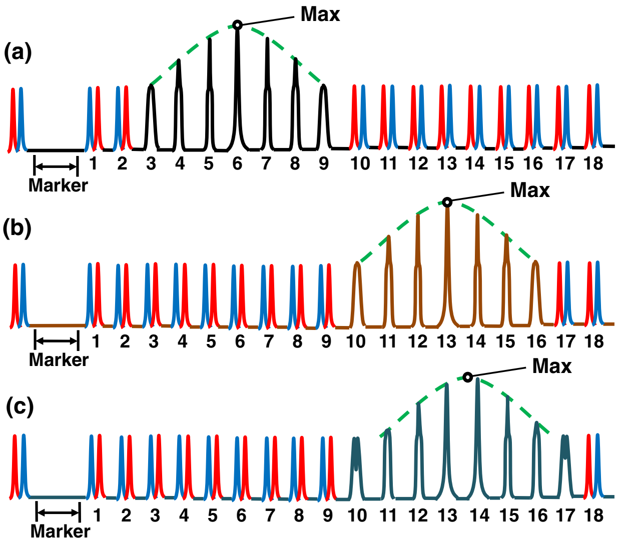

Fig. 2. (a) The reference trace. (b) After transmission, the index number of the peak intensity pulse in the hump zone is changed from 6 to 13. (c) When the propagation delay difference is not an integer multiple of δ, the pulse with peak intensity in the hump zone is not at the maximum of the hump envelope.

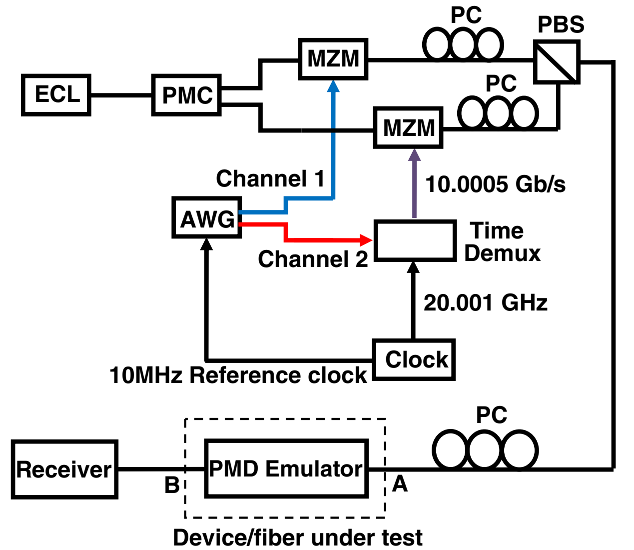

Fig. 3. Experimental setup of the proposed measurement system. ECL, external cavity laser; AWG, arbitrary waveform generator; Time Demux, time demultiplexer.

arms to be used for the two measurement pulse trains. The upper arm is modulated with a repeating pulse train of period T and the lower arm is modulated with a slightly shorter repeating period, $T - \delta$. For convenience, δ is chosen as a submultiple of T. The two arms are then combined with a polarization beam splitter (PBS), with a polarization controller on each arm to control the input polarization. The combined signal passes through the device/fiber under test and is detected at the receiver. When the pulses from the two polarizations arrive at the receiver are overlapped in time, their intensities are added. Assume the average full-width-half-maximum pulse-width is w. A hump zone is generated if the separation of two overlapped pulses is smaller than w, as shown in Fig. 2(a). First we obtain a reference trace by measuring the combined trace in back-to-back transmission. At the output of the device/fiber under test, PMD will cause a shifting of the time alignment between the two pulse trains in two polarizations, which is shown as a shifting of the hump zone in Fig. 2(b). The PMD value can be derived from the amount of shifting compared with the reference trace similar to that in [3,9].

The main advantage of TCM over the time-of-flight method is the scaling effect on the time shift that makes it possible to measure a small time delay. The scaling factor is derived to be $(T - \delta/2)/\delta$ [3]. For a time shift of $(T - \delta/2)$ of the hump zone, the corresponding dispersion value is δ. To evaluate the time shift, we consider the maximum intensity pulse in the hump zones before and after transmission. For illustration purpose, in Fig. 2(b) the measured propagation delay difference τ is 7δ when the index number of the maximum intensity pulse is changed from 6 to 13, as discussed in [3]. Next, we consider the scenario that the maximum intensity point of the hump zone lies between two pulses, rather than exactly on one pulse, in the hump zone after transmission, as shown in Fig. 2(c). This happens when the propagation delay difference is not an integer multiple of δ. If we still choose the maximum intensity pulse to derive the propagation delay difference, say the pulse with index number 14 in Fig. 2(c), the induced measurement error is less than $\delta/2$, because the peak of hump zone lies within the distance of $(T - \delta/2)/2$. By reducing the value of δ, TCM's measurement error can be reduced.

However, the smallest period difference δ demonstrated in [3] is 100 ps, which is limited by the equipment, an arbitrary waveform generator (AWG), used to generate the two pulse trains. In this Letter, the period difference δ of the TCM is reduced by 1000 times, from 100 to 0.1 ps using the same AWG together with a time demultiplexer. The experimental setup for generating two electrical pulse trains, with a period difference $\delta = 0.1$ ps, is shown in Fig. 3. Channel 1 of the AWG is a periodic signal with a period of 2 ns and a pulse width of 100 ps, as shown in Fig. 4(a). This is basically a 10 Gb/s data pattern with 20 bits in each period. The measurement range

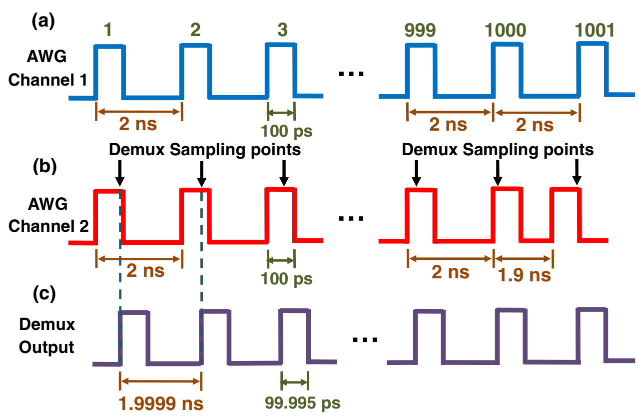

Fig. 4. Process of generating two pulse trains with a period difference $\delta = 0.1$ ps: (a) a periodic pulse train at AWG Channel 1 with period = 2 ns and pulse width = 100 ps; (b) specially designed pulse train at AWG Channel 2; (c) a periodic pulse train at demultiplexer output with period = 1.9999 ns and pulse width = 99.995 ps.

of the TCM is equal to the period length, 2 ns in this case. This is sufficient for most measurements of PMD. Our goal is to generate a periodic pulse train for the other polarization with 0.1 ps period difference compared to AWG Channel 1, as shown in Fig. 4(c). The period of the second pulse train should be $T - \delta = 1999.9$ ps with 20 bits in each period. Correspondingly, the bit length is $(T - \delta)/20 = 99.995$ ps and the bit rate for the data pattern is $1/99.995 = 10.0005$ Gb/s.

However, the minimum period difference δ that can be set on Channel 2 by the AWG is 100 ps. To circumvent this limit, a specially arranged pattern for Channel 2 is used. Our setup is to keep Channel 2's period for the first 999 periods as 2 ns, while reducing the 1000th period to 1.9 ns, as shown in Fig. 4(b). The whole pulse pattern is then repeated. Note that for Channel 2, it is still a 10 Gb/s data pattern, with 20 bits in the first 999 periods and 19 bits in the 1000th period. In order to obtain the desired periodic pulse train of period 1.9999 ns, a time demultiplexer is added to the system with an adjusted clock reference for the postprocessing of AWG Channel 2.

The time demultiplexer has two inputs, the data input and the clock input. By sampling the demultiplexer's data input, the demultiplexer constructs the output data using the values at the sampling points. The sampling rate of the demultiplexer is equal to half of the frequency of the clock input. For the 10 Gb/s data pattern, if the clock input of the demultiplexer is set to be 20 GHz, the sampling rate of the demultiplexer is 10 GSample/s, and the output signal of the demultiplexer is the same as the input. By slightly increasing the frequency of the clock input, the sampling points of the pulse train are readjusted, as shown in Fig. 4(b). The clock input of the demultiplexer is set to be 20.001 GHz. The corresponding output of the demultiplexer is a 10.0005 Gb/s pattern with a pulse width of 99.995 ps, which is the value of $(T - \delta)/20$ as discussed before.

Next, we need to verify whether the output of the demultiplexer is the desired periodic pulse train. The time separation between the sampling points of the adjacent bits of the demultiplexer is slightly shorter than the bit length of the output from AWG Channel 2 by 0.005 ps due to the clock offset. After 20 bits of accumulation, the sampling point is shifted to the left relatively by $0.005 * 20 = 0.1$ ps, shown as a relative shifting of sampling points between two adjacent pulses. This process is repeated for the first 1000 pulses. However, the 1001st pulse of the AWG Channel 2 is shifted to the left by 100 ps. The accumulated shifting of the sampling points for the first 1000 periods is $1000 * 0.1 = 100$ ps. The sampling point is equivalently reset to the *right* edge of the pulse again, as shown in Fig. 4(b). Since the pulse width of the pulse train from AWG Channel 2 is 100 ps, the shifting of sampling points is always within one pulse. The reduction of 100 ps in the 1000th pulse period can be considered as a reduction that is shared among the first 1000 periods. Thus equivalently, there is a 0.1-ps difference in period between AWG Channel 1 and the demultiplexer's output. Note that the pulse width reduction, down to 99.995 ps, at the demultiplexer output will only affect the hump zone's width but not the shifting of the hump zone. Only the shifting is needed to calculate the relative delay of two channels.

In actual implementation, the intensity of the received pulse train may suffer from intensity noises and jitters in the measurement system. Thus the pulse with maximal intensity may be changed due to the intensity noise. This leads to a limited accuracy in the estimation of the relative delay. Selecting the wrong maximal intensity pulse will result in measurement error. This error can be circumvented by an improved time-shift estimation algorithm. The algorithm includes using an average processing and taking the cross-correlation between the envelope of the reference trace and the received trace, similar to the time delay estimation method demonstrated in [10,11] using interpolation and cross-correlation.

In the following, we will describe the experimental setup. An external cavity laser (ECL) at wavelength 1500 nm is utilized as the laser source in the setup. The laser output power is split equally by a PMC to maintain the input polarizations to the modulators. The two pulse trains, generated using the aforementioned novel method, are used to drive two intensity modulators, and the outputs are polarization controlled and combined by a PBS. The peak output power after PBS is −7 dBm. To evaluate the performance of our proposed measurement scheme, we introduce different amount of PMD into the measurement system by using the polarization emulator. After the PMD emulator, the signals are received by a receiver with 10-GHz bandwidth. The PMD introduced by the PMD emulator ranges from 0.68 to 43.68 ps. As an illustration, Fig. 5 shows the hump of the combined trace after passing through the PMD emulator when PMD value is set to 12.07 ps (red) and 40.65 ps (blue) at wavelength of 1550 nm. By using the red trace as a reference trace, the blue trace has a relative delay of 28.58 ps, as set by the emulator. The derived delay between the two polarizations is 28.17 ps by estimating the relative time shifting of the hump using TCM. The measurement error is around 0.41 ps. Similar experiments are performed when the PMD emulator are set up to seven different PMD values, ranging from 5.67 to 39.97 ps.

The fluctuation of the measured values can be reduced by averaging over multiple measurement attempts. For each PMD value set by the emulator, up to 30 measurements have been performed to obtain the average measured PMD value. Figure 6 shows the average measured

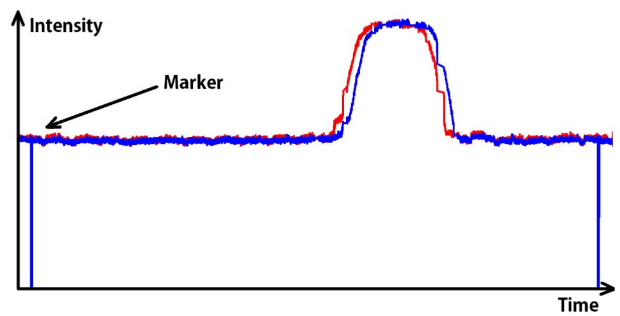

Fig. 5. Hump of the combined trace when PMD is set to 12.07 ps (red) and 40.65 ps (blue).

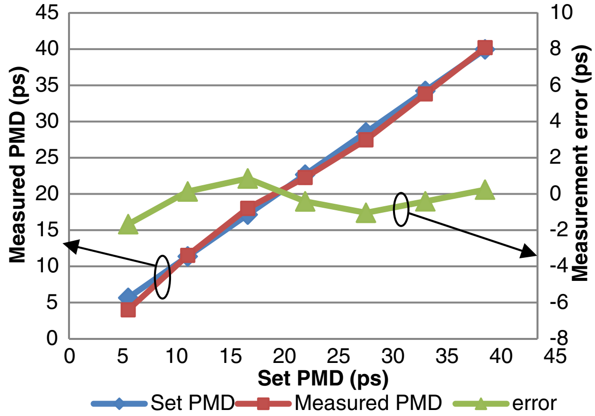

Fig. 6. Average measured PMD obtained by averaging over 30 measurements at PMD values of 5.67, 11.39, 17.16, 22.68, 28.52, 34.23, and 39.97 ps.

PMD values and errors. The measured PMD values are 4.00, 11.53, 18.02, 22.27, 27.48, 33.82, and 40.21 ps, corresponding to the set PMD values of 5.67, 11.39, 17.16, 22.68, 28.52, 34.23, and 39.97 ps. The measured results agree quite well with the set values. The mean of the measurement error is 0.68 ps over the PMD range of 5.67–39.97 ps, with a maximum error of 1.67 ps at the set PMD value of 5.67 ps.

In our experiment, for a period of $T = 2000$ ps and $\delta = 0.1$ ps, the scaling factor of $(T - \delta/2)/\delta$ is equal to 39,999. This can greatly facilitate the measurement of a small delay. From the aforementioned discussion, the accuracy of our proposed implementation depends on the period difference δ. With the new proposed scheme, the period difference can be greatly reduced from 100 to 0.1 ps, corresponding to a reduction of 1000 times. However, the improvement of measurement accuracy is about 100 times. This may be due to the noises and jitters in the two pulse trains generated and in signal detection. The experimental error can be further reduced by increasing the number of measurements to facilitate more averaging, but this is at the expense of longer processing time. Note that the pulse-width is much larger than δ in our experiment. Thus TCM can be implemented with lower bandwidth requirement, while maintaining high accuracy. Since the combined pulse train is periodic, the PMD can be estimated by averaging multiple periods of the combined trace to further improve the accuracy.

In conclusion, we have proposed a new method of generating a much shorter period difference for the measurement pulse trains for TCM-based measurement. A reduction of 1000 times in the period difference is achieved. The improvement is realized by utilizing the sampling property of a time demultiplexer to sample a specially designed pulse train from an AWG. The scheme is robust to the pulse-broadening effect as the relative delay of the hump zones does not depend on the pulse width. Measurement of PMD ranging from 5.67 to 39.97 ps is demonstrated. The experimental results show that a maximum measurement error of 1.67 ps can be obtained. The mean absolute measurement error is 0.68 ps after 30 times of averaging.

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