

Low-cost, signed online chromatic dispersion detection scheme applied to a 2×10 Gb/s RZ-DQPSK optical transmission system

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Abstract: Chromatic dispersion (CD) in single-mode optical fibres limits the maximum transmission distance of digital optical transmission systems at 10 and 40 Gb/s. It can be eliminated by a tunable CD compensator, provided that the residual dispersion is detected, including its sign. A low-cost hardware implementation of a signed online CD detection scheme is reported. It is based on synchronous detection of frequency modulation (FM)-induced arrival time modulations in the clock recovery phase locked loop (PLL) of a 2×10 Gb/s return-to-zero differential quadrature phase shift keying (RZ-DQPSK) optical receiver. The RZ-DQPSK transmitter laser is modulated by a synthesised 4.732 MHz sinusoidal signal. This results in $\approx 1\%$ (rms) intensity modulation and an optical FM with ≈ 105 MHz (rms) deviation. Low-cost components were used to build a synchronous detector for the arrival time signal that yields the fibre CD, including its sign. The total measurement interval is ≈ 84 μ s. The sign of the CD is detected within a range of ± 700 ps/nm. This range is limited by the locking range of the clock recovery PLL. The CD measurement readout is fairly linear over the range ± 360 ps/nm.

1 Introduction

Chromatic dispersion (CD) in optical fibres, that is the optical frequency dependence of the group delay, is a major obstacle in the deployment of high-speed optical communication systems at 10 and 40 Gbit/s. Even in dispersion-compensated long-haul optical fiber links, the temperature and the wavelength dependence of the CD is still problematic. In addition, the repair and the maintenance of the fibre link or the dynamic reconfiguration of the optical networks will result in different fibre dispersions. To overcome this problem, network operators need adjustable, drop-in CD compensators to compensate for the residual CD. In order to use these compensators in an automatic mode of operation, an online detection of CD including its sign is required. Some of the reported CD detection schemes (e.g. [1–6]) need extra optical fibres, receivers and/or high-frequency electronics. This introduces extra cost and makes them expensive and unaffordable. The range depends on the modulation format, the data rate and technique used for measuring the CD. For 10 Gb/s data transmission, the range was reported to be up to +1200 ps/nm, without detecting the sign by Petersen *et al.* [4]. For 40 Gb/s data transmission, the range was reported to be ± 100 ps/nm and ± 70 ps/nm for non-return-to-zero (NRZ) and return-to-zero (RZ) data, respectively [6].

The upgrading of existing dense wavelength-division-multiplexed (DWDM) systems to higher bit rates requires wider optical bandwidths per channel or advanced modulation formats with higher spectral efficiency, or a combination of both. Recently, there is a growing interest in optical differential quadrature phase shift keying (oDQPSK) as a promising modulation format, because it not only doubles the transmission capacity at the same symbol rate, but also offers better spectral efficiency, and, hence, better tolerance to CD and polarisation mode dispersion [7–10].

In this article, we use the CD detection scheme based on the synchronous detection of FM-induced arrival time modulations detected at the clock recovery phase-locked loop (PLL), which was previously demonstrated for amplitude-shift keying (ASK) and differential phase-shift-keying (DPSK) [11, 12]. Here, we apply it to a 2×10 Gb/s RZ-DQPSK optical transmission system and present a low-cost hardware solution for CD detection of such type of digital optical transmission systems.

Another similar method reported by Takushima *et al.* [13] is also based on the optical frequency modulation (FM) method, but the arrival time detection was asynchronous, the frequency deviation larger and the measurement interval longer.

2 CD detection principle

The complex field transfer function of an optical fibre with a length L is $H(\omega) = e^{-j\beta(\omega)L}$, where ω is the optical angular frequency, and attenuation has been neglected.

It is useful to approximate its phase by a truncated Taylor series, $\varphi = -\beta(\omega)L = -(\beta + (\omega - \omega_0)\beta' + (1/2)(\omega - \omega_0)^2\beta'')L$.

At ω_0 , the propagation constant $\beta(\omega)$ assumes the value β , and its first and second derivatives with respect to ω are β' and β'' , respectively.

The group delay $\tau_g = -\phi' = (\beta' + (\omega - \omega_0)\beta'')$ is a linear function of ω . Its derivative with respect to wavelength λ and length L is the CD coefficient $D = (\partial^2 \tau_g / \partial \lambda \partial L) = -(2\pi c / \lambda^2) \beta''$, ≈ 17 ps/(nm km) in standard single mode fibre (SSMF).

A small pump current modulation of a distributed feedback (DFB) laser will modulate the optical power and also the optical frequency, so there are amplitude modulation (AM) and FM. At low frequencies, there can be a considerable phase lag between pump current and FM, because the latter depends not only on the carrier density, but likewise on the chip temperature that is modulated by the pump current with a polarity opposed to that of the carrier density effect and an intrinsic delay [14]. The modulation frequency, where the phase lag is typically 90° , is also typically at 200 kHz or so. We operate at considerably higher frequencies where the phase lag is small and should vary only marginally from laser to laser.

In the presence of CD, a frequency excursion δf of the FM changes the arrival time delay by $\delta \tau_g = -\delta f(DL\lambda^2/c)$.

The laser signal carries data as its main modulation. The clock component is extracted at the receiver side in the clock recovery PLL circuit. In this PLL, the arrival time variations will be detected and tracked, if they are slow enough. The arrival time variations can be used to estimate the amount of CD present in the fibre. The parasitic AM can be detected at the receiver itself or in an extra low-speed photodiode. Very importantly, a reference signal for synchronous detection of the arrival time signal is thereby obtained (Fig. 1, top-left). The reference signal should have the same amplitude for different fibre lengths or CD values. This can be achieved by using an optical post-amplifier in an automatic power control (APC) mode at the receiver, in order to stabilise the power level received at the reference photodiode. The arrival time signal shown in Fig. 1 (bottom-left) changes its amplitude, depending on the amount of CD in the fibre. The amplitude increases by increasing the amount of CD where (B) corresponds to higher CD than (A), and changes its sign when the CD sign is inverted. Multiplication of both the arrival time signal and the reference signal in an analog multiplier and filtering the output results in a DC voltage signal shown in Fig. 1 (right), where its voltage level changes depending on the amount of CD in the fibre, and its sign flips with the sign change of the CD.

In most cases, one is only interested in eliminating the residual CD. Knowledge of the frequency excursion δf is therefore not necessary. If needed, the frequency excursion δf of each transmitter and the CD readout factor of each receiver can be trimmed in the factory against a set of a

reference transmitter, a reference receiver and a fibre with known CD. This allows to produce transmitters with equal frequency excursions and receivers with equal CD readout sensitivities. We also measure δf in an optical heterodyne experiment with an electrical spectrum analyser. In order to obtain an accurate result, the pump current modulation depth is temporarily chosen ten times larger than usual, and the measured δf is divided by ten.

3 oDQPSK transmission setup

The principle of DQPSK transmission is explained by Griffin and Carter [7]. Fig. 2 shows the details of our experimental setup. A 193.5 THz (1549.32 nm) DFB laser was used. A small laser pump current modulation at 4.732 MHz resulted in $\approx 1\%$ (rms) intensity modulation and in a FM with ≈ 105 MHz (rms) frequency deviation. These values are so small that transmission was not degraded noticeably by laser FM and AM. CD compensators are typically thermally tuned, and CD measurements are therefore automatically averaged over milliseconds, if they are utilised for online CD compensator control. This results in a more than sufficient accuracy, for example, in the order of 50 fs/nm at 40 Gb/s, if the averaging time is a few 100 ms [11, 12]. An increased pump current modulation does not seem to be required.

A fibre-pigtailed Bookham GaAs/AlGaAs DQPSK modulator was used to generate the DQPSK signals for the experiments mentioned in this article [10]. A pattern generator was used to generate a 10 Gb/s pseudo random bit sequence (PRBS) NRZ data stream with a PRBS data length of $2^{15} - 1$. The 10 Gb/s NRZ data stream was split and delayed by 31 bit durations to emulate two decorrelated patterns. The two 10 Gb/s NRZ data stream patterns (I and Q) were used to drive the oDQPSK modulator. No DQPSK precoder was implemented. The DQPSK modulator was followed by a polarisation controller and a LiNbO₃ Mach-Zehnder modulator. The latter was driven by a 10 GHz clock signal to generate RZ pulses, thereby completing a 2×10 Gb/s RZ-DQPSK signal.

The receiver employed an optical preamplifier, followed by a DWDM arrayed-waveguide grating (AWG) demultiplexer (DEMUX) with Gaussian passbands and 100 GHz channel spacing. It acted as a narrow bandpass optical filter. The detected photocurrent of an optical front end p-type intrinsic n-type (PIN) photodiode with trans-impedance amplifier (PIN-TIA) was stabilised by a

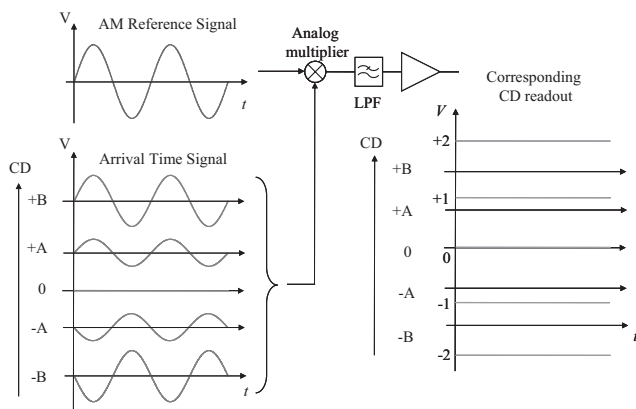


Fig. 1 Operation principle of CD detection

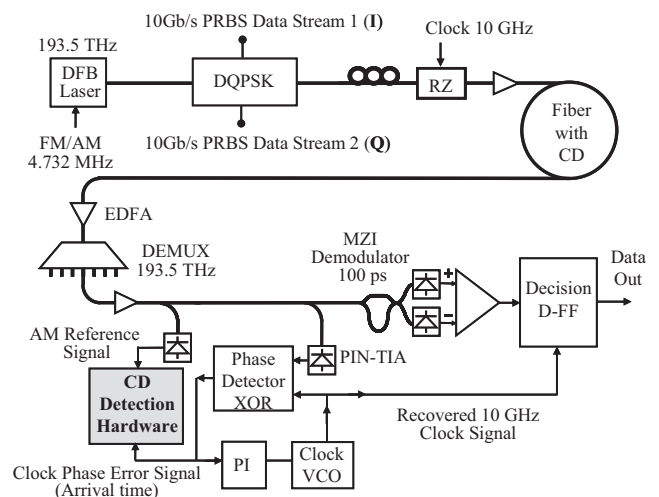


Fig. 2 Experimental setup for CD detection

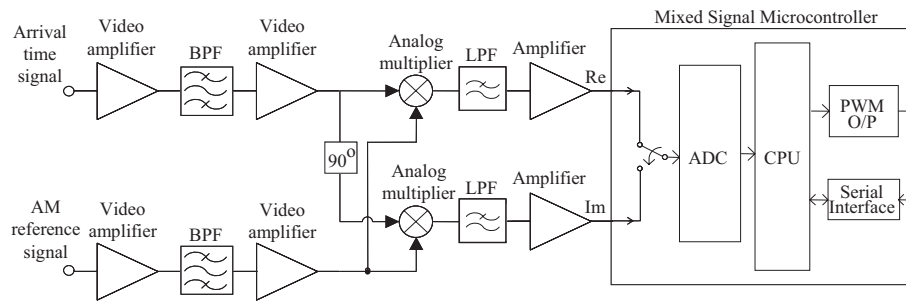


Fig. 3 CD detection hardware

feedback loop (not shown) that controlled the pump current of the last erbium doped fibre amplifier (EDFA) for APC. The output signal from this optical front-end PIN-TIA was fed to an EX-OR gate that acted as a phase detector for the clock recovery section of the receiver. The clock recovery section consisted of a phase detector, a proportional-integral (PI) controller and a voltage-controlled oscillator (VCO). They formed a PLL to recover the 10 GHz clock signal. The optical signal after the EDFA was finally connected to the demodulator, which was an integrated-optical Mach-Zehnder interferometer with a 100 ps (1 bit) delay. By adjusting the differential optical phase between the interferometer arms, it was possible to select either of the transmitted patterns. The demodulator outputs were connected to two more optical front ends (PIN-TIA). The outputs of the two optical front ends were connected to a 10 GHz differential amplifier and then connected to a decision circuit (D-FF), clocked by the recovered clock and set to the optimal threshold voltage. To allow for bit error rate measurements, the error detector was programmed with the expected data sequence received at the output of the demodulator.

4 Implementation of the CD detection scheme

The arrival time signal was detected by the clock phase detector. Amplitude and sign of the 4.732 MHz sinusoidal arrival time signal reflected the CD and its sign. A low-frequency photodiode was also placed at the output of the EDFA to detect the 4.732 MHz parasitic AM. Both the arrival time signal and the AM reference signal were fed to the CD detection hardware shown in Fig. 3.

The reference signal was amplified in video amplifiers and filtered using ceramic resonators. The arrival time signal was likewise amplified and filtered. The two signals have an initially unknown phase difference that is not only determined by the laser FM response but also by propagation delays in the fiber between the two photodetectors, and in the cables by the PLL dynamics and the processing in the CD detection hardware. For simplicity, the two signals were therefore multiplied by each other in two multipliers, once without and once with a 90° phase shift, to generate real (Re) and imaginary (Im) parts, respectively, of a complex arrival time amplitude that contains information not only about the CD but also about the unknown phase difference. The multiplier output signals were averaged in lowpass filters (LPF). One analogue multiplier, LPF and analog-to-digital converter (ADC) channel could be omitted, if the proper demodulation phase shift were set by trimming of a phase shifter. This may be advisable in production.

The averaged analogue signals were converted to digital values using an ADC that is part of a low-cost low-power mixed-signal microcontroller. The microcontroller calculated a suitable linear combination of the Re and Im components. This amounts to projecting the complex phasor

along a straight line, and it yields a value that is proportional to the CD, including its sign. The total measurement interval was $\approx 84 \mu\text{s}$. The microcontroller communicated with a PC through a serial interface for monitoring purposes. It also has pulse width modulation outputs that could be used to directly control a tunable CD compensator. Excluding the extra photodiode, which could be omitted if one measures the photocurrents of the data detectors, we estimate the cost of the CD detection hardware as $< 30 \text{ €}$, even for small quantities.

Fig. 4 shows the measured arrival time amplitude in the complex plane in arbitrary units (a.u.) for different CD values. Each point corresponds to a specific amount of CD.

5 CD detection results

For measuring negative CD, a switchable CD compensator was used that consists of short pieces of dispersion compensated fibres in the range from 0 to -700 ps/nm . For measuring positive dispersions, a 41.54 km long SSMF ($\approx +706 \text{ ps/nm}$) was added. The clock recovery PLL in the receiver could lock in a $\pm 700 \text{ ps/nm}$ CD range. Fig. 5 shows the CD measured readout (a.u.) as a function of the actual CD. The sign of the CD is correct over the whole $\pm 700 \text{ ps/nm}$ range, and the CD readout is fairly linear within a $\pm 360 \text{ ps/nm}$ range. The obtained range is similar to the state of the art [1–6]. The sine-like, rather than linear, behaviour is mainly caused by the sensitivity of the clock phase error detector as a function of residual CD, an EXOR gate in our case. In a different implementation with an Infineon 40 Gb/s clock-and-data recovery, the nonlinearity had opposite sign, yielding more of a

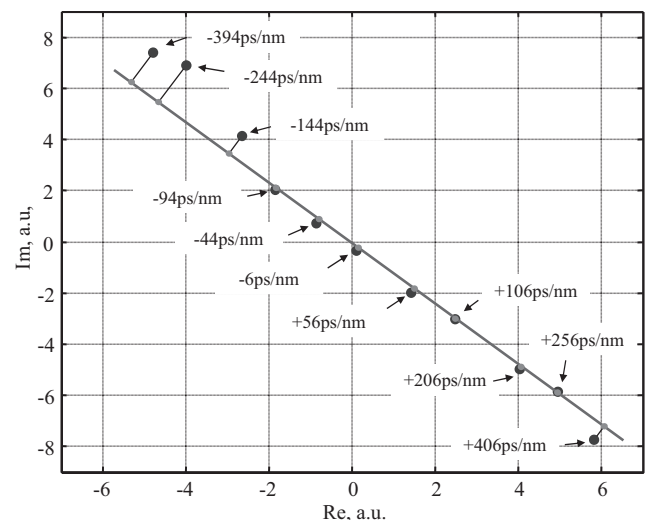


Fig. 4 Detected arrival time modulation amplitude (relative to the AM) in the complex plane, for different CD values

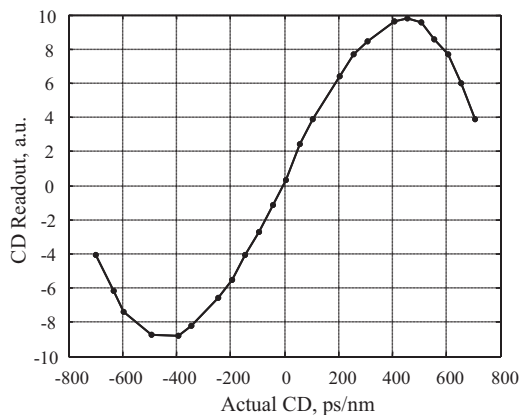


Fig. 5 Measured CD readout (a.u.) against actual CD

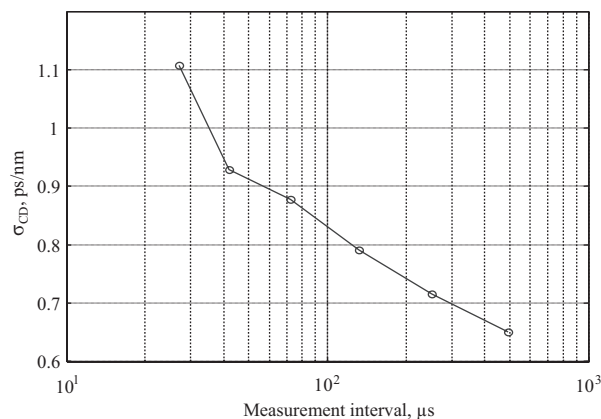


Fig. 7 Standard deviation of CD at 0 ps/nm residual dispersion as a function of measurement interval duration

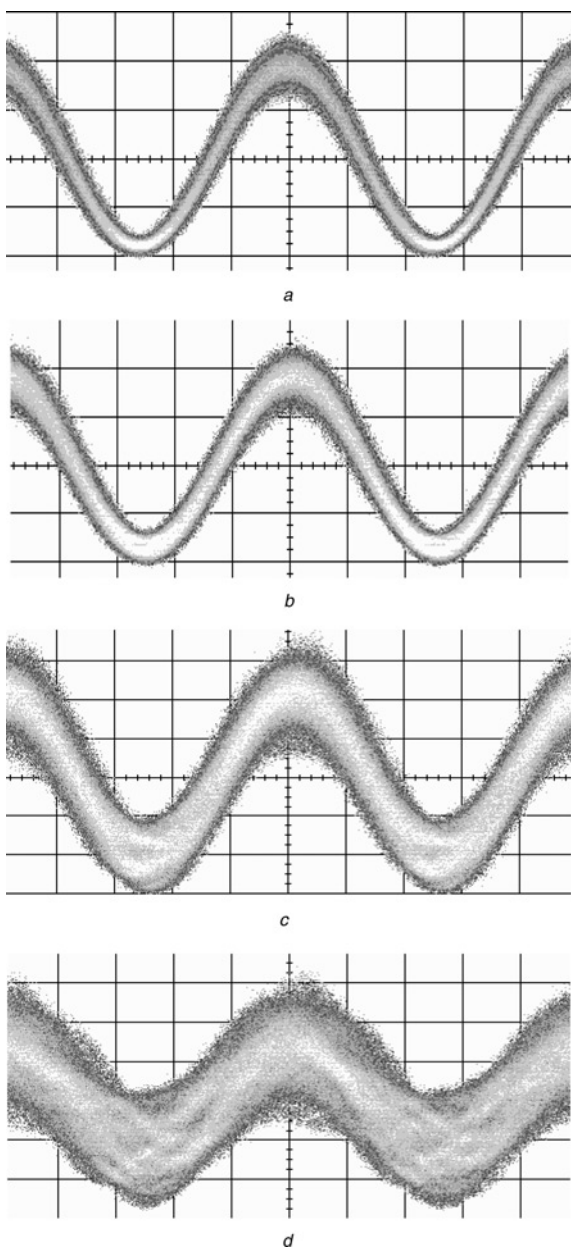


Fig. 6 Measured intensity measurements against time for different CD values

- a Back-to-back (0 ps/nm)
- b 21.3 km (≈ 362 ps/nm)
- c 32.2 km (≈ 547 ps/nm)
- d 41.5 km (≈ 706 ps/nm)

hyperbolic sine than a sine. Modulation format and threshold setting also play a role, but the detection characteristic is always an essentially odd function through the origin, where it can be linearised.

Fig. 6 shows the intensity measurements against time for a 2×10 Gb/s RZ-DQPSK signal measured before the MZI Demodulator of Fig. 2 after different lengths of SSMF, corresponding to different values of CD. The signal quality degraded when CD was higher, but the RZ clock signal was still successfully recovered, and this is necessary for correctly detecting at least the sign of the CD, as shown in Fig. 5. Note that in Figs. 6a–d, there is a decreasing 10 GHz AM because of dispersion, whereas the 4.732 MHz modulation that is so small that it cannot be seen in the diagrams, remains unchanged because of the APC. A tunable CD compensator will always manage to keep residual dispersion well within the ± 700 ps/nm range, near 0 ps/nm. Initial convergence can be conveniently achieved by scanning the compensator dispersion, until the clock recovery circuit locks. This task, as well as other supervisory functions, can be easily incorporated in the microcontroller program.

The dynamic CD readout accuracy was also assessed for $2^{15}-1$ data, at the point of 0 ps/nm residual CD that is typical under operation with compensator. Fig. 7 shows standard deviations of individual CD measurement samples. Even for measurement intervals of $27 \mu\text{s}$, the standard deviation is only 1.1 ps/nm, and it decreases to 0.65 ps/nm for a measurement interval of $492 \mu\text{s}$. This compares favourably against all figures that have been reported for other CD detection methods, to our knowledge. For example, an accuracy of < 3 ps/nm was given by Yu *et al.* [6] although the bit rate was higher.

6 Conclusions

This CD detection scheme is extremely cheap to implement and offers a wide range for measurement of CD, including its sign, together with a superb sensitivity and short measurement interval. It has been applied for a 2×10 Gb/s RZ-DQPSK signal. Scheme and developed hardware are ideally suited for adaptive control of an optical CD compensator.

7 References

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