

Automatic Tunable Chromatic Dispersion Compensation at 40 Gb/s in ASK and DPSK, NRZ, and CSRZ 263-km Transmission Experiments

D. Sandel, S. Bhandare, A. F. Abas, B. Milivojevic, R. Noé, Martin Guy, and Martin Lapointe

Abstract—Chromatic dispersion (CD) in single-mode optical fiber distorts pulses and is a big obstacle for the installation of long-haul dynamically routed transmission systems, especially at 40 Gb/s. Here the automatic residual CD compensation of a 263-km fiber link in the range -300 to -700 ps/nm is demonstrated for nonreturn-to-zero amplitude-shift keying (NRZ-ASK), carrier-suppressed return-to-zero (CSRZ)-ASK, NRZ differential phase-shift keying (DPSK), and CSRZ-DPSK modulation formats at 40 Gb/s. A thermally tunable dispersion compensator minimizes residual CD, which is measured by a synchronous arrival time detection scheme. The measured transmission penalty with online CD compensation is between ± 1.2 dB for various link lengths and compensated CD values.

Index Terms—Arrival time detection, chromatic dispersion (CD), optical fiber transmission, tunable dispersion compensator.

I. INTRODUCTION

TUNABLE chromatic dispersion (CD) compensation is needed in long-haul and dynamically routed transmission links, especially at 40 Gb/s. Various integrated optical dispersion compensators [1]–[5] have been demonstrated but fiber Bragg gratings (FBGs) exhibit the largest dispersion and lowest insertion loss with an associated tunability. Recent advances in FBG technology now allow the realization of single and multichannel tunable devices [6]. Among many CD detection schemes, synchronous arrival time detection with a sensitivity limit of 100 attoseconds [7] is the most promising option because the scheme has an extremely low incremental cost, provides the sign of CD, responds in ~ 1 ms and is usable for various modulation formats [8]. Prior to this, a similar method was reported by Takushima and Kikuchi [9], but arrival time detection was asynchronous. As a consequence, the required frequency deviation was larger, the measurement interval was longer, and the sign of dispersion remained ambiguous.

The tolerance to residual CD with respect to in-line CD compensation ratio for various modulation formats including nonreturn-to-zero amplitude-shift keying (NRZ-ASK), carrier-suppressed return-to-zero (CSRZ)-ASK, NRZ differential phase-shift keying (DPSK), and CSRZ-DPSK was evaluated

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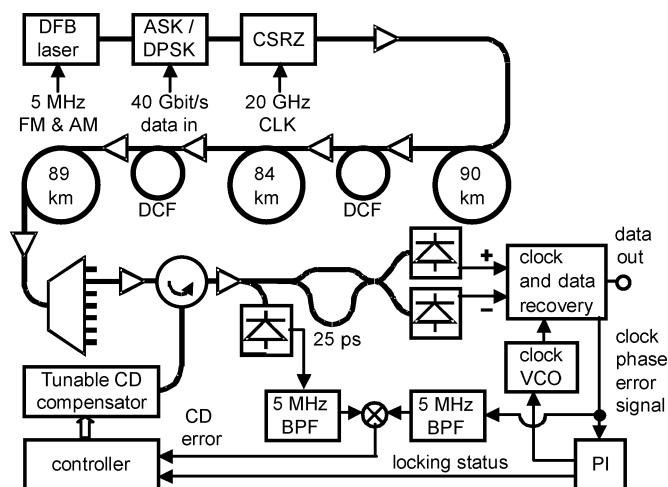


Fig. 1. Chromatic dispersion compensation (CDC) setup for 40-Gb/s ASK and DPSK transmission experiments.

numerically in [10] at 43 Gb/s. To our knowledge, we report for the first time an automatic CD compensation for all these modulation formats. We conduct 40-Gb/s transmission experiments, with a commercially available FBG-based thermally tunable dispersion compensator and synchronous arrival time detection.

II. TRANSMISSION SETUP

A small pump current modulation of a distributed-feedback (DFB) laser will not only modulate the optical power but also the optical frequency. At low frequencies, there can be a considerable phase lag between pump current and frequency modulation because the latter depends not only on the carrier density but likewise on the chip temperature which is modulated by the pump current with an intrinsic delay. In the presence of CD with a dispersion coefficient D and a fiber length L , a frequency excursion δf causes an arrival time delay $\delta\tau_g = -\delta f(DL\lambda^2/c)$. It can be neglected in comparison with the eye closure as long as $|\delta f T| \ll 1$. In the following, this will be the case. It allows the small-signal modulation frequency to be chosen so high that it is outside the phase-locked loop bandwidth of the clock recovery in the receiver.

Fig. 1 shows the transmission setup. A DFB laser at 192.5 THz (1557.366 nm) is modulated with a 5-MHz sinusoidal source to provide 1.8% [root mean square (rms)] power modulation and 336-MHz (rms) frequency modulation. The 40-Gb/s $2^7 - 1$ pseudorandom binary sequence data obtained from a 16:1

multiplexer that combines 16 2.5-Gb/s subchannels is impressed on to this optical carrier using a dual drive modulator, to generate NRZ-ASK or NRZ-DPSK signals. Another dual drive modulator driven at 20 GHz generates CSRZ pulses when required. This signal is transmitted over three fiber spans with a total length of 263 km. This is too short to introduce noticeable time-dependent dispersion changes in a lab environment. The spans were mixed from 165 km of standard single-mode fiber (SSMF), 62 km of nonzero dispersion-shifted fiber, and 35 km of dispersion-shifted fiber. Dispersion-compensating fiber (DCF) with a total dispersion of -2713 ps/nm was inserted between first and second stages of the two inline erbium-doped fiber amplifiers (EDFAs). At the receive end, there is an optical preamplifier followed by a 40-channel flat top wavelength-division-multiplexing demultiplexer. Our FBG-based tunable dispersion compensator is inserted just before the receiver using a three-port optical circulator followed by an optical tap and a low frequency power monitor photodiode to recover the 5-MHz power modulation which is used as a reference signal for arrival time detection. The DPSK signals are decoded using an all-fiber temperature-stabilized Mach-Zehnder interferometer with a 25-ps delay. Both interferometer outputs are connected to two high-speed photodiodes, which in turn are connected to the differential inputs of clock-and-data recovery (CDR) with built-in demultiplexer. For ASK operation, the interferometer at the receiver is left out and only one photodiode is used for reception.

For arrival time detection, the bandpass filter that follows the low frequency photodiode detects the parasitic 5-MHz amplitude modulation to provide a reference for a 5-MHz lock-in detection of the clock phase error signal in the CDR circuits. In the presence of CD, the frequency modulation causes small arrival time modulation, which is indicated by the clock phase detector. Due to the lock-in scheme, the CD error signal is directly proportional to the residual CD including its sign. The noise of the 5-MHz component of arrival time modulation has been shown to be only $2 \cdot 10^{-16}$ s for DPSK, and 10^{-16} s for ASK [7], [8]. In order to keep the CD readout independent of optical input power fluctuations, the detected photocurrent is stabilized by a feedback loop that controls the pump current of the last EDFA.

III. EXPERIMENT

The CD error signal is fed to a digital signal processor (DSP). CD is automatically compensated by the DSP controller as follows: At first, the FBG-based tunable CD compensator is thermally scanned through its -300 - to -700 -ps/nm tuning range. The clock recovery range for CSRZ-DPSK is ± 100 ps/nm of residual CD at a bit-error rate (BER) of 10^{-3} . At a BER of 10^{-9} , and for ASK as well as for NRZ, the range is wider. Then the compensator CD is set in this range to the point of expected zero residual CD. Finally, control is given to an integrator that controls the compensator CD. The integrator input is driven by the CD error signal. Integration stalls when the CD error signal vanishes and indicates zero residual dispersion.

The CD range in which the linear controller locks into the point of zero residual CD has also been assessed. It is identical with the range in which the sign of the CD readout signal is correct. For CSRZ-DPSK and BER = 10^{-3} (10^{-9}) at zero residual

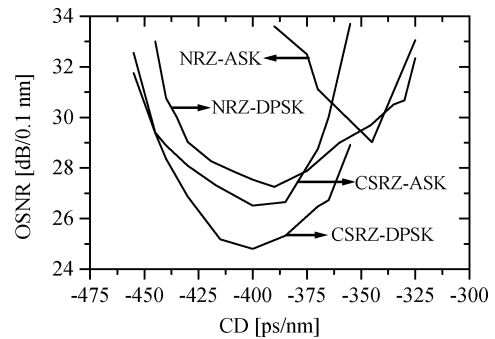


Fig. 2. OSNR needed for BER = 10^{-9} versus compensator CD.

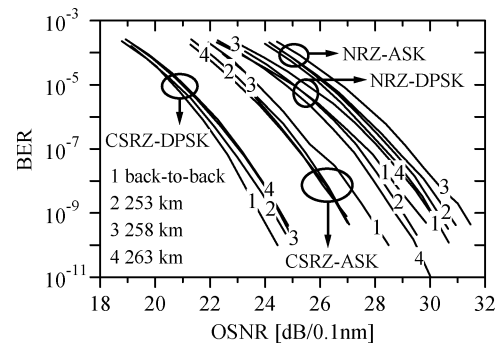


Fig. 3. BER versus OSNR. An optical attenuator was used to vary the OSNR.

CD, the range is at ± 50 (± 80) ps/nm. For all other formats the range is wider, e.g. ± 110 (± 120) ps/nm for NRZ-ASK.

Temporal variations of CD are automatically tracked. The electrical heating-cooling power required to control the CD compensator is 10 W. The thermal scan takes 10 min, and the control time constant is about 30 s, but control speed was not optimized. A proportional integral differential controller should work better.

Fig. 2 shows optical signal-to-noise ratios (OSNRs) in dB/0.1 nm, which all result in a BER = 10^{-9} . They are given as a function of a manually adjusted compensator CD values with a 258-km fiber link in place. The optimum CD value for NRZ-ASK differs from that for the other formats, maybe because the ASK modulator drive voltage was too large.

The back-to-back Q values for NRZ-ASK, CSRZ-ASK, NRZ-DPSK, and CSRZ-DPSK are 24.6, 26.6, 25.8, and 29.5 dB, respectively. The corresponding back-to-back receiver sensitivities of -25.7 , -27.3 , -26.8 , and -32.1 dBm are equivalent to OSNRs of 30.1, 27.7, 29.6, and 23.8 dB/0.1 nm, respectively. The 5-MHz modulation does not introduce a sensible penalty, not even for DPSK. Fig. 3 shows BER versus OSNR. With the 263-km fiber link in place, the Q factors are reduced to 17.3, 19.6, 19.1, and 20.4 dB, respectively, and they stay essentially unchanged when the tunable dispersion compensator is operational. In each case, 1 h of error-free operation was verified. The automatically set compensator CD was near -470 ps/nm and stayed constant within a few picoseconds per nanometer. As a consequence, no significant deterioration of transmission occurred when CD control was switched OFF. The observed CD variation is not likely to be due to a temperature drift of the fiber. A more likely cause is polarization changes and interferometer drift.

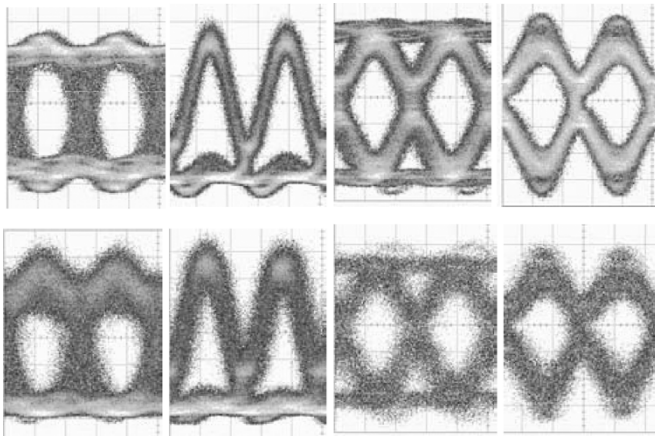


Fig. 4. 40-Gb/s eye diagrams back-to-back (top) and after 263-km transmission (bottom), for NRZ-ASK, CSRZ-ASK, NRZ-DPSK, and CSRZ-DPSK (from left to right).

In order to test other compensator CDs, either 5 or 10 km of SSMF and a -342 -ps/nm piece of DCF were taken out from the link. Compensator control was always successful, and error-free transmission was possible. Corresponding BER data (258, 253 km) is also plotted in Fig. 3, and required compensator dispersions were near -390 (see Fig. 2) and -635 ps/nm, respectively. The combined penalties of transmission and CD compensator were measured to be between -1.2 (an improvement) and $+1.2$ dB. Fig. 4 shows received eye diagrams for all modulation formats. For DPSK, the oscilloscope had to be triggered from the transmitter, and a short persistence time was, therefore, chosen for the 263-km case. All 263-km cases are also affected by EDFA noise.

IV. DISCUSSION

In [11], CD has been compensated at 43 Gb/s, but only for CSRZ-ASK. When that CD compensator was operational, the reported Q factors were about 12.5 dB, which were very close to the forward-error-correction (FEC) limit. On the contrary, our Q factors are >17 dB which corresponds to (almost) error-free transmission with a BER $< 10^{-12}$. Given the capability of all components to work at a BER = 10^{-3} ($Q = 10$ dB) transmission was also successfully tested for that case. Depending on the modulation format, there is a CD readout offset of about $-1, \dots, +9$ ps/nm compared to the $Q > 17$ dB case. In a practical system, the controller offset can be optimized at the Q value of typical operation, or can be adapted depending on the frequency of FEC-induced error correction events.

Our robust synchronous arrival time detection scheme operates with various modulation formats and allows to automatically adjust the tunable CD compensator. CSRZ-DSPK out-

performs the other modulation formats in receiver sensitivity, which recommends it for long and ultralong-haul optical transmission.

V. CONCLUSION

We have compensated residual CD in a 263-km fiber link at 40 Gb/s for the modulation formats NRZ-ASK, CSRZ-ASK, NRZ-DPSK, and CSRZ-DPSK. A low-cost synchronous arrival time detection scheme measured residual CD. It was in turn eliminated by automatic control of a commercially available FBG-based thermally tunable dispersion compensator in the range -300 to -700 ps/nm. The total measured penalty of transmission and CD compensation was between $-1.2, \dots, +1.2$ dB, for various link lengths and compensated CD values.

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