Adaptive chromatic dispersion compensation in 1.6 Tbit/s DPSK and ASK transmission experiments over 44...94 km of SSMF

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ABSTRACT

Chromatic dispersion (CD) in single-mode optical fiber distorts pulses and is a big obstacle against the upgrading of long-haul, dynamically routed wavelength division multiplexed (WDM) transmission systems at 10 Gbit/s and beyond. High-performance adaptive dispersion compensators are required as well as reliable low-cost hardware for the detection of residual CD. Targeting high-capacity metro systems, full-band 1.6-Tb/s (40x40Gbit/s) adaptive CD compensation is demonstrated in this experiment, using CSRZ-ASK and NRZ-DPSK modulation formats. A multichannel dispersion compensator, tunable in the range -700 to -1500 ps/nm, is automatically controlled by arrival time detection in one of the 40 transmitted WDM channels. Dispersion and its slope are tuned simultaneously by a thermal gradient of the grating-based compensator to match the parameters of standard single-mode fiber (SSMF) with lengths between 44 and 94 km.

Keywords: Adaptive chromatic dispersion compensation, fiber Bragg grating, WDM transmission, ASK, DPSK

1. INTRODUCTION

Tunable chromatic dispersion (CD) compensation is needed for the installation and upgradation of long haul and dynamically routed optical wavelength division multiplexed (WDM) transmission systems, especially at 40 Gbit/s per WDM channel. Upgrades presently require the measurement of CD and its subsequent compensation by tailored lengths of dispersion-compensating fiber (DCF). To avoid this costly process and to improve network reconfigurability, network operators would like to have adaptive dispersion compensators. For cost reasons, there is strong interest in developing multichannel tunable dispersion compensators with periodic frequency response[1—4]. Among various approaches[5—9], fiber Bragg grating (FBG)–based optical CD compensators exhibit largest dispersion and lowest insertion loss with an associated strong tunability. Recent advances in FBG technology now allow the realization of single and multi-channel tunable dispersion compensators[10].

For CD detection, synchronous arrival time detection with an ultimate sensitivity limit of 100 attoseconds[11] is the most promising option because this scheme has an extremely low incremental cost, provides the sign of CD, responds in ~ 1 ms and is usable for various modulation formats[12]. Prior to this, a similar method was reported by Takushima and Kikuchi[13], but arrival time detection was asynchronous. As a consequence the required frequency deviation was larger and 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 amplitude shift keying (CSRZ-ASK), nonreturn-to-zero differential phase shift keying (NRZ-DPSK) and carrier suppressed return-to-zero differential phase shift keying (CSRZ-DPSK) was evaluated numerically in reference 14 at 43 Gbit/s. Here we report on adaptive chromatic dispersion compensation for some of these modulation formats. We conduct 40 Gbit/s

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transmission experiments, with a commercially available FBG-based thermally tunable dispersion compensator and synchronous arrival time detection. This scheme was later expanded to demonstrate full band chromatic dispersion compensation at 40 Gbit/s per WDM channel, using a single multichannel, thermally tunable fiber Bragg grating-based, adaptive dispersion compensator that was initially designed for operation at 10 Gbit/s. The transmission setup of this experiment is given in the following section, and the transmission results are given and discussed in section 3.

2. TRANSMISSION SETUP

Figure 1 shows the 40×40 Gbit/s transmission setup, similar to reference 15. 2^7-1 PRBS data at 40 Gbit/s is obtained from an experimental 16:1 multiplexer that combines 16 2.5 Gbit/s sub-channels mutually delayed by multiples of 8 bits. The electrical multiplexer introduces too much intersymbol interference (ISI) and does not allow their error-free transmission of longer bit patterns, not even back-to-back (electrically). PRBS data is modulated onto 40 WDM channels (192.1 ... 196.0 THz) with 100 GHz channel spacing using a dual-drive Mach-Zehnder modulator (MZM). The modulation format is either CSRZ-ASK or NRZ-DPSK. Another dual-drive MZM driven at 20 GHz generates CSRZ pulses when required. In order to improve the receiver sensitivity the modulator driving voltage was reduced for ASK. Given the choice of available attenuators, the two arms of the dual-drive modulator are supplied with different amplitudes, which results in an ASK chirp of –0.22 (because available values of RF attenuation yielded optimum back-to-back sensitivity for unequal modulation amplitudes at the two modulator inputs). The CSRZ pulse width is 67%. The transmitted power is 2 dBm per channel.

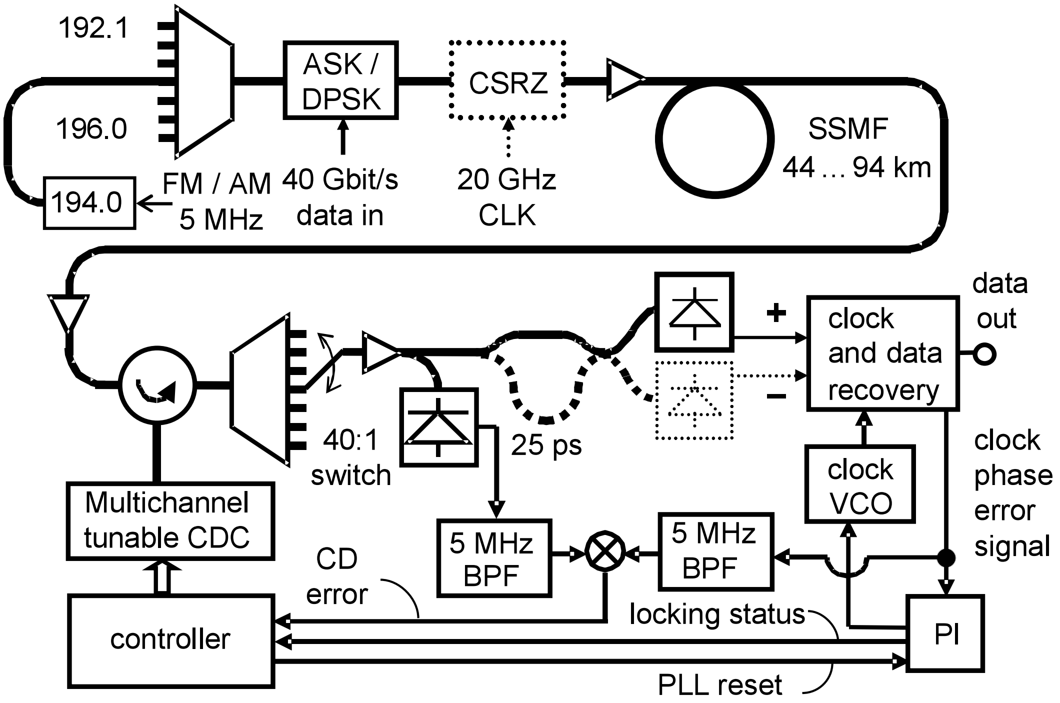

Fig. 1: 40x40 Gbit/s transmission setup with adaptive multichannel dispersion compensation

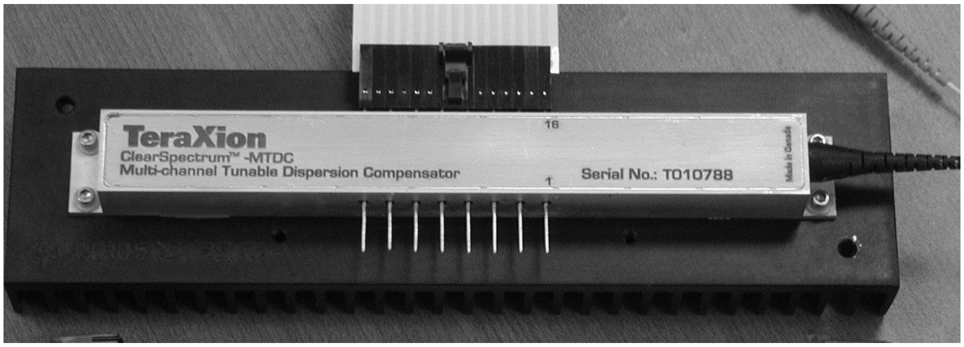

Fig. 2: Photograph of the multichannel tunable dispersion compensator

The signals are transmitted over various lengths of SSMF to the receiver. A fiber Bragg grating-based dispersion compensator as shown in Fig. 2 is inserted by means of an optical circulator after the optical preamplifier. Dispersion and its slope are tuned simultaneously by a thermal gradient to match SSMF lengths between 44 and 94 km.

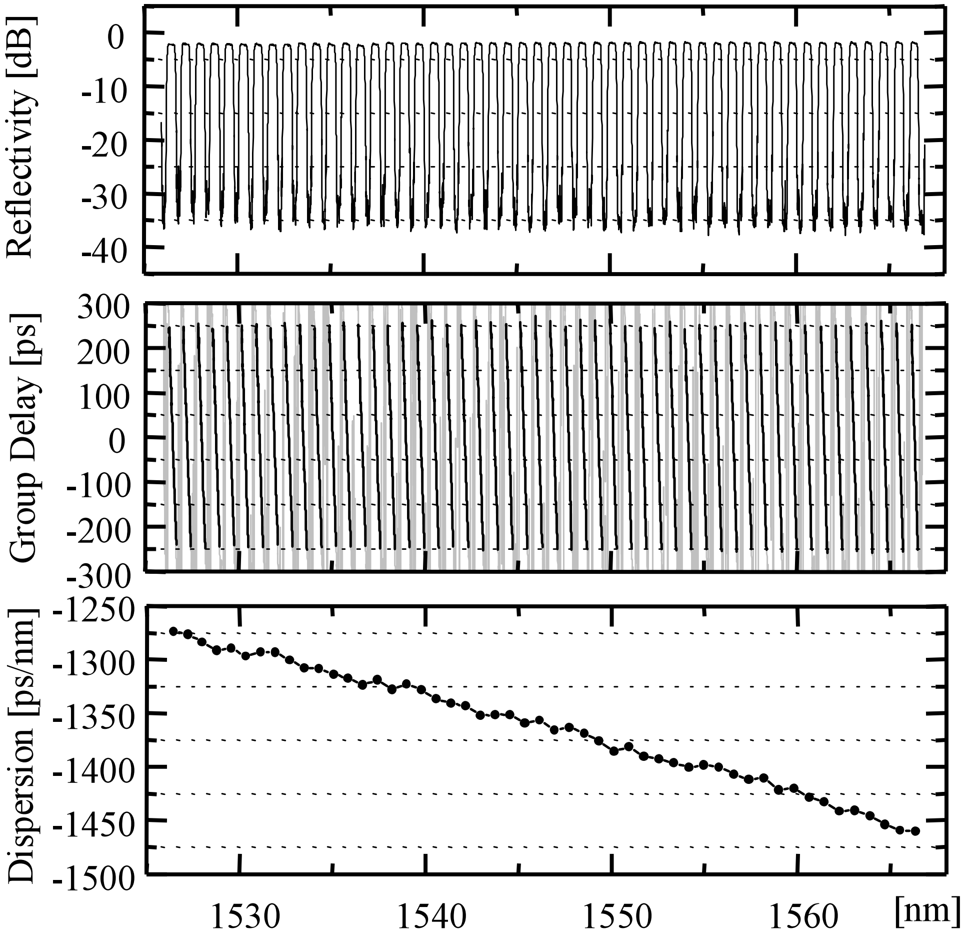

Fig. 3: Reflectivity, group delay and mid-channel dispersions vs. wavelength at –1350 ps/nm midband dispersion

The MTDC has a total of 51 channels with a bandwidth of at least ~35 GHz separated by 100 GHz. Thermal tuning is possible from –700 to more than –1500 ps/nm. Insertion loss of the compensator including the loss of the optical circulator is typically in the order of ~5 dB. Fig. 3 above shows reflectivity, group delay and mid-channel dispersions versus wavelength when the compensator CD at 194 THz is tuned to about –1350 ps/nm. The smoothed average group delay ripple (GDR) with 25 pm averaging window for each channel of this MTDC is typically in order of ±7 ps[4]. Polarization mode dispersion (PMD) is usually as low as 2 ps in other devices of this type, but this particular device has a PMD of 5 ps. By using the same fabrication process, compensators with any other residual dispersion slopes, or smaller tunability combined with larger bandwidth, could be designed for long haul systems.

Figure 4 shows how the bandwidth limitation of the compensator, which was initially designed for 10 Gbit/s operation, increases with the compensated fiber length. This bandwidth limitation in fact causes excess transmission penalties which limit performance at high dispersion settings.

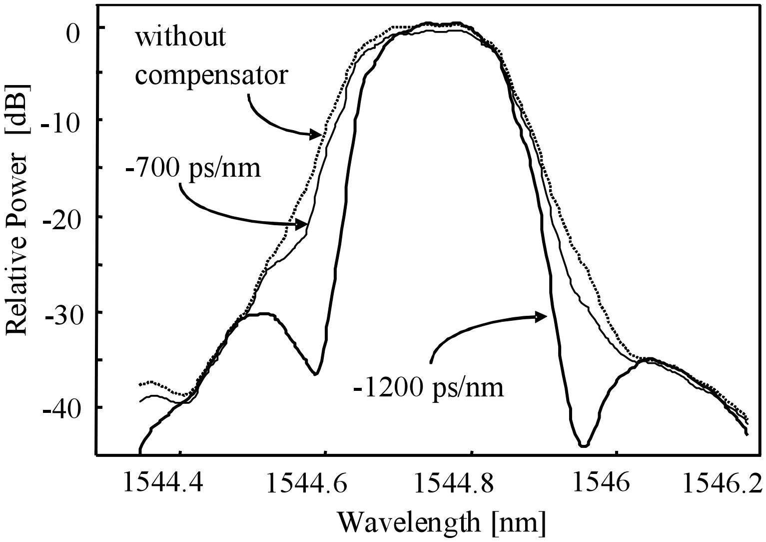

Fig. 4: Dispersion setting dependent narrowing of optical spectrum of a WDM channel by multichannel compensator

The dispersion-compensated signals pass a WDM DEMUX, a 40:1 fiber switch and subsequent EDFAs as well as a 2 nm wide tunable bandpass filter (not shown) for removal of broadband noise. The detected photocurrent is stabilized by a feedback loop that controls the pump current of the last EDFA. For ASK, the signal is detected with a single photodetector. For DPSK, a temperature-stabilized all-fiber Mach-Zehnder interferometer with a 25 ps delay is inserted, and two differentially connected photodiodes are used for balanced detection. The receiver interferometer is stabilized using a lock-in detection scheme[12]. A standard clock-and-data recovery (CDR) with 20 GHz clock signal is used. BER performance is almost identical in even and odd data subchannels.

A small sinusoidal 5 MHz pump current modulation is applied to the 194.0 THz transmitter laser. It causes a ~400 MHz peak-to-peak frequency modulation and a ~2% amplitude modulation. In the presence of CD, FM modulation causes a small arrival time modulation that is indicated by the clock phase error signal in the clock recovery phase locked loop (PLL). For arrival time detection, a low frequency power monitor photodiode recovers the 5 MHz amplitude modulation and provides a reference signal for the 5 MHz lock-in detection of the clock phase error signal. After amplification and bandpass filtering, the arrival time detection signal is multiplied with the reference signal in a signal processor. Due to lock-in detection scheme, the multiplier output signal is directly proportional to the experienced residual dispersion, including its sign[16]. For initial signal acquisition, the chromatic dispersion setting is swept and the locking of the clock PLL is monitored. Then the dispersion is tuned into the center of the PLL locking range.

Subsequently the dispersion is held, and tracked if necessary, by integrating the chromatic dispersion error signal. In a commercial system the signals of the 194.0 THz receiver would be utilized to control the compensator, and those of another (near) mid-band channel, also if equipped with laser pump current modulation, would constitute a reserve in case of a channel failure. Temporal variations of CD are automatically tracked when the 194.0 THz channel is received. Since we have only one receiver we freeze the integrator output signal (= CD control signal) when other channels are selected. The electrical heating/cooling power required to control the CD compensator is ~10 W. The thermal scan takes 10 minutes, and the control time constant is about 30 s, but control speed was not optimized. A proportional integral derivative (PID) controller should work better.

3. TRANSMISSION RESULTS

After transmission and dispersion compensation the WDM signals are decorrelated. For instance, 1350 ps/nm fiber dispersion introduces a group delay of 1080 ps between neighbor WDM channels. Due to its sampled nature and short physical length, the compensator removes only the intra- but not the inter-channel group delay spread. Therefore the setup can be considered as completely realistic even though all WDM channels are modulated together. Figure 5 shows the received optical spectra for 40 WDM channels before the optical preamplifier for CSRZ-ASK and NRZ-DPSK modulation format.

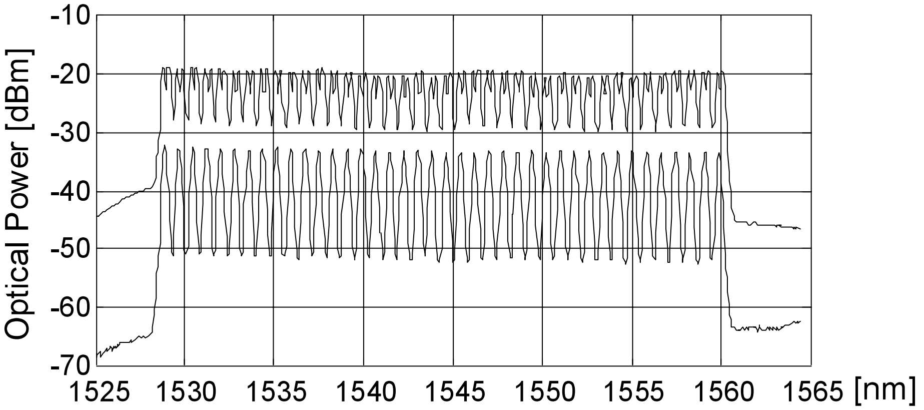

Fig. 5: Received optical spectra (rescaled) for 40 WDM channels before the optical preamplifier: CSRZ-ASK (top) and NRZ-DPSK (bottom)

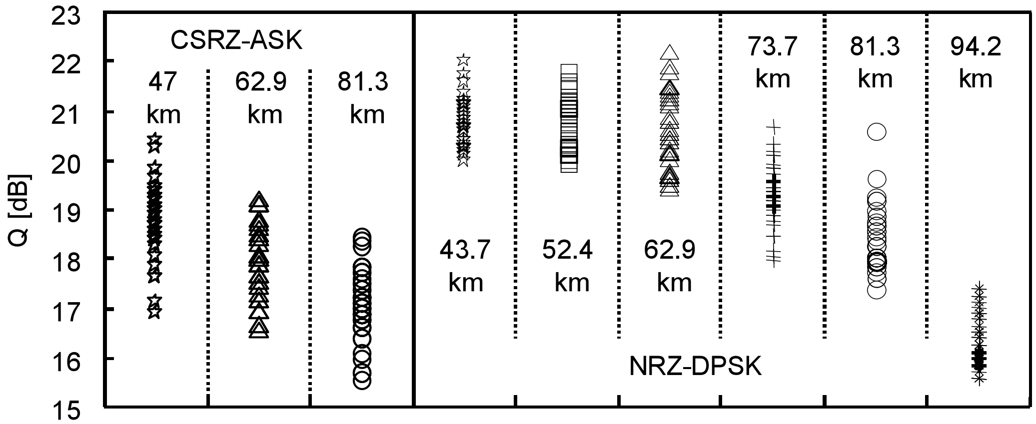

Fig. 6: Q factors for CSRZ-ASK and NRZ-DPSK at various transmission distances, in each case for 40 WDM channels.

Fig. 6 shows *Q* factors, derived from series of measured bit-error rates (BERs), for both modulation formats and various SSMF distances. E.g., average sensitivity and OSNR of 40 WDM channels were –27.1 dBm and 30.4 dB/0.1 nm, respectively, for NRZ-DPSK transmission over 62.9 km at BER = 10^{-9}. Associated nominal compensator settings ranged between –700 (43.7 km) and about –1520 ps/nm (94.2 km). Each column contains 40 symbols, one for each WDM channel. The worst-case *Q* factors for CSRZ-ASK range from 16.9 dB for 47 km to 15.6 dB (BER = 10^{-9}) for 81.3 km of SSMF. Due to the negative chirp the smallest possible distance was 47 km. The worst-case *Q* factors for zero-chirp NRZ-DPSK range from ≥ 20 dB for 43.7 km to 15.6 dB for 94.2 km of SSMF. The back-to-back Q factors were > 24 dB for both modulation formats.

The compensation of the SSMF dispersion slope (~0.06 ps/nm^2-km) is also satisfactory. This is seen from a number of eye diagrams, recorded at the lowest (192.1 THz), mid band (194.0 THz), and highest (196.0 THz) channel frequencies (Fig. 7). The limited bandwidth of the compensator, initially designed for 10 Gbit/s operation, decreases with the compensated fiber length and is the main transmission-degrading effect in this experiment. The use of a MTDC with larger bandwidth would improve the results.

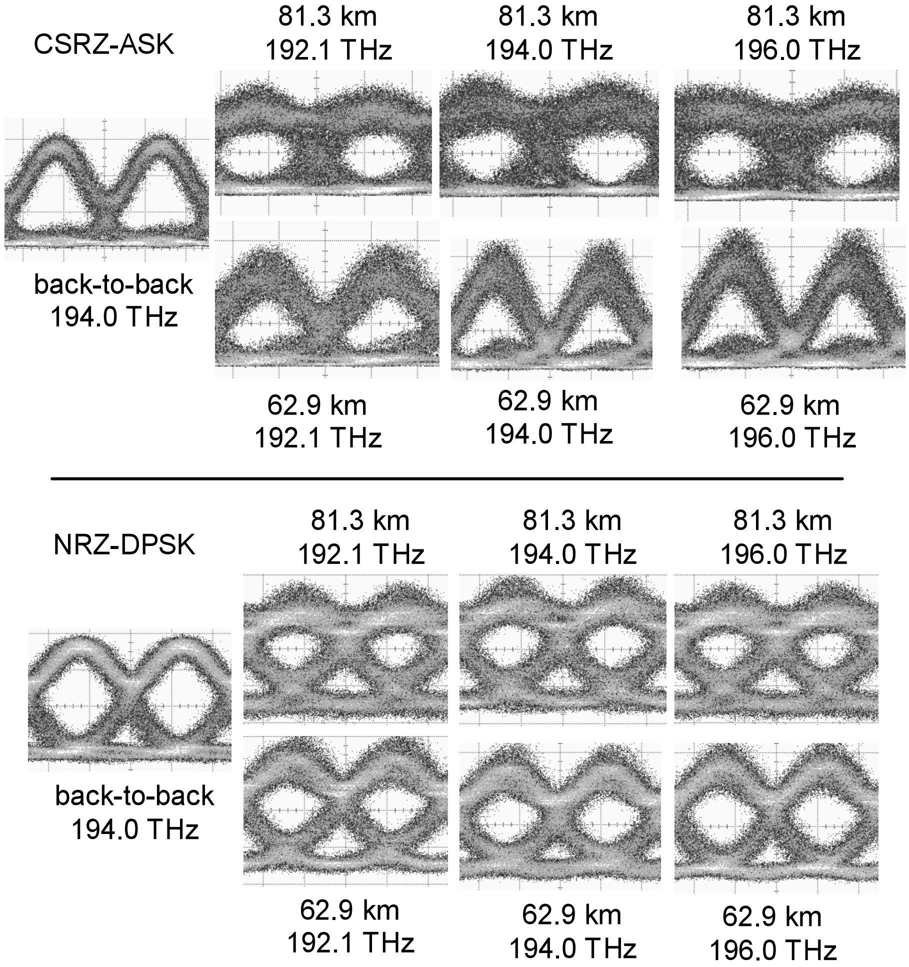

Fig. 7: Exemplary eye diagrams for CSRZ-ASK (left) and NRZ-DPSK (right).

4. DISCUSSION

In a commercial multichannel system, for example, the signals of the 194.0 THz receiver would be utilized to control the compensator, and those of another (near) mid-band channel, also if equipped with laser pump current modulation, would constitute a reserve in case of a channel failure.

Duobinary modulation was not available in this experiment. However, our results suggest that the dispersion compensator would be very well suited for a transmission system with duobinary modulation, which produces narrower spectra. Since compensator bandwidth scales inversely with dispersion while the Q factor drops gradually with increasing dispersion, we expect performance beyond the FEC limit to be possible at 43 Gb/s.

5. CONCLUSIONS

This 1.6 Tbit/s (40x40Gbit/s), 43.7...94.2 km SSMF transmission experiment shows that chromatic dispersion and its slope can be compensated in the fully populated C band at 40 Gb/s per WDM channel, using tunable devices that were initially designed for 10 Gbit/s operation. The compact FBG, thermally tuned from –700 to –1500 ps/nm combined with the arrival time detection scheme are suitable for a low-cost dispersion compensation solution in SSMF-based high-capacity metro systems.

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