1.6-Tb/s (40 × 40 Gb/s) Transmission Over 44, . . . ,94 km of SSMF With Adaptive Chromatic Dispersion Compensation

S. Bhandare, *Member, IEEE*, D. Sandel, A. Hidayat, A. F. Abas, H. Zhang, F. Wüst, B. Milivojevic, R. Noé, *Member, IEEE*, M. Guy, M. Lapointe, and Y. Painchaud

***Abstract*—Full-band 1.6-Tb/s adaptive chromatic dispersion compensation is demonstrated for the first time. A multichannel tunable dispersion compensator is automatically controlled by arrival time detection on one out of 40 wavelength-division-multiplexed transmitted channels.**

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

I. Introduction

THE upgrading of existing standard single-mode fiber (SSMF) links to 40 Gb/s per wavelength-division-multiplexed (WDM) channel presently requires measurement of fiber dispersion and its subsequent compensation by tailored lengths of dispersion-compensating fiber. To avoid this costly process and to improve network reconfigurability, operators would like to have adaptive dispersion compensators. For cost reasons, there is strong interest in a periodic frequency response and multichannel tunable dispersion compensation [1]–[4]. Here we report, for the first time to our knowledge, on full-band chromatic dispersion (CD) compensation at 40 Gb/s per WDM channel, using single multichannel, thermally tunable fiber Bragg grating-based, adaptive dispersion compensator that was initially designed for operation at 10 Gb/s.

II. Transmission Setup

Fig. 1 shows the 40 × 40 Gb/s transmission setup, similar to [5]. The $2^7 - 1$ pseudorandom binary sequence (PRBS) data at 40 Gb/s is obtained from an experimental 16 : 1 multiplexer that combines 16 2.5-Gb/s subchannels mutually delayed by multiples of 8 bits. The electrical multiplexer introduces too much intersymbol interference in longer bit patterns and does not allow their error-free transmission, 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. The modulation format is either carrier suppressed return-to-zero amplitude-shift keying (CSRZ-ASK), with a chirp of −0.22 for experimental convenience (because available values of radio-frequency attenuation yielded optimum back-to-back sensitivity for unequal modulation amplitudes at the two modulator inputs), or zero-chirp nonreturn-to-zero differential phase-shift keying (NRZ-DPSK). Another Mach–Zehnder modulator driven at 20 GHz carves 67% CSRZ pulses for ASK modulation. Transmitted power is 2 dBm per channel.

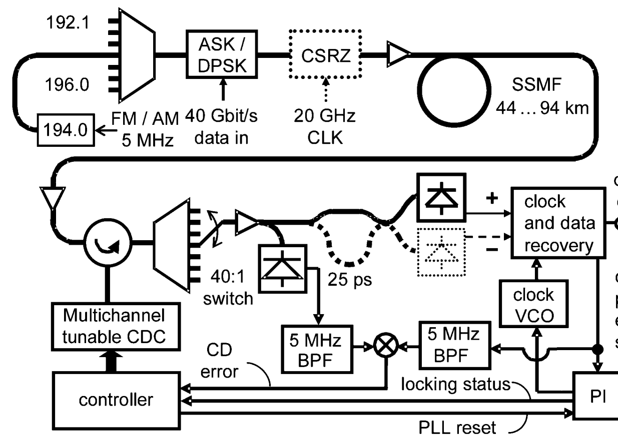

Fig. 1. 40 × 40 Gb/s transmission setup with adaptive multichannel tunable CD compensation.

The signals are transmitted over various lengths of SSMF to the receiver. A fiber Bragg grating-based multichannel dispersion compensator (MTDC) is inserted by means of a 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. 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. Fig. 2 shows reflectivity, group delay, and midchannel dispersions versus wavelength when the dispersion at 194 THz is tuned to about −1350 ps/nm. A representative close-up of the group delay is shown in Fig. 3. The averaged group delay ripple in a 25-pm spectral window for each channel of this MTDC typically is about ±7 ps [4]. Polarization-mode dispersion (PMD) is usually as low as 2 ps in other devices of this type but this particular device had a PMD of 5 ps. Insertion loss of the compensator including the loss of the optical circulator is ∼5 dB. Using the same fabrication process, compensators with other dispersion slopes, or smaller tunability com-

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S. Bhandare, D. Sandel, A. Hidayat, A. F. Abas, H. Zhang, F. Wüst, B. Milivojevic, and R. Noé are with the Department of Optical Communication and High Frequency Engineering, University of Paderborn, 33098 Paderborn, Germany (e-mail: suhas@ont.upb.de; noe@upb.de).

M. Guy, M. Lapointe, and Y. Painchaud are with TeraXion, Sainte-Foy, QC G1P 4S8, Canada (e-mail: mguy@teraxion.com; mlapointe@teraxion.com; ypainchaud@teraxion.com).

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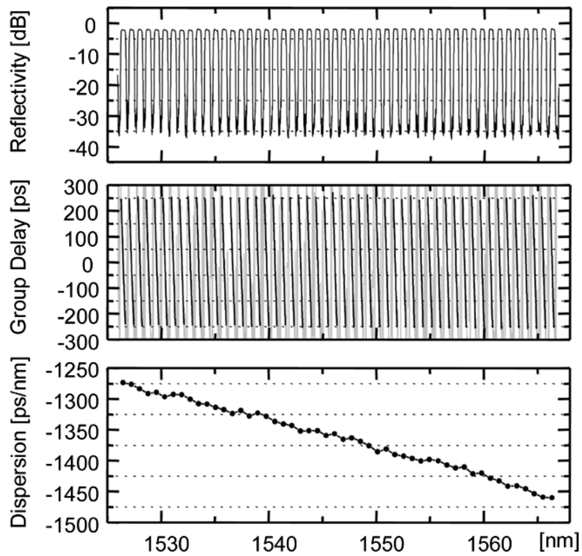

Fig. 2. Reflectivity, group delay, and midchannel dispersions versus wavelength at −1350-ps/nm midband dispersion.

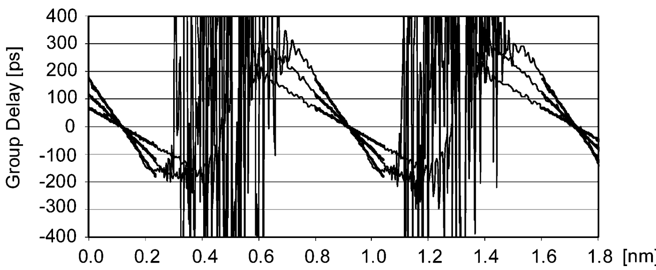

Fig. 3. Close-up of group delay versus wavelength at various dispersion settings.

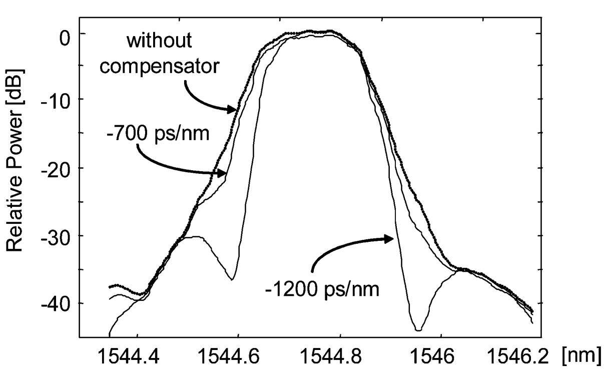

Fig. 4. Dispersion setting dependent narrowing of optical spectrum of a WDM channel by multichannel compensator.

bined with larger bandwidth, could be designed for long-haul systems [6].

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

The dispersion-compensated signals pass a WDM demultiplexer, a 40 : 1 fiber switch, and subsequent erbium-doped fiber amplifiers (EDFAs) as well as a 2-nm-wide tunable bandpass filter (not shown) for removal of broad-band noise. The detected

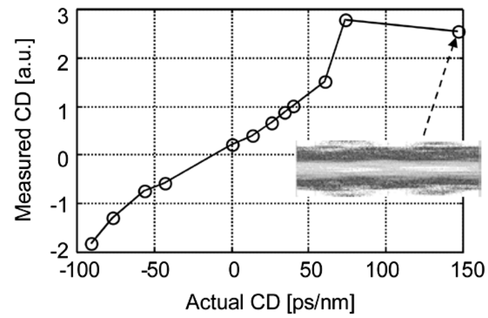

Fig. 5. CD detection readout versus actual dispersion. Inset: RZ-DPSK eye diagram at 147 ps/nm resulting from interferometer output signal difference is completely closed, yet the sign of CD is correctly measured.

photocurrent is stabilized by a feedback loop that controls the pump current of the last EDFA. For ASK, the signal is detected in 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. A standard clock-and-data recovery (CDR) with 20-GHz clock signal is used. Bit-error-rate (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 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 digital signal processor. Due to the lock-in detection scheme, the multiplier output signal is directly proportional to the experienced residual dispersion, including its sign [7]. An earlier obtained CD readout characteristic as a function of true residual dispersion is shown in Fig. 5, here for RZ-DPSK. The sign of CD readout is correct even when transmission is no longer possible, as is illustrated by the completely closed eye diagram (inset). The small offset at zero dispersion is due to the imperfection of the experimental 40-Gb/s CDR used in this experiment. It is quite stable and can, therefore, be subtracted.

For initial signal acquisition, the CD 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 CD 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) midband 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 and we freeze the integrator output signal (=CD control signal) when other channels are selected. The electrical heating/cooling power required to control

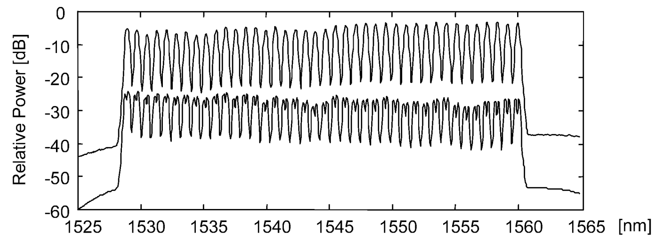

Fig. 6. Received optical spectra for 40 WDM channels before the optical preamplifier: CSRZ-ASK (bottom) and NRZ-DPSK (top).

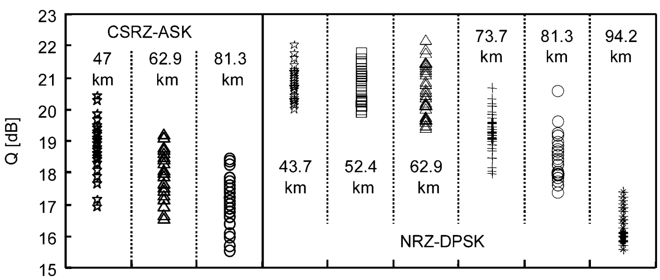

Fig. 7. Q-factors for CSRZ-ASK and NRZ-DPSK at various transmission distances, in each case for 40 WDM channels.

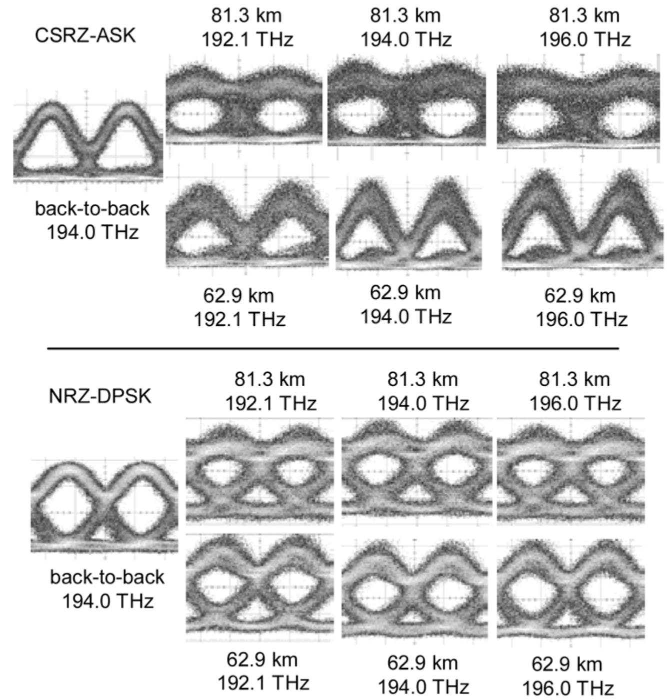

Fig. 8. Exemplary eye diagrams for CSRZ-ASK (top) and NRZ-DPSK (bottom).

the CD compensator is $\sim$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 derivative controller should work better.

III. Transmission Results

Fig. 6 shows the received optical spectra for 40 WDM channels before the optical preamplifier for CSRZ-ASK and NRZ-DPSK modulation format.

Fig. 7 shows Q-factors, derived from series of measured BERs, for both modulation formats and various SSMF distances, e.g., average sensitivity and optical signal-to-noise ratio 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 $(\mathrm{BER} = 10^{-9})$ 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 $\geq$20 dB for 43.7 km to 15.6 dB for 94.2 km of SSMF. The back-to-back Q-factors were $>$24 dB for both modulation formats. The compensation of the SSMF dispersion slope ($\sim$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), midband (194.0 THz), and highest (196.0 THz) channel frequencies (Fig. 8). The limited bandwidth of the compensator, initially designed for 10-Gb/s operation, decreases with the compensated fiber length and is believed to constitute the main transmission-degrading effect.

IV. Conclusion

This 1.6-Tb/s (40×40 Gb/s), $43.7, \ldots, 94.2$ km SSMF transmission experiment shows that CD 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-Gb/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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