Tunable Dispersion Compensation Experiment in 5.94 Tb/s WDM Transmission System

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ABSTRACT

The capacity limit of a thermally controlled fiber Bragg grating-based chromatic dispersion compensator, which was initially designed for 10 Gb/s operation, was investigated in a 40 Gb/s system. A CS-RZ DQPSK polarization division multiplex (PolDM) system was used as a testbed. An equivalent quasi error-free 5.94 Tb/s capacity was demonstrated when dispersion of up to 73.8 km of SSMF was compensated. The dispersion slope compensation was satisfactory for C-band operation. Additionally, it was found that the compensator introduced band-pass filtering behaviour, which reduced the compensator bandwidth as the dispersion setting was increased. It was also found that even after 41.5 km, there was around 2 dB penalty introduced to DQPSK system while 5 dB penalty to DQPDK-PolDM, referring to BER of 10^{-5}.

Keywords: Chromatic dispersion compensation, WDM transmission, Fiber Bragg Grating, DQPSK, polarization division multiplex

1. INTRODUCTION

Chromatic dispersion management is a critical issue in long-haul fibre links and high-speed reconfigurable optical networks. The main values of chromatic dispersion can basically be compensated by a dispersion compensating fiber (DCF), but this is not enough because dispersion is not constant and always varies due to several effects, including: 1) temperature-induced changes in the chromatic dispersion of the transmission fiber; 2) wavelength drift in wavelength-dependent components causing a variation of the induced chirp; 3) nonlinear phase drift caused by small variations in optical power due to, for example, imperfect gain flattening; 4) reconfigurable optical networking that can significantly change the path-average dispersion. While these dispersion variations may not significantly impact systems operating at low bit rates, they can severely degrade the performance at bit rates of 40 Gb/s and higher. Consequently, tunable chromatic dispersion management has become another critical issue for high bit rate transmission systems and reconfigurable optical networks.

A variety of tunable dispersion compensators (TDC) have been reported in the past years, including planar waveguide ring resonator filters[1, 2], virtually imaged phased array (VIPA) devices[3—5], planar waveguides[6], multi-channel all-pass etalon based tunable dispersion[7—10]. All these devices can simultaneously compensate the dispersion and dispersion slope in wavelength division multiplexing (WDM) transmission systems[11]. However, one issue with these approaches is the tradeoff between dispersion and bandwidth, resulting in a decrease of tuning range with increasing spectral bandwidth, which is required for high bit rate applications. A dispersion compensator, based on bulk diffraction grating and MEMS mirrors[12], is capable of individually addressing varying amounts of residual dispersion in different WDM channels, but with a relatively small tuning range. A novel device is designed based on selfphase modulation (SPM) effect in a specially designed highly nonlinear positive dispersion fiber (HNL-PDF)[13—15]. This fiber-based nonlinear device presents several unique advantages, including potentially broadband and wavelength-continuous

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operation, the ability to individually address different amounts of residual dispersion in different WDM channels, and the possibility to achieve simultaneous dynamic dispersion compensation and noise compression (2R regeneration). Another very important technology for tunable dispersion compensation is based on mechanically or thermally tunable chirped fiber Bragg gratings (CFBG)[16]. This CFBG-based dispersion compensator is initially limited to a single-channel application, which is unsuitable for WDM systems. To meet the wide bandwidth demand in WDM systems, various wideband or multi-channel grating-based approaches have been proposed[17—21], such as those based on a very long FBG, sampled CFBGs and superposition of a large number of CFBGs in the same section of fiber. The superimposed CFBGs compensator is produced by superimposing multiple CFBGs in a common section of fiber, each grating being characterized by a central wavelength and dispersion level. Using this approach, the compensation of the dispersion over up to 32 channels has been achieved in a compact device[22]. A key advantage of superimposed CFBGs is the ability to set accurately and independently the nominal dispersion of each individual channel. Generally speaking, this type of advanced and compact compensator can provide high dispersion, wide bandwidth and significant tunability as well as low insertion loss.

The advances in chirped Fiber Bragg Grating technology now allow the realization of colourless slope-matched tunable dispersion compensators that simultaneously compensate the whole C-band[23]**.** A recent report suggested that the idea to replace the bulky DCF by a single TDC which compensates the total CD of a transmission link independent of the WDM channel frequency could only be implemented in a 10 Gb/s system, while at 40 Gb/s a TDC could only be used as a residual CD compensator[24]. However, as Tb/s capacity transmission moves into the focus of interest it is necessary to explore the compensator capacity limit. In this experiment, a thermally-controlled FBG-based chromatic dispersion compensator which is initially designed for 10 Gb/s operation was tested. By using a CS-RZ DQPSK polarization division multiplex (PolDM) system as a testbed, a capacity of 5.94 Tb/s was successfully achieved above FEC limit with compensation for up to 73.8 km of SSMF, for the first time to our knowledge.

2. TUNABLE DISPERSION COMPENSATOR

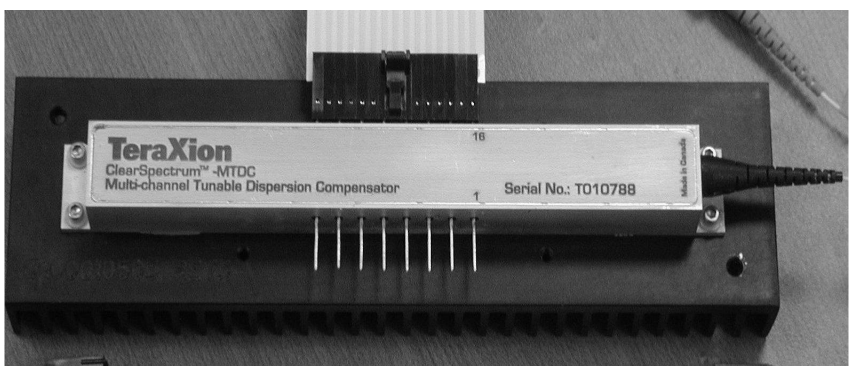

Fig. 1: Chromatic dispersion compensator

Fig. 1 is a CFBG based tunable dispersion compensator that was used for this experiment. As we know, chromatic dispersion causes the optical carriers inside the same pulse to travel at different speed, therefore arrive at the receiver at different time. As a result, the pulse is broadened. The CFBG based tunable dispersion compensator uses the same concept but in reverse direction to compensate this effect. Different optical carrier is reflected at different position along the fiber Bragg gratings. Further speaking, the fastest carrier arrives first at the TDC input and propagates along the gratings until it is reflected at the farthest position in the gratings. Then it will return to the input port, which is also used as the output port. Contrary, the slowest optical carrier arrives latest and is reflected at the first position in the gratings. As a result, at the TDC output the fastest and the slowest optical carrier return to the same relative position as at the transmitter side. Because the TDC uses the same port for input and output, a circulator is used to make the TDC a two ports device. In WDM transmission, the transmission signals with different center optical frequency experience different amount of chromatic dispersion with associated fiber dispersion slope. On the other hand different propagation distance also results in different accumulated dispersion. Based on these two parameters the total dispersion is obtained. The TDC dispersion tuning feature is important to compensate different dispersion level. Basically two thermoelectric coolers (TEC) are used at each end of the fiber Bragg gratings to introduce thermal gradient which control the dispersion level. The sign of the gradient decides the dispersion to increase or decrease. For a single channel TDC, the grating is designed to work only for one specified optical frequency. Contrary, this TDC shown by Fig. 1 is designed for WDM system that is capable of operating in whole C-band.

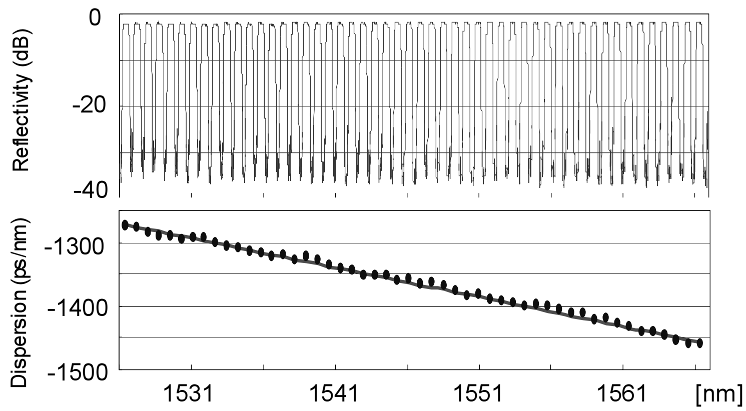

Fig. 2: Reflectivity and mid-channel dispersions vs. wavelength at –1350 ps/nm

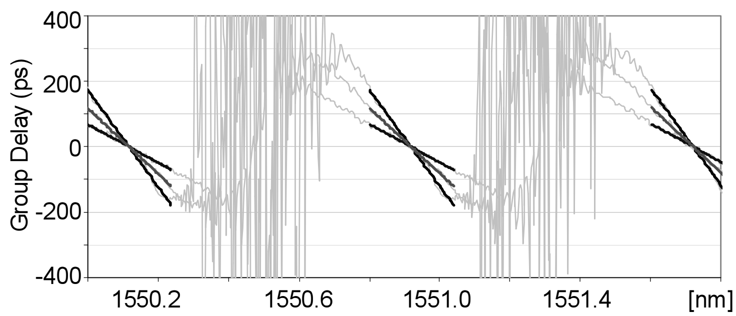

Fig. 3: Close-up figure of group delay vs. wavelength at various dispersion settings

Fig. 2 shows reflectivity and mid-channel dispersions vs. wavelength when the dispersion at 194.2 THz is tuned to about –1350 ps/nm. From the reflectivity, it could be noticed that there are a total of 51 channels with 100 GHz spacing. The reflectivity bandwith is at least ~35 GHz, which is sufficient for 10 Gbit/s system. The bottom figure of Fig. 2 shows the dispersion introduced for all wavelengths by only a single setting. The solid line is the set values, which refers to 194.2 THz and the dispersion slope, while the dotted points are the actual values. It could be concluded that the changes of the dispersion value from one wavelength to another wavelength are smooth and consistently follow the set value and the required dispersion slope of SSMF. This is a good characteristic that allows simultaneous compensation for all wavelengths by only a single setting, and satisfies the chromatic dispersion compensation requirement in WDM system. Fig. 2 indicates that the tuning is possible from –700 to more than –1500 ps/nm which corresponds to around 40 km to 90 km transmission distance, respectively. Total insertion loss of compensator, circulator and connectors is on the order of 5 dB. Total electrical cooling and heating power is ≤ 5 W.

A close-up of group delay vs. wavelength at various dispersion settings is shown in Fig. 3. This figure illustrates how the dispersion slope within one optical carrier changes with different dispersion setting. The slope represents the amount of negative group delay introduced to the signal. As we know the group delay increases with the transmission distance, therefore increases with dispersion setting. The steepest solid line is the slope for the higher dispersion channel among the three. The clear traces show the compensator bandwith. As the compensator is designed for 10 Gb/s operation, the group delay slope is constant within the marked 30 GHz fit bandwidth. If the blur traces are closely monitored the figure shows that the bandwith is larger than the specified value. However, the bandwidth reduces with increasing the dispersion setting.

3. CAPACITY AND TUNABILITY ASSESSMENT

A 40 channel, 2x2x40 Gb/s DQPSK PolDM system[25] was used to evaluate the compensator performance. This system allowed us to test the compensator on both DQPSK and DQPSK PolDM transmission. The raw aggregate data rate was therefore either 3.2 or 6.4 Tbit/s (Fig. 4). The compensator was placed after the first optical preamplifier. Several distances of SSMF ranging from 41.5 km to 73.8 km were used to test the compensator tunability. The 40 installed WDM channels were sufficient to test also the slope compensation of the device. Dispersion and its slope are tuned simultaneously by a thermal gradient to match SSMF lengths. Standard DQPSK signals applied with different polarizations allowed to determine the compensator PMD. It was ~5 ps for this particular device, while below 1 ps is the standard value for other devices of the same type.

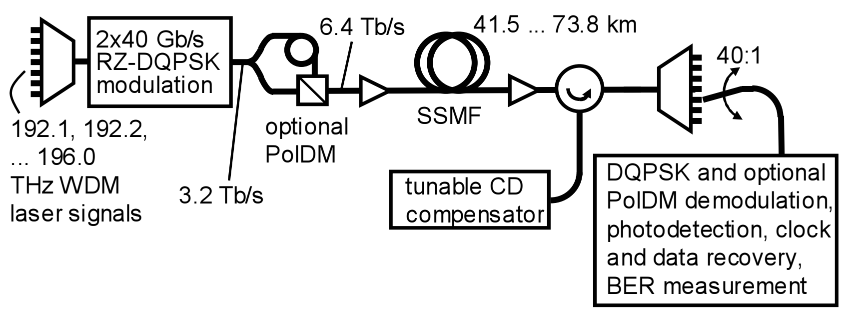

Fig. 4: 3.2 Tb/s RZ-DQPSK system, or 6.4 Tb/s using optional polarization division multiplex (PolDM)

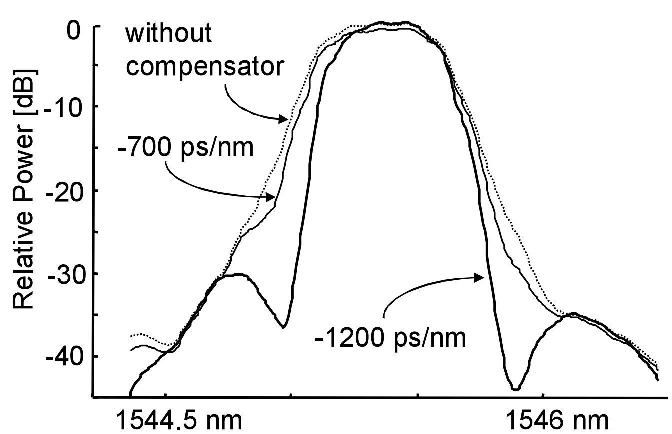

Fig. 5: Dispersion setting dependent narrowing of optical spectrum of a WDM channel by compensator

Fig. 5 shows the bandwidth limitation of the compensator. The passband is inversely proportional to the compensation value. This occurs because the group delay slope becomes steeper at higher compensation value and reduces the compensator passband as earlier shown in Fig. 3, which limits the system performance. It could be noticed that the bandwidth is reaching the border of 30 GHz for -1200 ps/nm setting. This will further be reduced for the higher dispersion setting.

Fig. 6 shows the system sensitivity before and after transmission of various distances, without and with PolDM. From back-to-back sensitivity, it is shown that the former system has better sensitivity. Generally the later system experienced more degradation than the first one. Besides 3 dB less OSNR in the system with PolDM, it is also more vulnerable to fiber nonlinearities. For the first system, referring to BER of 10^{-9} the penalty of around 5 dB is experienced after 41.5 km transmission. At the BER of 10^{-5} the penalty is around 2 dB. This clearly shows the higher bandwidth requirement of the system. For the second system the penalty could only be assessed at BER of 10^{-5} which is around 5 dB. At BER of 10^{-9}, very large penalty is experienced. This signifies that the bandwidth limitation effect is already severe on the system with PolDM even after minimum compensation.

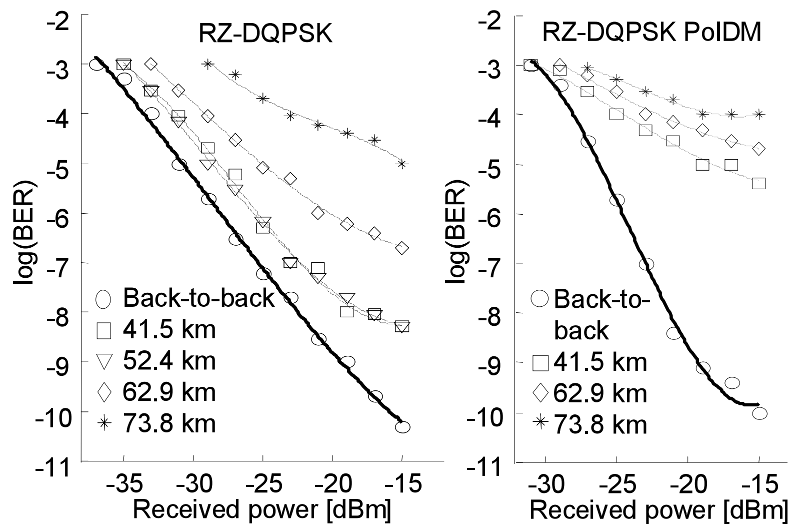

Fig. 6: Preamplified receiver sensitivity of one DQPSK WDM channel, without and with PolDM

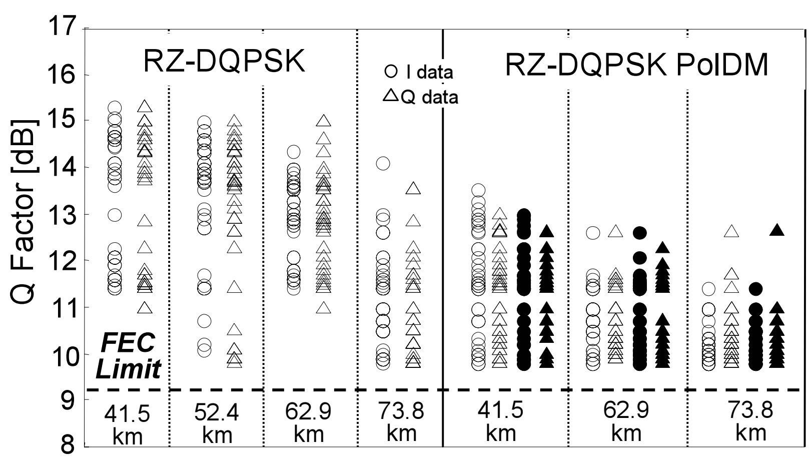

Fig. 7: Q factors for various SSMF distances. Hollow and filled markers differentiate the two polarizations in RZ-DQPSK PolDM.

Fig. 7 shows the measured Q factors for both modulation formats and various SSMF distances. From the figure, if only the best Q at every distance is compared, the Q degradation pattern is noticeable. Associated nominal compensator settings ranged between –700 (41.5 km) and about –1200 ps/nm (73.8 km). Each column corresponds to one quadrature and contains 40 Q factor entries, for the 40 WDM signals. DQPSK has 2 quadratures (I&Q), and PolDM doubles this number by the presence of 2 polarizations. Careful interferometer adjustment might increase some of the lowest Q factors, especially at low distances, but this was not undertaken in order to expedite measurements. This explains why the lowest Q factors are almost identical at various distances and formats; our goal was just to beat the FEC limit. FEC with the indicated 9.2 dB threshold requires a 7% overhead[26]. The transmitted raw capacities of 3.2 and 6.4 Tb/s for DQPSK without and with PolDM, all above the FEC limit, therefore correspond to quasi error-free net capacities of 2.97 and 5.94 Tb/s, respectively.

At each SSMF distance, the compensator setting was identical for all 40 WDM channels, which indicates that the dispersion slope compensation is satisfactory. This can also be seen from the eye diagrams, taken at the lowest (192.1 THZ) and highest (196.0 THz) WDM channel frequencies (Fig. 8; read caption). At 196 THz channel, the system experienced more ASE noise. This explained why the eye diagram is worse compared to 192.1 THz, even in back-to-back setup. At longer distance the eye diagram quality degrades due to the limited compensator bandwidth. The use of a TDC with larger bandwidth would improve the results presented in Fig 8.

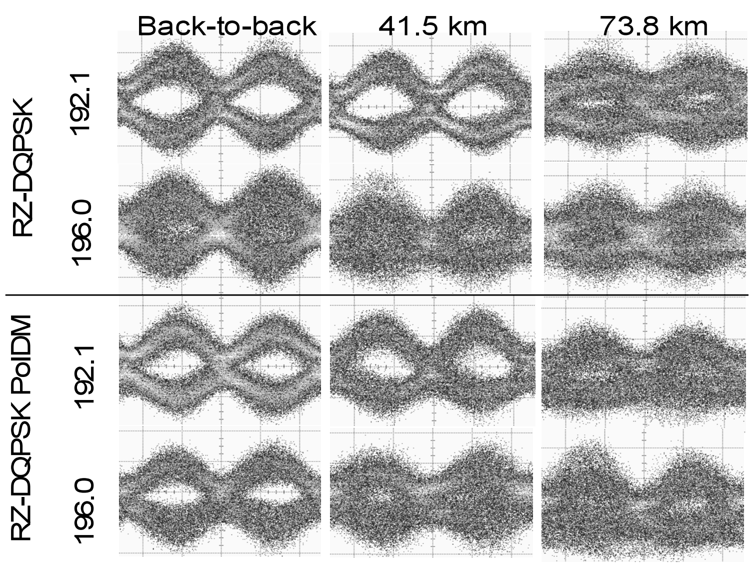

Fig. 8: Eye diagrams for both modulation format. Clock-and-data recovery contains an electrical highpass filter which could not be used during eye diagram recording. This explains why some of the eye diagrams seem to be more closed than permissible

4. CONCLUSIONS

A tunable dispersion compensator initially designed for 10 Gb/s operation was operated between –700 and –1200 ps/nm. By using 40 40Gbaud WDM channels, RZ-DQPSK modulation and optional polarization division multiplex, quasi error-free total net capacities of 2.97 and 5.94 Tb/s were demonstrated. This is, to our knowledge, the largest capacity demonstrated for a tunable dispersion compensator. The experiment results indicated the feasibility to use low cost 10 Gb/s compensator for 40 Gb/s system. It was also highlighted that the main limitation factor was the bandwidth reduction behaviour with increasing dispersion compensation setting. Therefore for 40 Gb/s system this problem need to be solved in order to obtain error free operation after high dispersion compensation.

REFERENCES

1. C. K. Madsen, G. Lenz, A. J. Bruce, M. A. Cappuzzo, L. T. Gomez, and R. E. Scotti, “Integrated all-pass filters for tunable dispersion and dispersion slope compensation,” *IEEE Photon. Technol. Lett.*, vol. 11, pp.1623–1625, 1999.
2. C. K. Madsen, S. Chandrasekhar, E. J. Laskowski, M. A. Cappuzzo, J. Bailey, E. Chen, L. T. Gomez, A. Griffin, R. Long, M. Rasras, A. Wong-Foy, L. W. Stulz, J. Weld, and Y. Low, “An integrated tunable chromatic dispersion compensator for 40 Gb/s NRZ and CSRZ,” in *Proc. Optical Fiber Communications*, pp.927–929, 2002.
3. M. Shirasaki, “Chromatic-dispersion compensator using virtually imaged phased array,” *IEEE Photon. Technol. Lett.*, vol. 9, pp.1598–1600, 1997.
4. M. Shirasaki, Y. Kawahata, S. Cao, H. Ooi, N. Mitamura, H. Isono, G. Ishikawa, G. Barbarossa, C. Yang, and C. Lin, “Variable dispersion compensator using the virtually imaged phased array (VIPA) for 40 Gbit/s WDM transmission systems,” in *ECOC’2000*, Postdeadline Paper PD 2.3.
5. L. D. Garrett, A. H. Gnauck, M. H. Eiselt, R.W. Tach, C. Yang, C. Mao, and S. Cao, “Demonstration of virtually-imaged phased-array, device for tunable dispersion compensation in 16x10 Gb/s WDM transmission over 480 km standard fiber,” in *Proc. OFC’2000*, pp. PD7-1–PD7-3.
6. C. R. Doerr, L. W. Stulz, S. Chandrasekhar, L. L. Buhl, and R. Pafchek, “Multichannel integrated tunable dispersion compensator employing a thermooptic lens,” in *Tech. Dig. OFC’2002*, paper PD-FA6.
7. D. J. Moss, S. McLaughlin, G. Randall, M. Lamont, M. Ardekani, P. Colbourne, S. Kiran, and C. A. Hulse, “Multichannel tunable dispersion compensation using all-pass multicavity etalons,” in *Tech. Dig. OFC’2002*, Paper TuT2.
8. D. J. Moss, M. Lamont, S. McLaughlin, G. Randall, P. Colbourne, S. Kiran, and C. A. Hulse, “Tunable Dispersion and Dispersion Slope Compensators for 10 Gb/s Using All-Pass Multicavity Etalons,” *IEEE Photon. Technol. Lett.*, vol. 15, No.5, pp. 730–731, 2003.
9. L. M. Lunardi, D.J. Moss, S. Chandrasekhar and L. L. Buhl, “An Etalon-based tunable dispersion compensator (TDC) device for 40-Gbit/s applications,” in *Proc. ECOC’2002*, Paper Tu6.4.2.
10. L. M. Lunardi, D. J. Moss, S. Chandrasekhar, L. L. Buhl, M. Lamont, S. McLaughlin, G. Randall, P. Colbourne, S. Kiran, and C. A. Hulse,“Tunable dispersion compensation at 40-Gb.s using a multicavity elaton all-pass filter with NRZ, RZ, and CS-RZ modulatrion,” *J. Lightwave Technol.*, vol. 20, pp. 2136–2144, 2002.
11. M. Shirasaki and S. Cao, “Compensation of chromatic dispersion and dispersion slope using a virtually imaged phased array,” in *Proc. OFC’2001*, pp. TuS1-1–TuS1-3.
12. T. Sano, T. Iwashima, M. Katayama, T. Kanie, M. Harumoto, M. Shigehara, H. Suganuma, and M. Nishimura, “Novel multi-channel tunable chromatic dispersion compensator based on MEMS & diffraction grating,” in *Proc. Optical Fiber Communications*, vol. 2, 2003, pp. 722–723.
13. M. Sauer, D. Nolan, M. Li, and G. Berkey, “Simultaneous multi-channel pulse compression for broadband dynamic dispersion compensation,” in *Proc. Optical Fiber Communications*, vol. 1, 2003, pp. 298–300.
14. D. Kuksenkov, S. Li, M. Sauer, and D. Nolan, “Simultaneous 2R regeneration and dynamic dispersion compensation at 40 Gb/s in a nonlinear fiber-based device,” in *Proc. OFC’2003*, postdeadline, PD05, pp.PD-5-1–PD-5-3.
15. Shenping Li, Michael Sauer, Zagorka D. Gaeta, Dmitri V. Kuksenkov, Scott R. Bickham, George E. Berkey, Ming-Jun Li, OSA, and Daniel A. Nolan, “ Broad-band Dynamic Dispersion Compensation in Nonlinear Fiber-Based Device,” *J. Lightwave Technol.*, vol. 22, No. 1, pp. 29–38, 2004.
16. F. Ouellette, “Dispersion cancellation using linearly chirped Bragg grating filters in optical waveguides,” *Opt.Lett.* 12, pp. 847–849, 1987.
17. J. F. Brennan III *et al.*, “Realization of >10-m-long chirped fiber Bragg grating”, in *OSA Trends in Optics and Photonics (TOPS)* Vol. 33, Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides, Technical Digest, (Optical Society of America, Washington DC, 1999), pp. 35-37.
18. M. Durkin, M. Ibsen, M. J. Cole, and R. I. Laming, “1 m long continuously-written fiber Bragg gratings for combined second- and third-order dispersion compensation,” *Electron. Lett.*, vol. 33, no. 22, pp.1891–1893, 1999.

19. J. X. Cai, K. M. Feng, A. E. Willner, V. Grubsky, D. S. Starodubov, and J. Feinberg, “Simultaneous tunable and dispersion compensation of many WDM channels using a sampled nonlinearly chirped fiber Bragg grating,” *IEEE Photon. Technol. Lett.*, vol. 11, pp.1455–1457, 1999.
20. Y. Painchaud, A. Mailloux, H. Chotard, Epelletier, and M. Guy, “Multichannel fiber Bragg gratings for dispersion and slope compensation,” in *Proc. OFC'2002*, pp.581–582.
21. A. Othonos, X. Lee, and R. M. Measures, “Superimposed multiple Bragg gratings,” *Electron. Lett.* 30, pp.1972-1974, 1994.
22. Y. Painchaud *et al*., “Multi-channel fiber Bragg gratings for dispersion and slope compensation”, in *OSA Trends in Optics and Photonics (TOPS)* Vol. 70, Optical Fiber Communication Conference, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002), pp.581-582.
23. M. Morin, M. Poulin, A. Mailloux, F. Trépanier, Y. Painchaux, “Full C-band slope-matched dispersion compensation based on a phase sampled Bragg grating,” in *Proc. OFC'2004*, Paper WK1.
24. C. R. Doerr, S. Chandrasekhar, M. Cappuzzo, E. Chen, A. Wong-Foy, L. Gomez, S. Patel, and L. Buhl, “Two Mach-Zehnde-Type Tunable Dispersion Compensators Integrated in Series to Increase Bandwidth and/or Range While Maintaining Single-Knob Control, ” *IEEE Photon. Technol. Lett.*, vol. 17, No. 4, pp.828-830, 2005.
25. Suhas Bhandare, David Sandel, Biljana Milivojevic, Ariya Hidayat, Abas Ahmad Fauzi, Hongbin Zhang, Selwan K. Ibrahim, Frank Wüst, and Reinhold Noé, “5.94-Tb/s 1.49-b/s/Hz (40 2 2 40 Gb/s) RZ-DQPSK Polarization-Division Multiplex C-Band Transmission Over 324 km,” *IEEE Photon. Technol. Lett.*, vol. 17, No. 4, pp.914-916, 2005.
26. N. Yoshikane and I. Morita, “160% spectrally-efficient 5.12 Tb/s (64_85.4 Gb/s) RZ DQPSK transmission without polarization demultiplexing,” in *Proc. ECOC'2004*, Stockholm, Sweden, Paper Th4.4.3.