Comparison of Dispersion Compensation Techniques for Real-Time up to 160 Gbit/s DWDM C-Band Transmission

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***Abstract*—The exponential growth of data traffic related to the progress of newest technologies (e.g., 4K/8K live stream videos, virtual reality (VR) applications, etc.), new services, and a fast-growing number of end-users require higher bandwidth and increase of user bitrate, as a result pushing hard the telecommunication infrastructure for upgrading. Expected usage of more complex modulation formats in fiber optical link infrastructure for cellular network transmission and data center interconnections (DCI) are still affected with fundamental chromatic dispersion influence on the signal quality, which consequently increases bit error rate (BER). We experimentally demonstrate a real-time comparison of commercially used dispersion compensation techniques for 100 GHz spaced dense wavelength division multiplexed (DWDM) optical transmission system with a total transmission speed capacity of 160 Gbit/s.**

***Index Terms*—Dense wavelength division multiplexing (DWDM); Chromatic dispersion (CD); Fiber Bragg grating dispersion compensation module (FBG-DCM); Dispersion compensation fiber (DCF); Non-return-to-zero on-off keying (NRZ-OOK).**

I. INTRODUCTION

The newest technology trends being transformed by technology in a variety of ways of next-decide fulfilled by consumer-driven data consumption eventually lead to unprecedented pressures for fiber optical metro, i.e. long-haul networks. With the massive deployment of coherent optical fiber transmission systems at 100 Gbit/s in backbone networks, the pressure has shifted to the metro networks. Communication infrastructures of the next decade will be based on the integration of information and communication technologies (ICT) to optimize the efficiency of operations and large-scale deployment of connected and automated mobility (CAM), cloud computing, wireless sensor networks, e.g., large scale next-generation cellular network coverage connections provide possibility in urban areas [1]–[3]. The evolution towards higher bitrates is mainly driven by the point-to-point (P2P) Fiber-to-the-home/building (FTTh/b) and wireless fronthaul, e.g., new mobile interfaces for fifth-generation (5G), where 25 Gbit/s could be needed soon for either backhauling or new functional split based interfaces [4]–[6].

Intensity modulation with direct detection (IM-DD) transmission technique is preferred due to its advantages of low cost and easy implementation, where chromatic dispersion (CD) induced power fading is one of the key limiting factors in IM/DD transmission systems [2], [7], [8], [9]. Chromatic dispersion CD is possible to compensate in the both optical and electrical domains. Depending on the optical domain dispersion profile, the effects of CD can be either removed locally by fiber Bragg grating (FBG) or can be compensated throughout the dispersion-compensating fiber (DCF) [3], [7].

In our previous research, we concluded that intensity non-return-to-zero on-off keying (NRZ-OOK) modulation format, as well as 4-level amplitude modulation PAM-4 modulation format, which has higher spectral efficiency and potentially can provide higher data transmission speeds in fiber optical networks with limited bandwidth, are still affected with the chromatic dispersion (CD), which is one of the main distance-limiting factors [10], [11]. In particular, the most common solution due to a cost-effective way is re-use the already developed and used commercially available components operating at 10 Gbit/s PONs (10G PON) technology for the desired NG-PONs at least increases bitrates for 25 Gbit/s either 40 Gbit/s per channel [12].

The main purpose of this work is to evaluate the performance of experimentally developed dense wavelength division multiplexed DWDM transmission system and compare the most often used CD compensation techniques. To protect signals and avoid dispersion effects during their transmission, two widely commercially implemented dispersion compensation techniques are experimentally shown: CD compensation based on fiber Bragg grating

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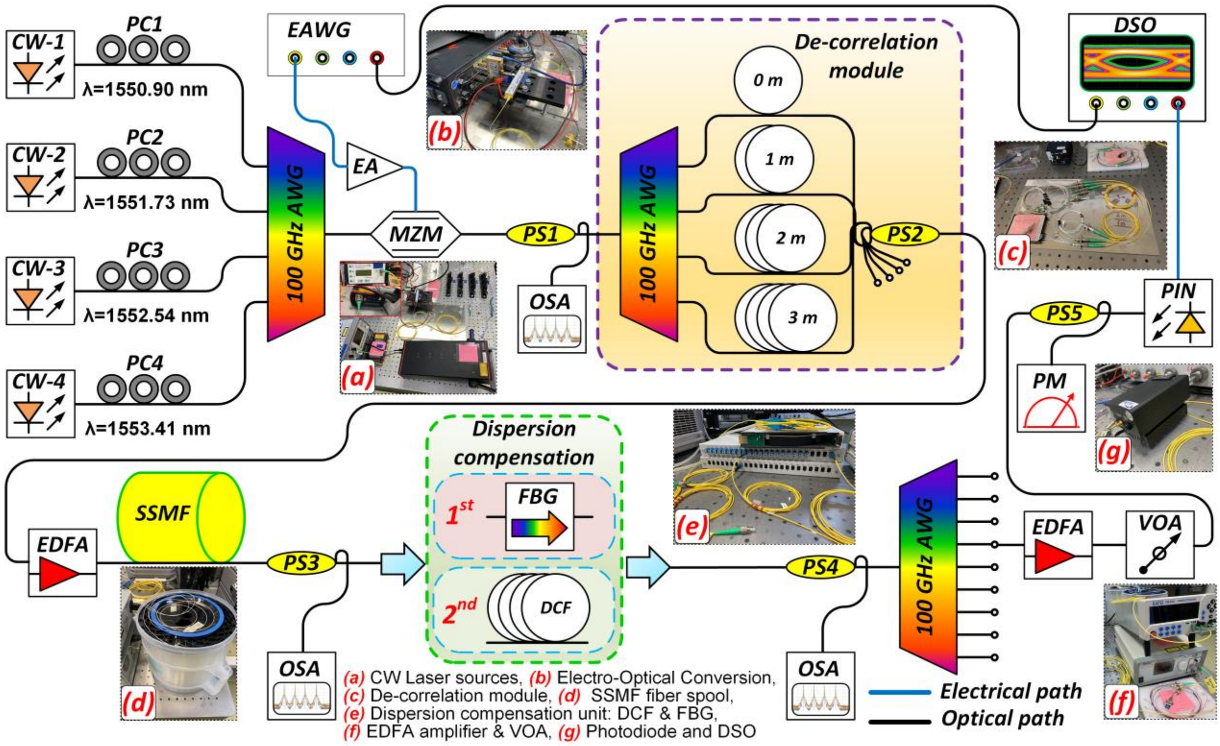
(FGB) dispersion compensation module (DCM) and compensation based on dispersion compensation fibers (DCF). Finally, the influence of the nonlinear effects (NOE) causing signal distortion in DCF optical fiber is analysed [11], [13]. The experimental 4-channel DWDM optical transmission system model is used to evaluate system effectiveness for different bitrates of up to 40 Gbit/s per wavelength and compare widely used techniques of CD post-compensation in terms of received signal quality, e.g., bit-error-ratio (BER) and eye diagrams [14]. The total transmission capacity of the investigated DWDM system is up to 160 Gbit/s.

II. EXPERIMENTAL SETUP OF DWDM C-BAND TRANSMISSION SYSTEM

Through the development of experimental 100 GHz spaced dense WDM optical system, we compared most often used dispersion compensation CD techniques and obtained system performance indicators at operating bitrate of up to 40 Gbit/s per channel under the condition that is still possible to achieve BER threshold of 10^{-3} with the 7 % Forward Error Correction (FEC) overhead [9], [11], [13].

Experimentally we have shown chromatic dispersion CD compensation technique's effectiveness with the use of implemented fiber Bragg grating dispersion compensation module (FBG-DCM) and dispersion compensating fiber (DCF) for 4-channel 100 GHz spaced dense NRZ-OOK modulated WDM optical transmission system after 40 km transmission through standard single-mode fiber (SSMF) span. A more detailed description of both techniques is given in Section IV. The experimental system part is depicted in Fig. 1. The output of four continuous-wave (CW) laser sources with channel spacing of 100 GHz with related 10 dBm output power for each particular source are coupled together by 100 GHz spaced arrayed waveguide grating (AWG) multiplexer/de-multiplexer [15]. Polarization controllers (PCs) are placed before the multiplexer to reduce the polarization-dependent loss of each laser source. The output of AWG is connected to the input of the external Mach-Zehnder modulator (MZM). MZM (bias point 3.14 V) is driven at bitrates from 20 Gbit/s up to 40 Gbit/s by a 2^{11} long pseudo-random bit sequence (PRBS11) non-return-to-zero (NRZ) signal from Keysight M9502A electrical arbitrary waveform generator (EAWG).

The modulated output from the MZM is connected to the de-correlation module through a monitoring splitter (PS1) for measurements of the optical spectrum by Advantest Q8384 optical spectrum analyzer (OSA). A more detailed description of this module is given in Section III. The output of the de-correlation module with four separated and delayed WDM channels is amplified by the first erbium-doped fiber amplifier (EDFA) with fixed output power (+23 dBm) and transmitted through 40 km long ITU-T G.652 standard SSMF fiber span with dispersion coefficient 17.15 ps/(nm × km), dispersion slope 0.096 ps/nm^2, and 0.27 dB/km attenuation coefficient (at λ = 1550 nm reference wavelength). The monitoring splitters, (PS3) after transmission through? SSMF fiber before dispersion CD post-compensation and (PS4) after CD post-compensation for optical spectrum measurements, are used as well.



CW: Continuous wavelength laser source, **PC**: polarization controller, **EAWG**: electrical arbitrary waveform generator, **EA**: electrical amplifier, **MZM**: Mach-Zehnder modulator, **PS**: power splitter, **OSA**: optical spectrum analyzer, **EDFA**: erbium-doped fiber amplifier, **SSMF**: standart single mode fiber, **FBG-DCM**: fiber Bragg grating dispersion compensation module, **DCF**: dispersion compensating fiber, **VOA**: variable optical attenuator, **PM**: optical power meter, **PIN**: photodiode, **DSO**: digital storage oscilloscope.

- 4 WDM channels
- NRZ coding
- CD compensation: FBG-DCM & DCF
- Channel spacing Δf = 100 GHz
- Optical line length L = 40km
- Transmission over: *C-band*
- Transmission speed per channel R = *20, 25, 28, 32, 40 Gbit/s*

Fig. 1. Experimental setup for comparison of effectiveness of dispersion compensation techniques in 4-channnel NRZ-OOK modulated DWDM optical transmission system with total transmission capacity of up to 160 Gbit/s.

The CD post-compensation is consecutively investigated by using:

1. *Tunable fiber Bragg grating dispersion compensation module FBG-DCM*, which has 3.5 dB insertion loss at λ = 1550 nm wavelength, dispersion coefficient of -680 ps/(nm × km);
2. *Dispersion compensation fiber (DCF)* spool with a length of 5.684 km, which has 4.75 dB insertion loss (at λ = 1550 nm reference wavelength) with dispersion coefficient of -686.76 ps/nm/km, and -2.48 ps/nm^2 dispersion slope was used as well.

After transmission thought SSMF fiber span and CD post-compensation, the 100 GHz spaced AWG de-multiplexer is connected to the second EDFA with fixed +10 dBm output power. The output of the EDFA amplifier is connected to 50 GHz photodiode (PIN) with sensitivity equal to +4 dBm for BER of 10^{-12}, the dark current of 10 nA and responsivity of 0.8 A/W through a variable optical attenuator (VOA). The received signal is sampled by Keysight DSAZ334A digital storage oscilloscope (DSO) with 33 GHz analogue bandwidth operating at 80 GSa/s for measurements of received signal bit patterns quality (e.g., eye diagrams) and BER [16].

III. WAVELENGTH DIVISION MULTIPLEXED (WDM) CHANNEL SEPARATION AND DELAY WITH THE USE OF A DE-CORRELATION TECHNIQUE

In our research, to increase the capacity of the experimental communication system and observe the effects of crosstalk, we increased the number of WDM channels by implementing a symmetrical adaptive de-correlation (SAD) method, which has also been used in other research works [17]. MZM modulator used in our experimental transmission system is driven at bitrates from 20 Gbit/s up to 40 Gbit/s by a 2^{11}-1 long pseudo-random bit sequence NRZ signal from an electrical arbitrary waveform generator (EAWG).

The outputs of four laser sources with a spacing of 100 GHz are coupled together by AWG multiplexer and sent to the MZM input. After MZM output, four 100 GHz spaced modulated optical channels are being separated with the de-correlation module, which consists of (1) (see Fig. 2) 100 GHz spaced AWG de-multiplexer, (2) (see Fig. 2) SMF optical fiber spans with different length, and (3) (see Fig. 2) optical coupler. After separation of modulated optical signals, the optical SMF fiber spans with different lengths are used for time delay, where 1 meter long optical fiber span is used for the second channel, 2 meters and 3 meters long SMF spans are used for third and fourth separated WDM channels, respectively. The first output of 100 GHz spaced AWG de-multiplexer is connected directly to the coupler. After each optical channel has been de-correlated, optical coupler for further data transmission combines all channels.

Each transmitted bit length of the optical fiber according to the used bitrate is calculated by the following equation, where SMF fiber core refraction index is 1.4682 at λ = 1550 nm wavelength

$$L = T \times \left(\frac{c}{n_g} \right) \times 100, \quad (1)$$

where L is fiber length for 1 bit (cm), T - bit duration (s), c - light speed in vacuum (km/s), and n_g - optical fiber effective group index of refraction.

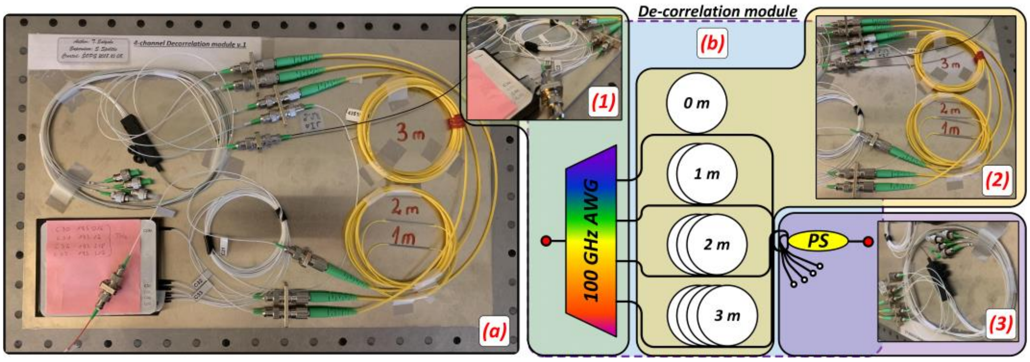


Fig. 2. Setup of de-correlation module: (a) experimentally created; (b) schematics of channel separation principle, where such optical components are used: (1) 100 GHz spaced AWG de-multiplexer, (2) SMF optical fiber spans, (3) 1×8 optical couplers.

According to the bitrate (from 20 Gbit/s up to 40 Gbit/s) of the NRZ-OOK signal, the optical path length of 1 bit is shown in Table I.

TABLE I. OPTICAL PATH LENGTH FOR 1 BIT OF TRANSMISSION.

Bitrate (Gbit/s)	**20**	**25**	**28**	**32**	**40**
Fiber length for 1 bit transmission (cm)	1,02	0,81	0,72	0,63	0.51

The each separated modulated NRZ-OOK signal based on the used de-correlation technique accordingly by the used bitrate per channel with PRBS11 sequence has a constant bit-stream delay (Table II).

TABLE II. PRBS11 DELAY IN BITS FOR TRANSMISSION SYSTEM BY USE OF DE-CORRELATION TECHNIQUE.

Experimentally used bitrate Gbit/s						
Bitrate (Gbit/s)		**20**	**25**	**28**	**32**	**40**
PRBS delay (bits)	CH2	98	122	137	157	196
% of total PRBS length		5 %	6 %	7 %	8 %	10 %
PRBS delay (bits)	CH3	196	245	274	313	392
% of total PRBS length		10 %	12 %	13 %	15 %	19 %
PRBS delay (bits)	CH3	294	367	411	470	587
% of total PRBS length		14 %	18 %	20 %	23 %	29 %

IV. EVALUATION OF CHOSEN DISPERSION COMPENSATION TECHNIQUES

Different chromatic dispersion CD compensation methods are used for wavelength division multiplexed (WDM) optical transmission networks, such as for passive optical access networks (PONs). The most commonly used CD compensation techniques for optical transmission networks are realized with Fiber Bragg grating (FBG), dispersion compensation fiber (DCF), electronic dispersion compensation (EDC), digital filters, and optical phase conjugator (OPC) [18]. Widely used FBG and DCF CD compensation methods are considered for comparison in our research. Implementation of FBG and DCF post-compensation in experimental DWDM 100 GHz spaced optical transmission system shows the relevance of system's performance depending on the used CD compensation technique.

Next-generation (NG) dense wavelength division multiplexed (DWDM) optical transmission systems will deal with the rising bandwidth needs of backbone optical transport networks. With the use of narrow spacing according to ITU-T G.654.2, the definition of flexible grids between wavelength bands will increase the number of optical channels and enable bitrates of several Terabits per second (Tbps) in a single optical fiber [4]. Nowadays, optical transmission systems are developed for laser-light wavelengths in the C-band, and later in the L-band leveraging the wavelengths with the lowest attenuation rates in optical fibers. The use of optical amplification methods is a key enabling technology for WDM systems, which might use many wavelengths at the same time. Several amplification methods are used for enhancing signals of WDM transmission systems. Therefore, widely erbium-doped fiber amplification EDFA technology is conventional for more common use in C-band (1530 nm to 1562 nm). Thereby, it is introduced in our investigated experimental 4-channel 100 GHz spaced NRZ modulated DWDM optical system [13]. Chromatic dispersion CD is a fundamental problem in optical networks related to broadening light pulses as they travel through the optical fiber. The propagation characteristics of each wavelength depend on the optical fiber glass refractive index of the medium and on the non-linearity of the propagation constant. Eventually, it will result in a distortion of the signal, which leads to inter-symbol interference (ISI) begin to overlap causing the bit error rate to increase. To protect the optical signals from the affection of CD during transmission in our investigated 4-channel 100 GHz spaced NRZ modulated DWDM optical system, the comparison of appropriate CD post-compensation techniques located at remote terminal (RT) section under NG-PON2 mentioned requirements are discussed [11], [14].

In the first scenario, we realize dispersion post-compensation based on fiber Bragg gratings (FBG) tunable dispersion compensation module (DCM) designed for use of compensation for all channels across the entire C-band enabling to apply for 100 GHz channel grid with the bandwidth of 100 GHz for current WDM channel. The main advantage is low insertion loss of 3.5 dB and greater power capacity without introducing additional non-linear signal effects (NOE).

Secondly, we introduce dispersion post-compensation based on dispersion compensating fiber DCF, which is being used previously, as well as extensively used for optical fiber links operating at a 1550 nm band. The longer wavelengths will travel slower than the smaller wavelengths of the pulse in case of SMF fiber comparatively to dispersion compensating fiber manufactured for telecom wavelengths. In such a case of DCF, the longer wavelengths will travel faster than the shorter wavelengths and the pulse will tend to reshape itself into its original form. To determine the exact dispersion coefficient for the standard single-mode optical fiber used in the experimental part and find out the necessary length of DCF fiber spool for total accumulated dispersion compensation, we previously performed CD and optical time-domain (OTDR) measurements with EXFO FTB-500 for SSMF fiber span. We prepare OTDR measurements for experimentally used SMF fiber span to clarify the optical link section match of our experimental 4-channel 100 GHz spaced NRZ modulated DWDM system to ITU-T G.989.2 recommendation defined optical distribution network ODN length. In our experimental optical transmission system, the second EDFA was used in terms to satisfy the input optical power level of high power InGaAs 50 GHz PIN photoreceiver. In such case under high-speed up to 40 Gbit/s WDM transmission systems conditions, where post-amplification is not required, as PIN photo receiver's avalanche photodiode (APD) with a much lower input power level is used [16]. According to verified measurements, we conclude that the length of our experimentally used SSMF fiber span is 42.13 km with 11.49 dB total insertion loss. The obtained OTDR graphs of the results are not included in this paper. The experimentally measured SMF fiber span chromatic dispersion coefficient and total chromatic dispersion depending on bandwidth in telecommunication S, C, and L transmission bands (Fig. 3). As one can see in Fig. 3, the standard single-mode optical fiber span measured dispersion coefficient and total dispersion at reference wavelength λ = 1550 nm is 17.15 ps/(nm × km) and 688.71 ps/nm at dispersion slope of 0.096 ps/nm^2, respectively.

The most suitable DCF optical fiber span was selected to perform the necessary accumulated dispersion compensation. Afterward, after the most appropriate choice, we prepare optical domain OTDR measurements to latest calculate achieved DWDM system's optical link sections length. According to verified OTDR measurements, we conclude that the length of our experimentally used dispersion compensating fiber spool is 5.68 km with 4.75 dB total insertion loss of 0.83 dB/km. Experimentally obtained dispersion compensating fiber spool CD coefficient and total chromatic dispersion depending on bandwidth in telecommunication S, C, and L transmission bands (Fig. 4). As one can see in Fig. 4, the DCF fiber spool measured dispersion coefficient and total dispersion at reference wavelength λ = 1550 nm is -123.06 ps/(nm × km) and -697.82 ps/nm at -2.48 ps/nm^2 dispersion slope, respectively. DCF fiber gives us the opportunity to increase the length of our 4-channel 100 GHz spaced DWDM optical transmission system for an additional 5.68 km or extra 13.5 % and achieve the maximum DWDM system's link length of 47.81 km.

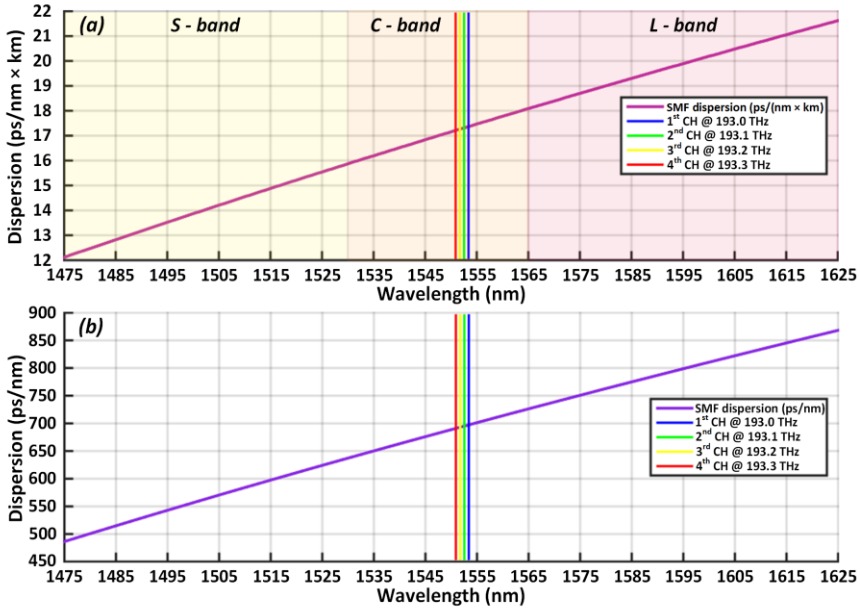


Fig. 3. Experimentally measured SMF fiber span: (a) chromatic dispersion coefficient and (b) total chromatic dispersion depending on bandwidth and wavelength used.

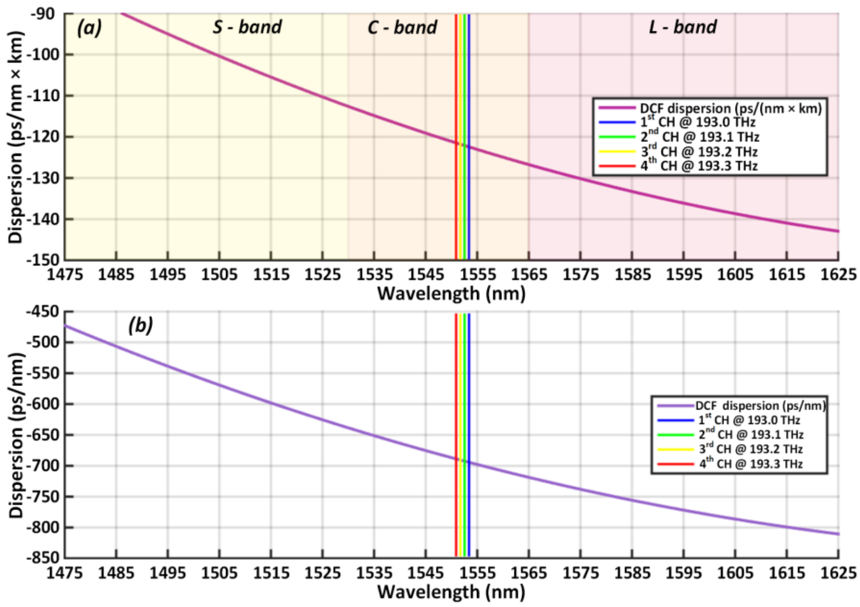


Fig. 4. Experimentally measured DCF fiber spool: (a) chromatic dispersion coefficient and (b) total chromatic dispersion depending on bandwidth and wavelength used.

V. RESULTS AND DISCUSSION

In our research, we implemented experimentally two different CD compensation techniques to observe the quality of the received signal and obtain limiting factors of physical parameters, the impact of used components, such as fiber Bragg grating dispersion compensation module (FBG-DCM) and widely used dispersion compensating fiber allowing us to observe additional non-linear optical effects (NOE).

According to next-generation (NG-PON2) ITU-T G.989.2 rec. requirements, we extend the SSMF link section up to 40 km [4]. Results are obtained in two different scenarios: 1st by use of fiber Bragg grating DCM and 2nd with the use of dispersion compensating fiber DCF for total dispersion compensation of 688.71 ps/nm. Figure 5 shows experimentally obtained BER of transmitted NRZ-OOK signal with a bitrate from 20 Gbit/s up to 40 Gbit/s per channel versus received optical power at 50 GHz PIN photoreceiver. The measured optical output power after transmission through a 40 km fiber link section with FBG-DCM post-compensation varied from –0.21 dBm to 6.8 dBm, where the BER of received signal was from 5×10^{-2} to 1×10^{-10}. In such a way, the second scenario with DCF post-compensation, where measured optical output power after transmission through 47.81 km fiber link section (SMF + DCF length) varied from −1.65 dBm to 6.8 dBm, the BER of received signals was from 5.8×10^{-2} to 9.73×10^{-12}, respectively.

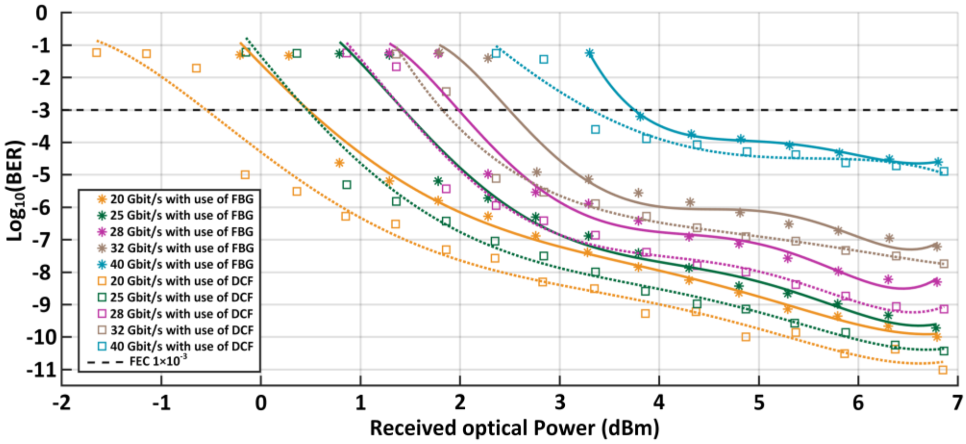


Fig. 5. Comparison of experimentally measured BER versus received optical power with use of: (1) fiber Bragg grating dispersion compensation module (FBG-DCM), (2) dispersion compensation fiber (DCF) depending of bitrate per channel for investigated 4-channel 100 GHz spaced DWDM optical transmission system.

As one can see in Fig. 6(a), the 4-channel 100 GHz spaced NRZ modulated and de-correlated optical signals spectrum before launching into a 40 km long SSMF fiber span of DWDM optical transmission system, which is driven by one Mach-Zehnder modulator MZM and operating at a bitrate up to 40 Gbit/s per channel, are shown. Ensuring difference of received optical signals firstly after transmission through 40 km long SSMF fiber span and secondly after use of DCF dispersion post-compensation for 4-channel 100 GHz spaced NRZ modulated and de-correlated DWDM transmission system (Figs. 6(b) and 6(c)). We conclude that the optical spectrum after the FBG-DCM post-compensation module has only impact depending on FBG module physical bandwidth limitations with independent 3.5 dB insertion loss at the reference wavelength λ = 1550 nm. Therefore, optical signals spectrum after transmission through 40 km long optical fiber link section with the use of FBG-DCM post-compensation is not shown.

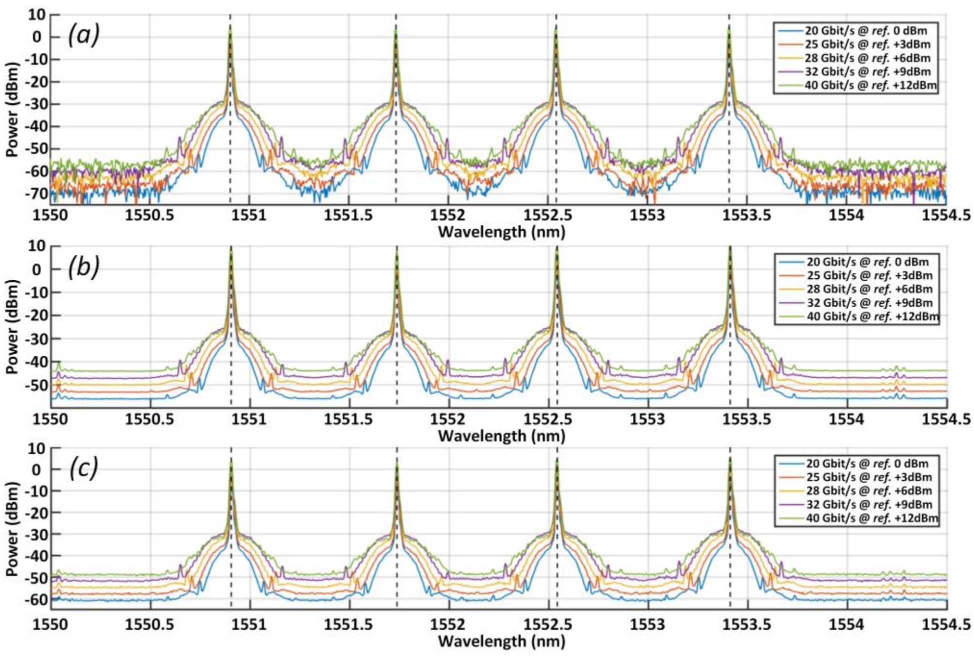
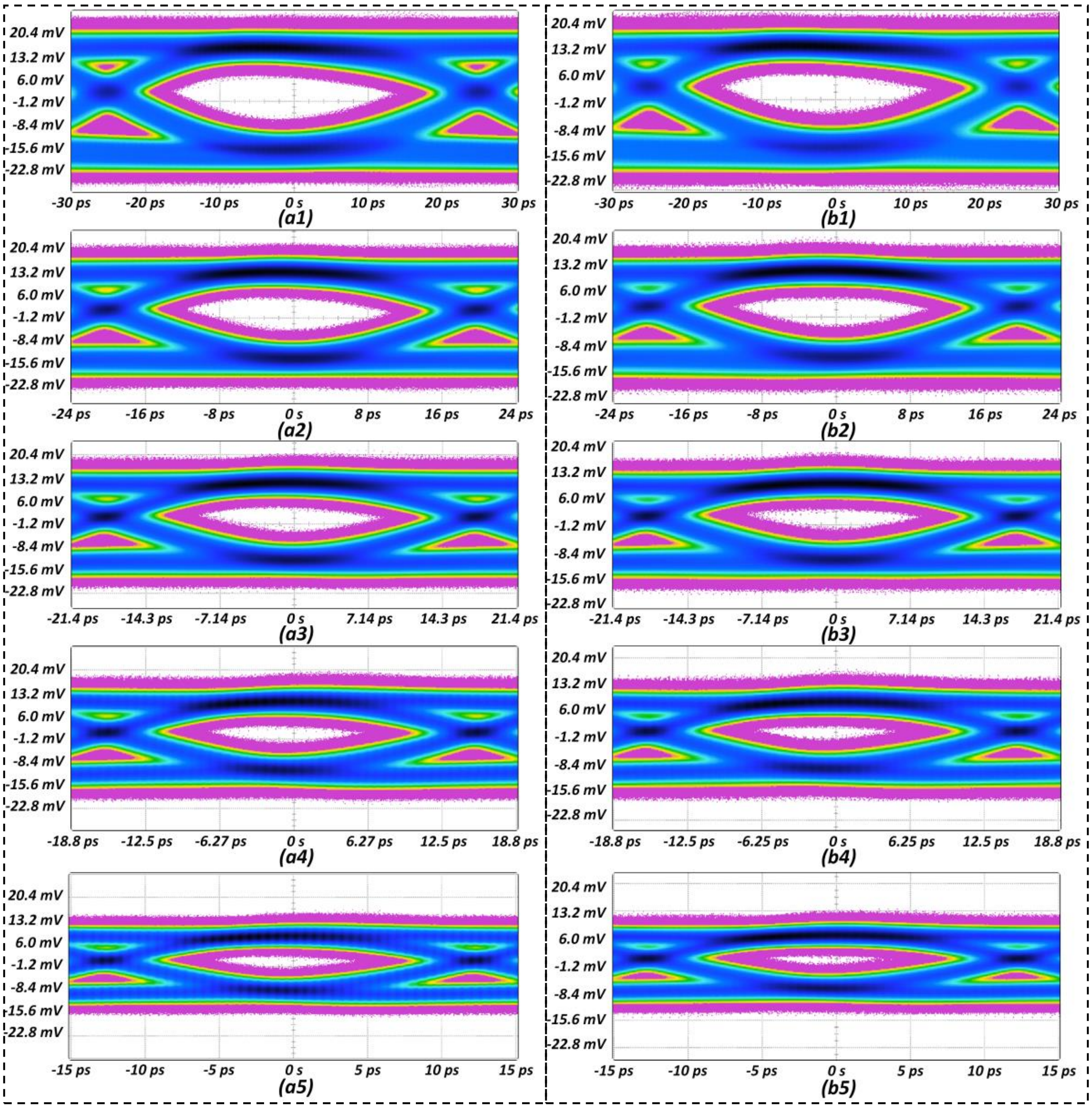


Fig. 6. Optical spectra: (a) after B2B transmission through SSMF fiber; (b) after 40 km transmission through SSMF fiber; (c) after 40 km transmission through SSMF fiber with use of dispersion compensation by DCF for multiplexed 4-channel NRZ modulated DWDM optical transmission system at bitrates of up to 40 Gbit/s per channel.

Therefore, we conclude that the optical spectrum after direct transmission through a 40 km SSMF fiber span and after transmission with the use of DCF post-compensation additionally extending the total length of the optical link section up to 47.81 km has significant changes. Applying for use of DCF post-compensation for our 4-channel 100 GHz spaced NRZ modulated DWDM transmission system, the received optical signals are mainly affected by the impact of NOE effects. The Four-Wave Mixing (FWM) generating interactions between the information signals and the fiber medium occurs in the case of WDM systems, where the wavelength channel spacing is very close to each other. The reason for that is the input optical power of a DCF fiber, which exceeds a certain value optical power density in the fiber core and becomes excessively high because the effective cross-sectional area of the fiber is only A_{eff} = 20 μm^2 triggering the non-linear polarization of fiber materials. Changes in the decrease of received optical power level before PIN photoreceiver applying for use of dispersion compensation fiber have explained by the impact due to fiber insertion loss 0.83 dB/km at the reference wavelength λ = 1550 nm.

As one can see in Fig. 7, the experimentally received signal after 40 km transmission through SSMF optical fiber link with dispersion compensation by (a) fiber Bragg grating dispersion compensation module (FBG-DCM) and (b) by dispersion compensation fiber (DCF) for investigated NRZ modulated 4-channel 100 GHz spaced DWDM optical transmission system at operating bitrates of up to 40 Gbit/s per channel is good, eye is open, and error-free transmission is provided. In our research, we show received signal with the worst BER performance for the 2nd channel, where the highest impact of crosstalk is observed compared to other WDM channels in the current transmission system.



section (a) section (b)

Fig. 7. Eye diagrams of experimentally received signal after 40 km transmission trough SSMF fiber with dispersion compensation by (a1–a5) fiber Br

agg grating dispersion compensation module (FBG-DCM), (b1–b5) dispersion compensation fiber (DCF) for investigated NRZ-OOK modulated 4-channel 100 GHz spaced DWDM optical transmission system at bitrates of 20 Gbit/s, 25 Gbit/s, (3) 28 Gbit/s, (4) 32 Gbit/s, and (5) 40 Gbit/s per channel.

We have demonstrated performance comparison for 4-channel 100 GHz spaced NRZ modulated DWDM transmission system at operating total capacity up to 160 Gbit/s over 40 km SSMF fiber optical link with different dispersion-compensating techniques. Additional insertion losses in dispersion compensating optical fiber DCF line and affection of NOE on transmitted signals lead to performance decrease of our experimental 4-channel 100 GHz spaced DWDM optical transmission system, where the BER at operating 20 Gbit/s and 40 Gbit/s bitrate per channel of received signal was 5.8×10^{-2} and 1.27×10^{-5} due to optical power level on PIN photoreceiver -1.65 dBm and +2.36 dBm (see Figs. 7(b1) and 7(b5)).

After decreasing total optical link length by replacing DCF and applying for fiber Bragg grating tunable DCM module, from obtained results, we conclude that NOE effects are reduced significantly, where the BER of operating at 20 Gbit/s and 40 Gbit/s bitrates per channel was 5×10^{-2}

and 2.45×10^{-5} due to optical power level on PIN photoreceiver -0.21 dBm and 3.3 dBm (see Figs. 7(a1) and 7(a5)). As one can see in Fig. 7, comparison depending on bitrate per channel from 20 Gbit/s up to 40 Gbit/s, with previously discussed dispersion compensation techniques implementation into our experimental 4-channel DWDM optical transmission system, according to systems performance, the received signal quality is shown (e.g., eye diagrams of received bit patterns).

VI. CONCLUSIONS

The newest technology of the next decade fulfilled by mobile and broadband services, e.g., large-scale latest-generation cellular network coverage inter-connections and data center interconnections (DCI), pushes hard communication infrastructures to be optimized and upgraded. Enabling the development of new technologies, the choice of dispersion compensation technique plays a critical role in high-speed fiber optical communication system performance and the possibility to provide and satisfy high demand bitrates for bandwidth-hungry end-users. Nowadays, the problems of transmission capacity and channel utilization are related to the correct choice of modulation format, which is a key to enable higher spectral efficiency and potentially provide higher data transmission speeds through fiber optical networks with limited bandwidth, where one of the physical main distance-limiting factors is chromatic dispersion, which leads to inter-symbol interference and distortion of the signal waveform.

The purpose of the experimental system created during this research was to compare the effectiveness of such a widely used chromatic dispersion compensation techniques like fiber Bragg grating dispersion compensation module (FBG-DCM) and dispersion compensating fiber (DCF). This comparison was performed by implementing both techniques into developed 4-channel DWDM transmission system allowing to provide high bitrate transmission over 40 km standard single-mode fiber line section reaching total WDM system capacity of 160 Gbit/s under the condition that is still possible to achieve commercial pre-FEC BER threshold 1×10^{-3} with 7 % FEC overhead being used.

Experimentally obtained data and implemented CD compensation techniques showed that with the significant increase of channel bitrate from 20 Gbit/s up to maximal achievable bitrate - 40 Gbit/s per channel the performance reduction was observed in 4-channel 100 GHz spaced DWDM optical transmission system.

Depending on NRZ-OOK modulated signal bitrate, the BER of the signal at the receiver at 20 Gbit/s and 40 Gbit/s bitrates varied from 5×10^{-2} to 1×10^{-10} and 5.8×10^{-2} to 9.73×10^{-12} with CD post-compensation by FBG-DCM and DCF, respectively. When the FBG-DCM post-compensation module was applied, we observed the negative filtering effect of channelized FBG, which has physical bandwidth limitations. Therefore, in our setup, DCF post-compensation extended the total length of the optical link section more than it was observed with FBG-DCM. Also, when DCF was used for CD compensation, we observed the signal degradation caused by NOE effects, such as FWM. In addition to DCF fiber losses, which reduce the optical power output level, caused an adverse effect in terms of receiver sensitivity, which depends on the targeted BER level and the signal bitrate.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] ITU-T Recommendation Y.Supp.29 to ITU-T Y.4250 series - series y: global information infrastructure, internet protocol aspects and next-generation networks, internet of things and smart cities: ITU-T Y.4250 series - Smart Sustainable Cities - "Multi-service infrastructure in new-development areas", pp. 4–27, 2016.

[2] X. Sun, M. Yang, and I. B. Djordjevic, "Real-time FPGA-based rate adaptive LDPC coding for data center networks and PONs", in *Proc. of 2018 European Conference on Optical Communication (ECOC)*, Rome, Italy, Sept. 2018, pp. 1–3. DOI: 10.1109/ECOC.2018.8535131.

[3] T. Salgals, I. Kurbatska, S. Spolitis, V. Bobrovs, and G. Ivanovs, "Research of M-PAM and duobinary modulation formats for use in high-speed WDM-PON systems", in *Telecommunication Systems: Principles and Applications of Wireless-Optical Technologies*. IntechOpen, Feb. 2019. DOI:10.5772/intechopen.84600.

[4] ITU-T Recommendation G.989.2, "Digital sections and digital line system - Optical line systems for local and access networks–40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification", pp. 10–92, 2014.

[5] K. Zeb, X. Zhang, and Z. Lu, "High capacity mode division multiplexing based MIMO enabled all-optical analog millimeter-wave over fiber fronthaul architecture for 5G and beyond", *IEEE Access*, vol. 7, pp. 89522–89533, 2019. DOI: 10.1109/ACCESS.2019.2926276.

[6] G. N. Liu, L. Zhang, T. Zuo, and Q. Zhang, "IM/DD transmission techniques for emerging 5G fronthaul, DCI, and metro applications", *Journal of Lightwave Technology (JLT)*, vol. 36, no. 2, pp. 560–567, Jan. 2018. DOI: 10.1109/JLT.2018.2793313.

[7] K. Keykhosravi, M. Secondini, G. Durisi, and E. Agrell, "How to increase the achievable information rate by per-channel dispersion compensation", *Journal of Lightwave Technology (JLT)*, vol. 37, no. 10, pp. 2443–2451, 2019. DOI: 10.1109/JLT.2019.2907311.

[8] R. K. Ahmed and H. A. Mahmood, "Performance analysis of PAM intensity modulation based on dispersion compensation fiber technique for optical transmission system", in *Proc. of 2018 1st International Scientific Conference of Engineering Sciences - 3rd Scientific Conference of Engineering Science (ISCES)*, Diyala Iraq, Jan. 2018, pp. 126–130. DOI: 10.1109/ISCES.2018.8340540.

[9] ITU-T Recommendation G.709/Y, "Transmission systems and media digital systems and networks - Global information infrastructure, internet protocol aspects and Next-generation networks, internet of things and smart cities", pp. 1–89, 2016.

[10] F. Lu, M. Xu, L. Cheng, J. Wang, S. Shen, H. J. Cho, and G. Chan, "Adaptive digitization and variable channel coding for enhancement of compressed digital mobile fronthaul in PAM-4 optical links", *Journal of Lightwave Technology (JLT)*, vol. 35, no. 21, pp. 4714–4720, Nov. 2017. DOI: 10.1109/JLT.2017.2749567.

[11] T. Salgals, S. Spolitis, S. Olonkins, and V. Bobrovs "Investigation of 4-PAM modulation format for use in WDM-PON optical access systems", in *Proc. of Progress in Electromagnetics Research Symposium (PIERS 2017)*, St. Petersburg Russia, May 2017, p. 1–4. DOI: 10.1109/PIERS.2017.8262162.

[12] R. Lin, J. V. Kerrebrouck, X. Pang, M. Verplaetse, O. Ozolins, A. Udalcovs, L. Zhang, L. Gan, M. Tang, S. Fu, R. Schatz, U. Westergren, S. Popov, D. Liu, W. Tong, T. D.Keulenaer, G. Torfs, J. Bauwelinck, X. Yin, and J. Chen, "Real-time 100 Gbps/λ/core NRZ and EDB IM/DD transmission over multicore fiber for intra-datacenter communication networks", *Opt. Express*, vol. 26, no. 8, pp. 10519–10526, 2018. DOI: 10.1364/OE.26.010519.

[13] S. Olonkins, V. Bickovs, T. Salgals, V. Bobrovs, and G. Ivanovs, "Investigation of dual-pump FOPA performance in a 4-channel 40 Gbps WDM transmission system", *Elektronika ir Elektrotechnika*, vol. 23, no. 6, pp. 85–89, 2017. DOI: 10.5755/j01.eie.23.6.19699.

[14] A. Korra, T. Salgals, J. Porins, E. Kazoks, R. Miho, and S. Spolitis, "Performance analysis of cost-efficient high-speed up to 32 Gbit/s WDM-PON next-generation access network with dispersion

compensation”, in *Proc. of Progress in Electromagnetics Research Symposium (PIERS 2019)*, Rome, Italy, Jun. 2019, pp. 1–7. DOI: 10.1109/PIERS-Spring46901.2019.9017854.

[15] ITU-T Recommendation G.694.1, “Transmission media and optical systems characteristics - Characteristics of optical systems: Spectral grids for WDM applications: DWDM frequency grid”, pp. 7–12, 2012.

[16] Discovery Semiconductors Inc., High optical power handling InGaAs photodiodes to 50GHz, Technical Specification, 2003.

[17] Z. Tao, W. Yan, L. Dou, L. Li, S. Oda, T. Hoshida, and J. C. Rasmussen, “The impact of DWDM channel de-correlation method in optical PSK coherent transmission experiment”, in *Proc. of 2009 35th European Conference on Optical Communication (ECOC)*, Vienna, Austria, Sep. 2009, pp. 1–2.

[18] K. Nakshdeep and K. Gurmeet “Various dispersion compensation techniques for optical system: A survey”, *Open Journal of Communications and Software*, vol 1, no. 1, p. 1–10, May 2014. DOI: 10.15764/CS.2014.01006.