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Performance analysis of optimized non-zero dispersion shifted fiber without amplification and without dispersion compensation for wavelength division multiplexing optical networks

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In this paper, we have analyzed the performance of our optimized non-zero dispersion shifted fiber with three different test fibers, namely, single mode fiber, conventional non-zero dispersion shifted fiber and dispersion shifted fiber. While comparing the performances of those fibers, our optimized non-zero dispersion shifted fiber has yielded a better quality factor of 5.24 at 2.5 Gbit/s for long haul fiber length of 120 km in the absence of amplification and dispersion compensation. In order to measure the nonlinear impairments of wavelength division multiplexing channel, the quality factor values are measured at the sample channel 193.1 THz for 150 km lengthed fiber with peak input power of 6 dBm. Due to a very large effective area of optimized non-zero dispersion shifted fiber, it delivers a better quality factor of 6.12 compared to the other test fibers. We have also carried out the analysis for higher bitrates and different modulation formats at the transmission end. More phase encoded modulations of carrier-suppressed return-to-zero–differentiated phase shift keying and carrier-suppressed return-to-zero–differential quadrature phase shift keying offered optimum performances for a distance of 120 km at 10 Gbit/s bitrate. By including optical amplifiers, we could achieve a record fiber transmission length of 4000 km at the bitrate of 2.5 Gbit/s which can help the future wavelength division multiplexing optical networks to a great extent.

Keywords: non-zero dispersion shifted fiber (NZDSF), repeaterless wavelength division multiplexing (WDM) links, dispersion, nonlinear effects, four wave mixing (FWM), refractive index profile, bit error rate (BER).

1. Introduction

In this modern era, wavelength division multiplexing (WDM) networks are widely used for long haul fiber optical applications. In order to satisfy the thirst for increasing bandwidth, WDM systems are being implemented. The major advantages of WDM networks are enormous capacity, tremendous speed, they are also cost effective and easily upgradable. Recently, optical networks are developed with the usage of three different types of single mode optical fibers, namely, conventional single mode fiber (SMF), dispersion shifted fiber (DSF) and non-zero dispersion shifted fiber (NZDSF). The crucial way to distinguish between the fiber types is by means of their chromatic dispersion. By implementing these fibers in optical transmission systems, we can analyze the eye diagram and bit error rate (BER) results which will in turn help us to estimate the overall performance of the WDM networks [1].

The WDM network performance is constricted by dispersion and nonlinear effects. The various types of nonlinear effects observed in optical fibers are self-phase modulation (SPM) in a single channel system, cross-phase modulation (XPM), four wave mixing (FWM), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS) among the channels in a WDM network [2, 3]. To transmit an optical signal in WDM networks, physical impairments like XPM, FWM, and SRS must be taken into account because those directly affect the BER. In addition, narrow spacing between the WDM channels is not preferable because it increases the BER [3].

Four wave mixing crosstalk plays a major role in determining the performance of WDM networks [4]. WDM systems which use the DSF with the zero dispersion wavelength within the transmission band are rigorously distorted by FWM. To shun this problem and also to evade the distortions due to the high chromatic dispersion of conventional SMF, NZDSF is now extensively deployed for long haul optical transmission links [5]. Therefore, NZDSF with about 3–6 ps/(nm·km) dispersion at 1550 nm can reduce FWM crosstalk by avoiding the phase matching condition which finally improves the WDM system performance to a great extent [6].

For submarine networks and terrestrial spans in far-flung areas, it is really very complicated to install inline service access. So, the solution for this problem is to deploy repeaterless optical transmission systems. Repeaterless systems were introduced with the help of the G.652 standard SMF. But such systems have used hybrid optical amplifiers (EDFA/Raman amplifiers) as booster and pre-amplifiers. Also the accumulated chromatic dispersion was compensated through the use of dispersion compensation modules (DCM) based on dispersion compensating fibers (DCF), as well as by means of electronic chromatic dispersion compensation through a time domain equalizer (TDE) algorithm performed through off-line digital signal processing. In order to attain the required BER within the forward error correction (FEC) limit, the launch power of transmission hybrid amplifiers has to be boosted up for long span applications [7]. The disadvantage of using optical amplifiers is that it will induce amplified spontaneous emission (ASE). Consequently, ASE-induced noise will degrade the performance of optical communication systems due to the amplitude fluctuations and frequency fluctuations. Frequency fluctuations will result in timing jitter. Such timing jitter will lead to increased power penalties if left uncontrolled [8].

Unrepeatered transmission systems were designed using NZDSFs for terrestrial network applications. But here long haul transmission was possible due to the addition of bidirectional Raman amplification [9]. But here the drawback is the requirement of

Raman pump lasers to provide bidirectional pumping, which will further increase the overall system cost.

NZDSF based transmission systems without in-line dispersion compensation are attractive for system simplicity and cost effective. However, researchers have employed DCM at the transmitter and receiver ends of the NZDSF for long haul optical link applications [10].

In this paper, we have designed an optimized NZDSF which has diminished nonlinear effects accompanied with reduced relative dispersion slope (RDS). We have implemented our optimized NZDSF in 8 channel WDM transmission system without using optical amplifiers as well as without including DCF for long haul applications.

2. Design of our optimized NZDSF

We have designed and reported an optimized NZDSF with diminished nonlinear effects which can be implemented for the future optical networks [11]. Figure 1 represents the refractive index profile of our optimized NZDSF. Our optimized NZDSF has a central graded index core region surrounded by penta cladding regions. The central core region is described by the alpha-peak profile which determines the electrical field distribution of the designed refractive index profile.

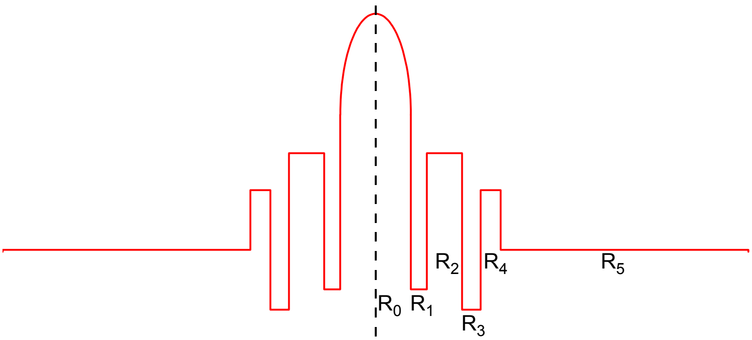

Fig. 1. Refractive index profile of our optimized NZDSF.

Fiber parameters of our optimized NZDSF: zero-dispersion wavelength of 1.4795 nm, dispersion of 5.7571 ps/(km·nm), dispersion slope of 0.05 ps/(nm^2·km), RDS = 0.008 nm^{-1}, A_{eff} = = 120 μm^2, n_2 = 1.40949×10^{-16} cm^2/W.

Using the OptiFiber software, we have optimized our fiber design by varying the radius parameters and the refractive indices of our optimized NZDSF. The simulated results show that our fiber has a non-zero dispersion (5.7571 ps/(km·nm)) and a very small dispersion slope (0.05 ps/(nm^2·km)) at 1550 nm. Consequently, the calculated RDS value is 0.008 nm^{-1}. Since the RDS value is lower than 0.01 nm^{-1}, the dispersion compensation of our fiber can be done easily. Also, our optimized fiber has resulted with a very large effective area of above 120 μm^2 as well as with lower n_2 (1.40949×10^{-16} cm^2/W), while maintaining a very low bending loss (1.40×10^{-14} dB/km). As we have achieved a very large effective area and reduced value of n_2, the nonlinear effects of the fiber could be reduced to a great extent. Thus, our newly designed, optimized NZDSF has reduced dispersion and diminished nonlinear effects which have made our optimized fiber more suitable for the long haul WDM optical network applications.

3. Experimental set-up

The basic experimental set-up for our proposed WDM long haul transmission is illustrated in Fig. 2. We have transmitted eight WDM optical wavelengths with 100 GHz frequency spacing between the adjacent channels. Here the transmission wavelengths range from 1552.52 nm (193.1 THz) to 1546.91 nm (193.8 THz) which lie in the C-band window (1530–1565 nm). Furthermore, the 8 channels are modulated by Mach–Zehnder modulator (MZM) for different modulation formats as we have already reported [4]. Then the eight channels are combined together through a WDM multiplexer and the

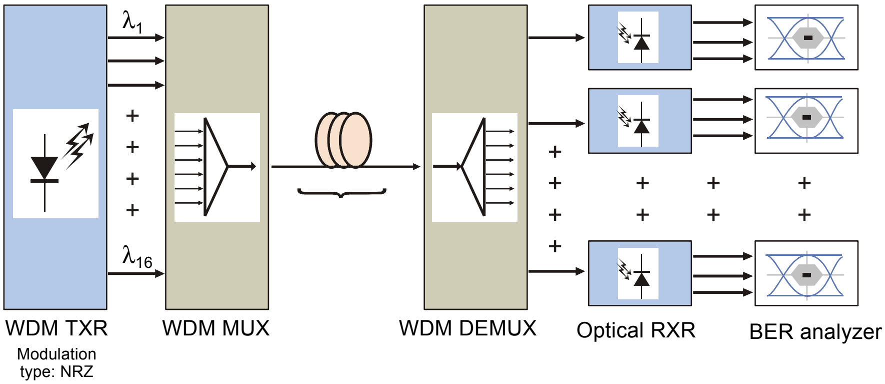

Fig. 2. Basic experimental set-up for our proposed WDM long haul transmission using NZDSF without any nonlinear impairments.

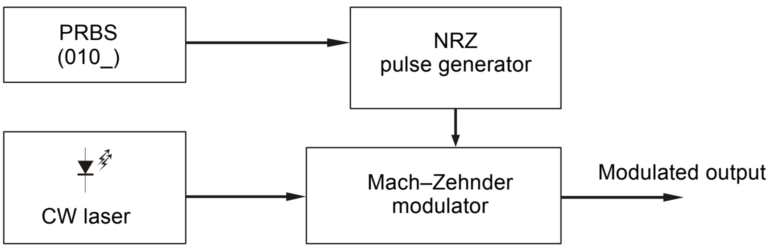

Fig. 3. Sample block diagram for the Mach–Zehnder modulator with non-return-to-zero (NRZ) modulation format; PRBS – pseudo-random bit sequence.

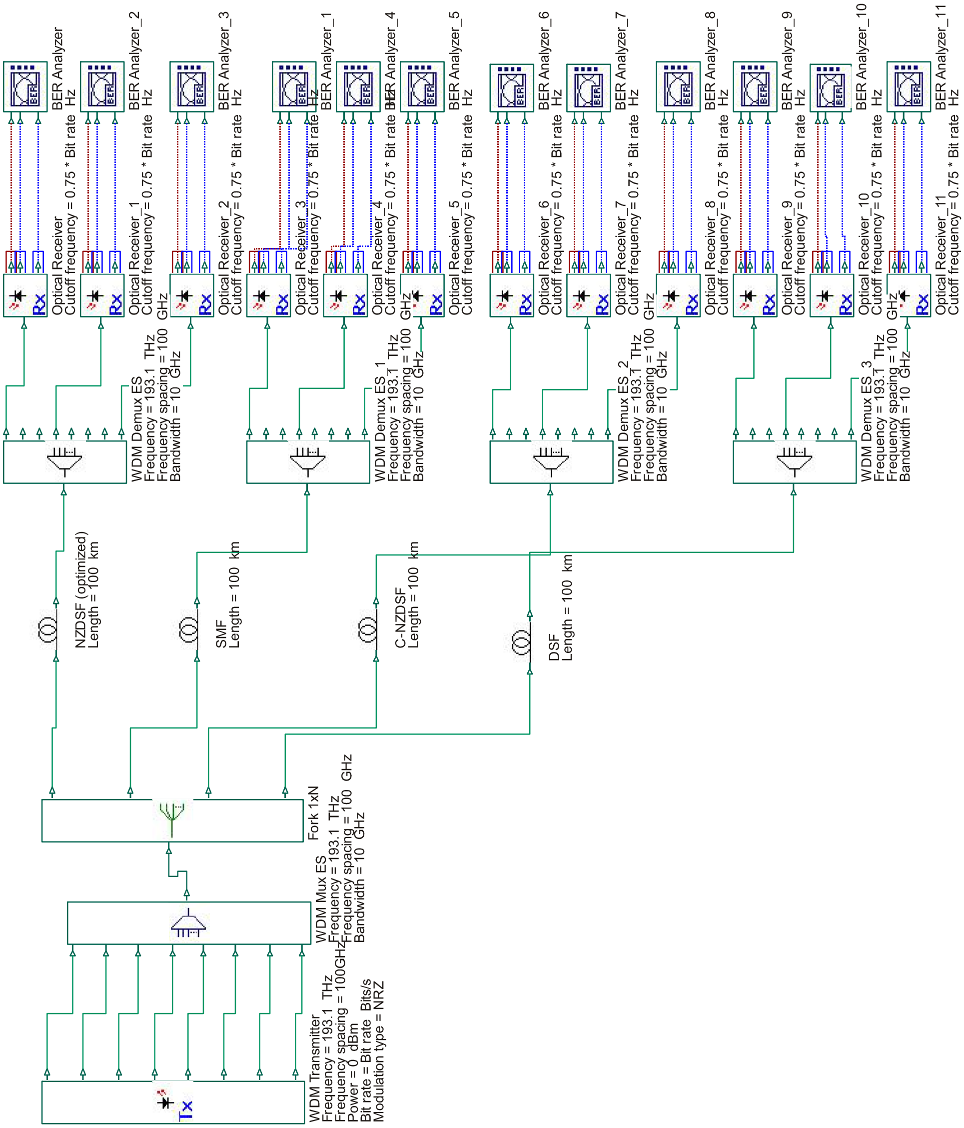

Fig. 4. OptiSystem layout for long haul WDM transmission system for future optical networks.

multiplexed output is given to the optical fiber. Here we have performed the WDM transmission at 2.5, 5 and 10 Gbit/s data rates. After transmission, the demultiplexed outputs from WDM demultiplexer are received at the corresponding optical receivers. At the receiver end, we have used BER analyzer to evaluate the quality factor and BER which determine the optical performance of the WDM system. Furthermore, Fig. 3 depicts the block diagram of the NRZ modulation format which we have used in the WDM transmitter. Here, the output of the CW laser source is modulated by applying the electrical signal to the MZM. The non-return-to-zero (NRZ) modulation format is frequently used for the reason that the signal bandwidth is about 50% smaller than the RZ (return-to-zero) format [8]. We have also discussed the analysis of optimized NZDSF with NRZ modulation format for different bitrates and the same analysis is carried out for different modulation formats [4] at higher bitrates.

The receiver performance is determined by measuring the BER as a function of the received average optical power. The average optical power related to a BER of 10^{-9} is a measure of receiver sensitivity. Hence, the receiver sensitivity is measured by transmitting a long sequence of pseudorandom bits generated from PRBS over a single-mode optical fiber and then detecting it by using an optical receiver [8].

Initially, we have implemented our optimized NZDSF in the WDM system design using OptiSystem software. Then we have taken three other fibers (standard SMF, conventional non-zero dispersion shifted fiber (C-NZDSF) and DSF) under test for comparison purposes, in order to evaluate the WDM optimal performance characteristics. Figure 4 represents the OptiSystem layout of our newly designed long haul WDM transmission for future optical networks.

Table 1 shows the comparison of various parameters of our optimized NZDSF with other three test fibers: SMF, C-NZDSF and DSF.

T a b l e 1. Fiber parameters of our optimized NZDSF, SMF, C-NZDSF and DSF.

Parameters	NZDSF (optimized)	SMF	C-NZDSF	DSF
Dispersion [ps/(km·nm)]	5.8	16.75	4.2	0.146
Dispersion slope [ps/(nm^2·km)]	0.05	0.075	0.09	0.08
Polarization mode dispersion (PMD) [ps/km]	0.08	0.2	0.04	0.02
A_{eff} [μm^2]	120	80	72	54
n_2 [m^2/W]	14.09×10^{-21}	26×10^{-21}	21.8×10^{-21}	18.32×10^{-21}

Using $1\times N$ fork, we have simultaneously implemented all the four ($N = 4$) different optical fibers in the WDM system design as illustrated in the layout (see Fig. 4).

4. Results and discussions

In order to estimate the overall performance characteristics of our optimized NZDSF, we have simulated our WDM network design with various parameter sweeps by changing the length of transmission, power, *etc*. The quality of the signal transmission can be determined by the quality factor and BER results measured in the BER analyzer.

Thus, the system performance could be evaluated by using either quality factor or BER results. But, here for our convenience, we have shown all the results through quality factor. Also by using the relation between the BER and quality factor Q we can calculate the corresponding BER values from the tabulated quality factor results:

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \tag{1}$$

4.1. Performance analysis without amplification and without dispersion compensation for fiber length variations

For a fixed transmission power of 1 mW (0 dBm), for a change in the fiber length of our optimized NZDSF and other three test fibers, the quality factor results are measured at the sample channel (193.1 THz) for different bitrates and the results are displayed in Table 2.

From Table 2 it is very clear that our optimized NZDSF is capable of transmitting the signal up to a maximum length of 120 km. Compared to SMF, C-NZDSF and DSF,

T a b l e 2. Quality factor measured at 193.1 THz for our optimized NZDSF, SMF, C-NZDSF and DSF with respect to fiber length variations in three different bitrates. WDM channel power of 1 mW.

	Quality factor measured at 193.1 THz					
	NZDSF (optimized)			SMF		
Fiber length [km]	2.5 Gbit/s	5 Gbit/s	10 Gbit/s	2.5 Gbit/s	5 Gbit/s	10 Gbit/s
20	189.04	175.6	113.97	146.34	106.96	48.13
40	114.31	96.02	54.13	75.36	44.09	26.07
60	51.41	43.49	26.19	39.96	23.17	10.06
80	25.98	19.53	13.06	16.8	11.43	2.75
100	12.5	9.03	6.03	6.6	5.11	2.18
120	5.24	3.86	2.5	2.65	0	0
140	0	0	0	0	0	0
	C-NZDSF			DSF		
Fiber length [km]	2.5 Gbit/s	5 Gbit/s	10 Gbit/s	2.5 Gbit/s	5 Gbit/s	10 Gbit/s
20	171.11	154.75	93.56	43.18	41.19	35.66
40	94.21	64.8	42.04	41.61	37.45	31.35
60	31.65	23.85	17.95	31.65	27.17	20.8
80	13.98	8.48	7.36	19.04	14.71	10.46
100	4.33	3.34	2.61	8.98	6.52	4.81
120	0	0	0	3.91	2.77	0
140	0	0	0	0	0	0

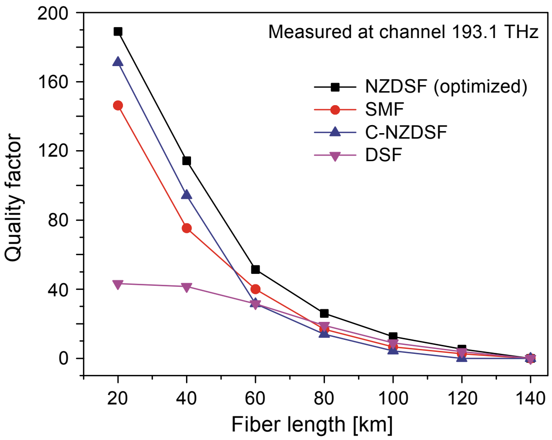

Fig. 5. Comparative analysis of our optimized NZDSF, SMF, C-NZDSF and DSF with respect to fiber length variations.

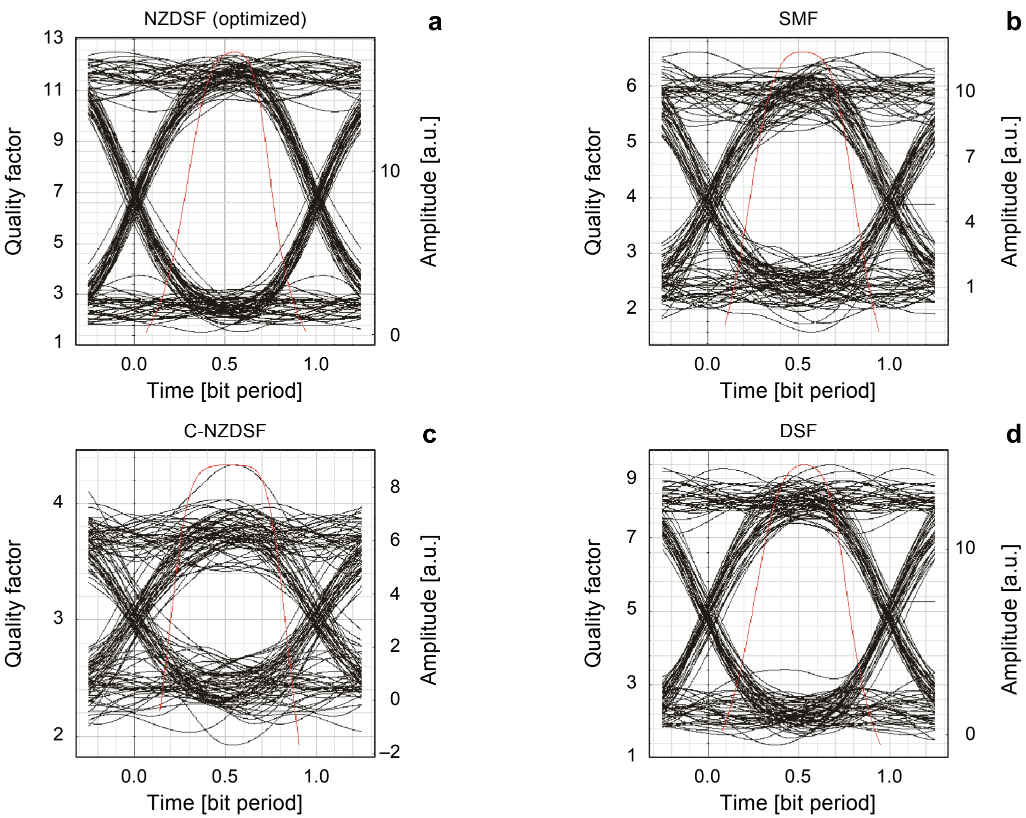

Fig. 6. BER pattern of our optimized NZDSF (**a**), SMF (**b**), C-NZDSF (**c**) and DSF (**d**) measured at channel 193.1 THz, power 1 mW and fiber length 100 km.

our optimized NZDSF has produced excellent quality factor results. Here the signal transmission is not possible above 140 km because of the absence of amplification and dispersion compensation.

The most sufficient quality factor for which the original source information can be retrieved completely is ≥5.9. The corresponding BER (1×10^{-9}) is calculated (Eq. (1)). Lower BER value up to 2.9×10^{-3} could be corrected to error free condition by using forward error correction (FEC) code [7]. Figure 5 depicts the performance analysis of our optimized NZDSF and other three test fibers with respect to fiber length variations measured at the demultiplexed channel at 193.1 THz with 2.5 Gbit/s bitrate.

While comparing the performance of our optimized fiber with the other three test fibers for the transmission length variations, our optimized NZDSFs have shown best quality factor characteristics.

Figure 6 represent the BER pattern of the NZDSF (optimized), SMF, C-NZDSF and DSF, respectively. Here various fibers eye patterns are measured at channel 193.1 THz, power of 1 mW and fiber length of 100 km.

Figure 7 shows that our optimized NZDSF performs well even at higher bitrates. However, as the bitrate increases, it reduces the transmission distance due to the limitation of dispersion. Here also our NZDSF has the optimal transmission distance of 100 km with quality factor of 6.03 for the 0 dBm input signal at the bitrate of 10 Gbit/s.

Thus, our optimized NZDSF has produced better quality factor results at long haul transmission length of 100 km without amplification as well as without dispersion compensation. Next to our optimized NZDSF, DSF has resulted with good quality factor values. At fiber length 120 km, by using FEC techniques, we can retrieve the original signal information for both of the optimized NZDSF and DSF.

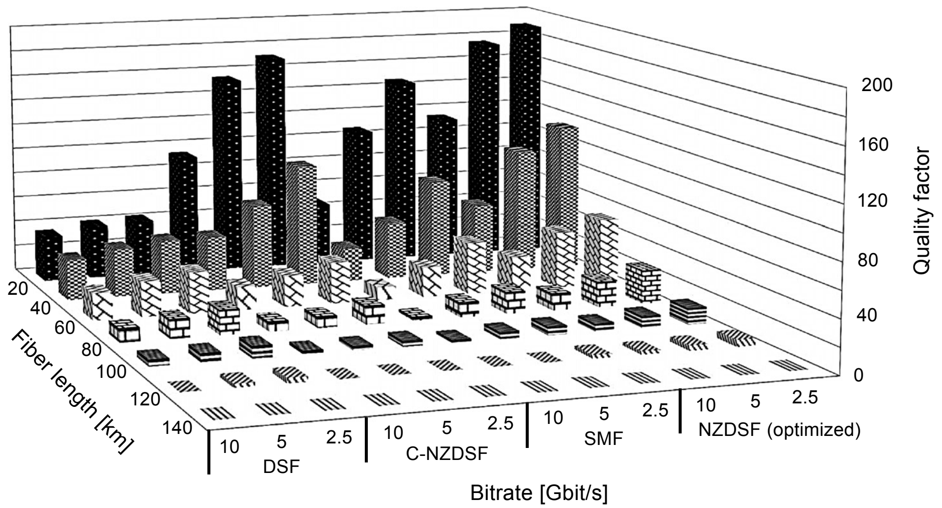

Fig. 7. Comparative analysis of our optimized NZDSF, SMF, C-NZDSF and DSF with respect to fiber length variations at three different bitrates.

4.2. Performance analysis for the nonlinear characteristics for input power variations

As the number of channels in a WDM network increases, the average transmission power density also increases. The refractive index gets modulated because of the rapid increase in the optical intensity of the signal [12]. Consequently, nonlinear effects occur, which will degrade the overall performance of the fiber optical networks. In order to overcome the signal distortion due to the nonlinear effects, large effective area fibers (LEAF) are developed [13]. To analyze the nonlinear characteristics, we have simulated and tabulated the quality factor results in Table 3, by varying the transmission power for a fixed fiber transmission length of 150 km.

While varying the transmission power, our optimized NZDSF has given comparatively better quality factor results without dispersion compensation as well as without amplification. Since we have used our optimized NZDSF which has an enormous large effective area, the nonlinear effects are reduced to a great extent.

But in the case of DSF, the quality factor has degraded because of the nonlinear effects. FWM is the one of the major nonlinear effects which reduce the quality of the transmitted signal at higher transmission powers [4]. Figure 8 shows the comparison of the performances of our optimized NZDSF and other three test fibers at bitrate of 2.5 Gbit/s with respect to transmission power variations measured at channel 193.1 THz.

Figure 9 illustrate the BER pattern of the NZDSF (optimized), SMF, C-NZDSF and DSF, respectively. Here the corresponding eye patterns are measured at channel fre-

T a b l e 3. Quality factor measured at 193.1 THz for our optimized NZDSF, SMF, C-NZDSF and DSF with respect to transmission power variations. Fiber length of 150 km.

		Quality factor measured at 193.1 THz					
		NZDSF (optimized)			SMF		
		2.5 Gbit/s	5 Gbit/s	10 Gbit/s	2.5 Gbit/s	5 Gbit/s	10 Gbit/s
Input power [dBm]	3	3.04	2.12	0	0	0	0
	4	3.84	2.81	0	0	0	0
	5	4.85	3.53	2.46	2.24	0	0
	6	6.12	4.39	3.07	2.83	0	0
	8	9.49	6.9	4.81	4.39	2.96	0
	10	14.83	10.72	7.35	7.04	4.51	1.95
		C-NZDSF			DSF		
		2.5 Gbit/s	5 Gbit/s	10 Gbit/s	2.5 Gbit/s	5 Gbit/s	10 Gbit/s
Input power [dBm]	3	0	0	0	0	0	0
	4	0	0	0	2.62	0	0
	5	0	0	0	3.2	2.23	0
	6	0	0	0	3.8	2.69	0
	8	2.45	0	0	4.4	3.39	2.49
	10	3.88	2.71	0	4.04	3.44	2.29

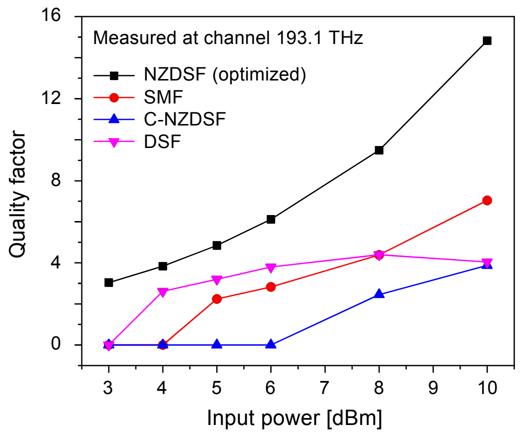

Fig. 8. Comparative analysis of our optimized NZDSF, SMF, C-NZDSF and DSF with respect to transmission power variations.

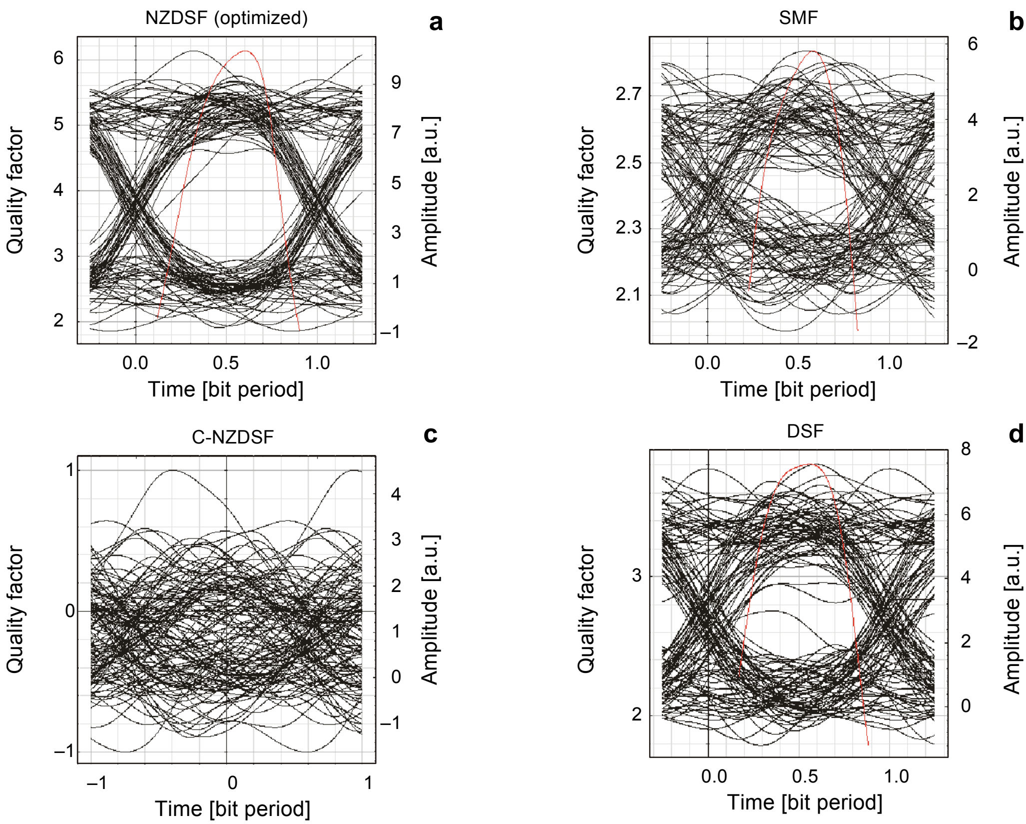

Fig. 9. BER pattern of our optimized NZDSF (**a**), SMF (**b**), C-NZDSF (**c**), and DSF (**d**) measured at channel 193.1 THz, power 6 dBm and fiber length 150 km.

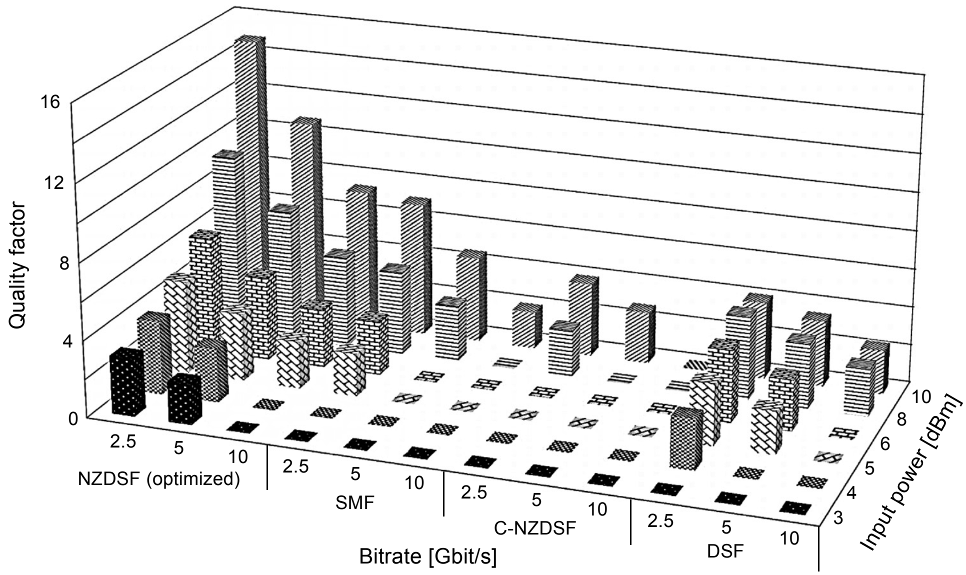

Fig. 10. Comparative analysis of our optimized NZDSF, SMF, C-NZDSF and DSF with respect to transmission power variations with different bitrates.

quency of 193.1 THz with the input power of 6 dBm in order to ensure the impact of nonlinearity in the channel. The bitrate is kept at 2.5 Gbit/s and fiber length is chosen to be 150 km. Figure 10 depicts that our optimized NZDSF overcomes the nonlinear effects due to its high effective area and gives the better quality factor of 7.04 at the bitrate of 10 Gbit/s.

4.3. Performance analysis for different modulation formats

Modulation formats also have an important role in the performance of optical transmission system. In the WDM transmission, spectral characteristics of modulation formats decide about the dispersion, nonlinear and power tolerance and also the spectral efficiency of the transmitting signal [4]. In order to analyze the performance of our optimized NZDSF under various modulation formats, we have simulated and tabulated the quality factor results in Table 4, by varying the modulation formats at a fixed bitrate of 10 Gbit/s at a constant input power of 4 dBm and a fixed fiber transmission length of 120 km. Here we have taken both the less phase encoded modulation schemes such as RZ, NRZ, CSRZ (carrier suppressed return-to-zero) and duobinary and the more phase encoded modulation schemes such as 33% DPSK (RZ-DPSK), 67% DPSK (CSRZ-DPSK), 33% DQPSK (RZ-DQPSK) and 67% DQPSK (CSRZ-DQPSK) [4].

The more phase encoded modulation formats of CSRZ-DPSK and CSRZ-DQPSK give a superior performance due to their peculiar spectral characteristics such as carrier suppression and double peak RF clock that are located at a half bitrate distance from

Table 4. Quality factor measured at 193.1 THz for our optimized NZDSF, SMF, C-NZDSF and DSF with respect to different modulation formats. Fiber length of 120 km, WDM channel power of 4 dBm.

	Quality factor measured at 193.1 THz			
	RZ	NRZ	CSRZ	Duobinary
NZDSF (optimized)	2.75	5.41	4.16	5.49
SMF	0	2.26	0	3.67
C-NZDSF	0	0	0	2.04
DSF	2.64	4.16	3.35	3.84
	RZ-DPSK	CSRZ- DPSK	RZ- DQPSK	CSRZ- DQPSK
NZDSF (optimized)	3.9	6.12	3.61	5.73
SMF	0	0	0	3.53
C-NZDSF	0	2.87	0	2.99
DSF	3.52	4.93	2.95	3.51

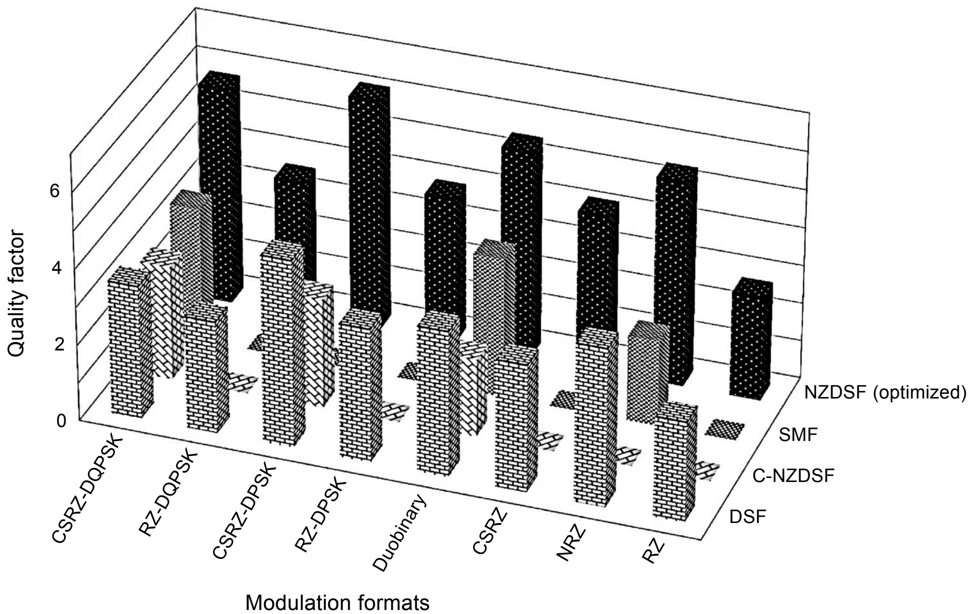

Fig. 11. Comparative analysis of our optimized NZDSF, SMF, C-NZDSF and DSF with respect to different modulation formats at the bitrate of 10 Gbit/s.

the carrier frequency of the spectrum [4]. These spectral characteristics give good nonlinear tolerance and power tolerance and they ensure the transmitted signal to reach long distance. Figure 11 shows the comparative analysis of optimized fibers with other test fibers for different modulation formats at the bitrate of 10 Gbit/s. For the 120 km fiber transmission with bitrate of 10 Gbit/s, our optimized NZDSF has recorded the better quality factor of 6.12 and 5.73 for the modulation formats of CSRZ-DPSK and

CSRZ-DQPSK, respectively. In the less phase encoded modulation formats, duobinary and NRZ have accounted the next better quality factor values of 5.49 and 5.41, respectively. Around the zero dispersion region of DSF, its minimum chromatic dispersion

Table 5. Measurement of quality factor for our optimized NZDSF, SMF, C-NZDSF and DSF with amplification for both fiber length and input power variations.

	Quality factor measured at 193.1 THz			
Fiber length [km]	NZDSF (optimized)	SMF	C-NZDSF	DSF
	Input power = –5 dBm			
100	52.36	38.32	32.50	48.52
500	21.98	13.21	14.25	19.11
1000	15.76	7.46	10.78	13.12
1500	11.49	2.61	7.55	9.60
2000	9.27	2.32	8.08	9.30
	Input power = 0 dBm (1 mW)			
100	85.59	57.79	56.15	42.43
500	31.67	15.35	24.58	14.39
1000	19.44	9.11	18.15	9.75
1500	13.82	2.44	13.45	7.30
2000	12.71	2.34	9.33	6.55
2500	10.45	2.04	8.51	6.12
3000	9.20	0	7.14	5.24
3500	7.33	2.78	6.37	5.07
	Input power = 1 dBm			
100	87.23	60.34	63.09	35.09
500	32.53	16.06	28.31	11.84
1000	19.45	9.19	18.01	7.95
1500	13.54	2.39	13.33	6.25
2000	12.83	2.27	10.06	5.24
2500	10.59	3.09	8.21	4.93
3000	8.98	0	6.75	4.69
3500	7.16	3.47	6.22	4.68
4000	6.35	3.91	5.35	4.29
	Input power = 2 dBm			
100	103.82	65.37	70.66	28.34
500	35.81	15.19	31.29	9.59
1000	21.28	9.27	17.68	6.25
1500	15.05	2.62	12.39	5.18
2000	13.42	0	10.27	4.59
2500	10.51	2.29	8.13	4.27
3000	9.24	3.08	6.55	4.12
3500	7.08	3.40	5.94	3.83
4000	6.44	3.13	5.10	3.84

and enhanced nonlinearity disturb the transmitted signal dramatically and the signal is not preserved with the required quality at the receiving end.

4.4. Performance analysis with amplification for both fiber length and input power variations

After including optical amplifiers with the optical fiber, thereby increasing the fiber transmission length, once again we have calculated the quality factor produced by our optimized NZDSF and other three test fibers of NRZ modulated signal at the bitrate of 2.5 Gbit/s and the results are listed in Table 5 for different input power levels. Signal is amplified by EDFA on every 100 km of the entire fiber link.

Here initially we have considered a very low input power level of –5 dBm, so that it will not induce any nonlinear effects in the fiber transmission. From the above tabulated results, it is very clear that while we are performing WDM optical transmission at a lower input power level, our optimized NZDSF and DSF have yielded more or less equal quality factor, particularly at 2000 km, whereas the other two (SMF and C-NZDSF) test fibers have produced comparatively lower quality factor results. Moreover, here as the fiber length increases, the quality factor value degrades due to the dispersion effect but not due to nonlinearity. Next, we have considered a moderate input power level of 0 dBm (1 mW) and once again we have calculated and tabulated the quality factor results in Table 5. In this case, the transmission length is further increased to 3500 km. Here our optimized NZDSF's performance is much better than that of DSF as well as other test fibers.

For implementing higher speed internet services, the average power density of the WDM optical networks should be increased. Hence, here we have finally simulated higher transmission power levels of 1 and 2 dBm and thereby we have achieved a very high transmission length of 4000 km. The results in Table 4 show that our optimized

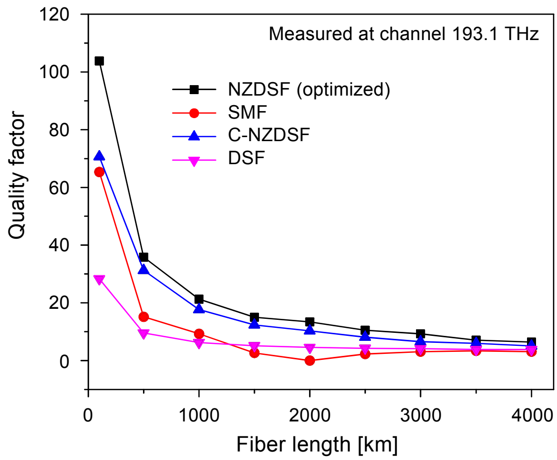

Fig. 12. Comparative analysis of our optimized NZDSF, SMF, C-NZDSF and DSF with respect to fiber length.

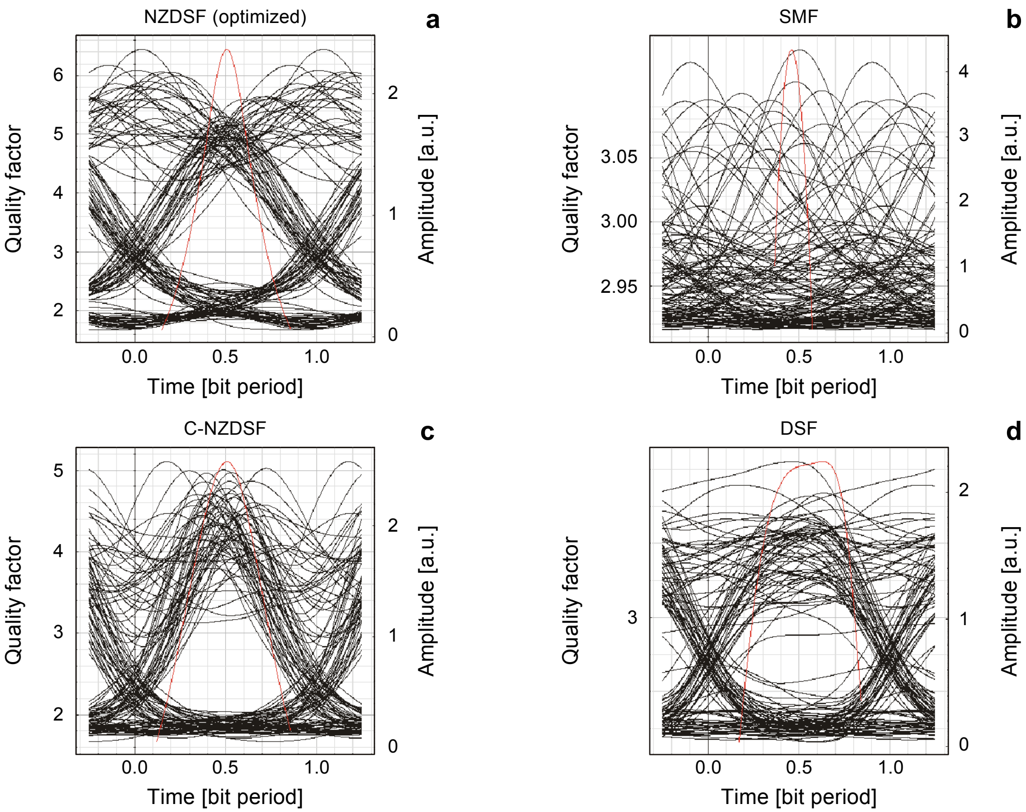

Fig. 13. BER pattern of our optimized NZDSF (**a**), SMF (**b**), C-NZDSF (**c**), and DSF (**d**) measured at channel 193.1 THz, power 2 dBm and fiber length 4000 km.

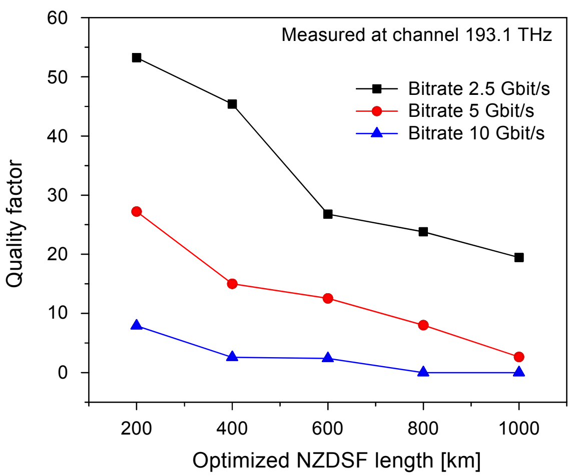

Fig. 14. Performance of optimized NZDSF with attenuation compensation for different bitrates.

NZDSF has yielded excellent quality factor values without dispersion compensation. Furthermore, the performance of DSF is degraded severely due to both dispersion and nonlinear effects. Figure 12 shows the comparison of the performances of our optimized NZDSF and other three test fibers measured at channel 193.1 THz, power 2 dBm and fiber length 4000 km at the bitrate of 2.5 Gbit/s.

Figure 13 shows the BER pattern of the NZDSF (optimized), SMF, C-NZDSF and DSF, respectively. Here the eye patterns are measured for the channel 193.1 THz, Channel input power of 2 dBm and fiber length of 4000 km at the bitrate of 2.5 Gbit/s.

Figure 14 shows the performance of our optimized NZDSF for different bitrates with respect to the fiber length. For a fixed input power of 0 dBm, the transmission distance is reduced if the bitrate is increased. For a bitrate of 5 Gbit/s, our optimized NZDSF could reach up to 800 km with a quality factor of 8.01. If the bitrate is increased to 10 Gbit/s, then the transmission distance is reduced to 200 km with a quality factor of 7.91 due to the dispersion.

Figures 8, 9**d** and 13**d** clearly depict how the DSF signal got degraded due to FWM crosstalk effect among WDM channels operating at high input powers. Thus, our optimized NZDSF has improved the overall performance to a great extent as in the simulations carried out by us in OptiSystem simulation tool.

5. Conclusion

We have demonstrated our earlier simulated optimized NZDSF in an eight channel WDM network and we have analyzed the quality factor and BER patterns at the measured sample channel 193.1 THz. We have compared the performance of our optimized NZDSF with other three test fibers (SMF, C-NZDSF and DSF) for NRZ modulation at different bitrates of 2.5, 5 and 10 Gbit/s. Performance of this optimized NZDSF has been verified for various modulation schemes at a fixed data rate of 10 Gbit/s. While varying the fiber transmission length without amplification and without dispersion compensation, the obtained quality factor values of the NZDSF (optimized), SMF, C-NZDSF and DSF for the 2.5 Gbit/s NRZ signal at 120 km are 5.24, 2.65, 0 and 3.91, respectively. In case of 10 Gbit/s, the transmission distance is reduced to 100 km with quality factor values of 6.03, 2.18, 2.61 and 4.81, respectively. By using FEC techniques, we can retrieve the original signal information from both of the optimized NZDSF and DSF. However, our optimized NZDSF has a better quality factor result than the other test fibers. Furthermore, by increasing the transmission power up to 10 dBm, we have analyzed the impact of nonlinear characteristics and there also our optimized NZDSF has showed a very good quality factor of 14.83 and 7.85 at the bitrates of 2.5 and 10 Gbit/s at a fixed fiber length of 150 km. CSRZ-DPSK and CSRZ-DQPSK modulation formats give the optimum quality factor values of 6.12 and 5.73, respectively, for our optimized NZDSF at the bitrate of 10 Gbit/s. By adding the optical amplifiers along with our optimized NZDSF based WDM optical network, we can achieve a very high fiber transmission length of 4000 km along with much better quality factor of 6.44 at the bitrate of 2.5 Gbit/s. Thus, our optimized NZDSF will be very much suitable for future long haul WDM transmission and PON networks.

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