Performance Enhancement of 12 X 160 Gbps (1.92 Tbps) WDM Optical System for Transmission Distance upto 8000 km with Differential Coding

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Abstract: In the past few years the demand for high capacity optical transport platform is rapidly increasing. It has drawn the attention of the researchers. The optical networks with the capacity of the order of Tbps are evolving. The capacity of individual optical channel is increasing towards 100 Gbps and beyond. In this paper, we demonstrate design and performance of 1.92 Tbps WDM Optical System. Three CW lasers are used to generate optical carriers. Twelve sub carriers, each spaced 80 GHz apart are produced using two dual tone generators. Each subcarrier carries information at transmission rate of 160 Gbps to enhance the spectral efficiency to 2 b/s/Hz. The analysis is carried out for 12 x 160 Gb/s (1.92 Tb/s) PDM-QPSK WDM optical system considering three different cases that is without coding, with gray coding and with differential coding for 100 km transmission distance. Extensive simulations are carried out to evaluate symbol error rate, error vector magnitude and Q-factor in each case. From the comparison, it is observed that the system with differential coding gives better performance in comparison with other two cases. An improvement in Q-factor with differential coding is achieved in the range of 2 to 5 dB with respect to other two cases. It is also shown that the transmission distance for PDM-QPSK WDM optical system with differential coding can be extended upto 8000 km keeping the Q factor above the FEC limit requirement (BER value 3.8 x 10-3).

Keywords: **polarization division multiplexed quadrature phase shift keying (PDM–QPSK), forward error correction (FEC), Wavelength Division Multiplexing (WDM), symbol error rate (SER), erbium doped fiber amplifier (EDFA)**

I. INTRODUCTION

WDM optical transportation systems with per channel data rate of 100 Gb/s or more are in demand to meet the ever increasing requirement of traffic growth [1]. These systems are realized employing coherent detection with digital signal processing (DSP) at the receiver side. Linear fiber impairments like chromatic dispersion (CD) and polarization mode dispersion (PMD) are limiting factors for WDM optical systems at higher data rates. DSP at the receiver side is a well developed technology to compensate these linear fiber impairments [2, 3]. Coherent detection at receiver side contributes in compensation for fiber nonlinearities [2, 3]. Fiber nonlinearities can also be compensated by DSP through implementation of numerical inversion of optical fiber propagation [4, 5].

For high speed WDM optical system, two or more bits per symbol transmission is preferred for long distance communication. Phase modulation schemes like QPSK and DQPSK are appropriate choices to fulfill the current and future requirements of optical communication systems. Multilevel phase modulation formats with polarization multiplexing schemes are extensively preferred for future high speed optical communication systems [6]. Higher spectral efficiency can be obtained by increasing transmission data rates with smaller spacing between channels. Fiber impairments get worse at higher spectral efficiency which reduces the optical communication link length [7].

In this paper we have demonstrated the performance of WDM optical system of 160 Gb/s transmission rate employing PDM-QPSK modulation format with and without forward error correction (FEC) coding. Gray coding and differential coding are used for FEC. Channel spacing is reduced to increase the spectral efficiency (SE) using the concept of sub carrier generation. The remainder of the paper is organized as follow. Section II shows the system design. Section III presents results and discussion and finally conclusion is given in section IV.

II. SYSTEM DESIGN

A. TRANSMITTER SECTION

Fig. 1 shows the transmitter section setup created for 12 x 160 Gbps (1.92Tb/s) PDM-QPSK WDM optical system. Three optical signals from CW lasers with frequency centered at 193.1 THz, 193.42 THz and 193.74 THz are multiplexed through WDM multiplexer at power level of 0 dBm for each channel.

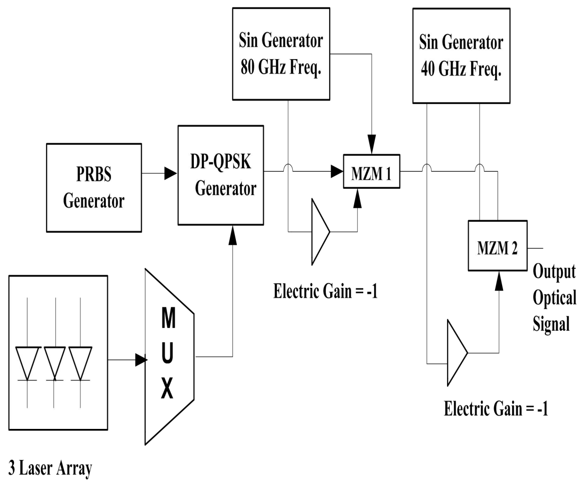
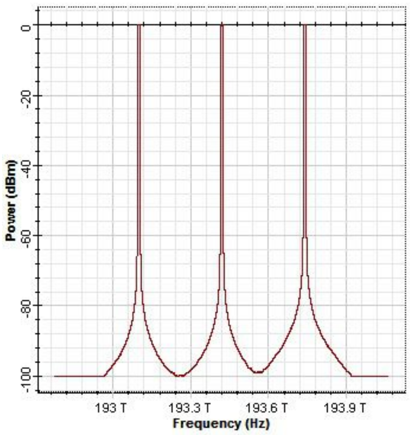
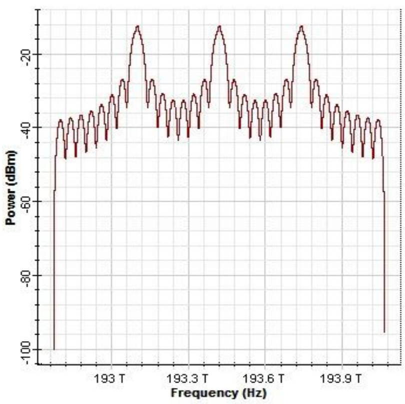


Fig.1. Transmitter section

Spectrum of this multiplexed signal is shown in Fig. 2(a). 320 GHz spaced apart multiplexed signal is applied to PDM-QPSK modulator. PDM-QPSK modulator comprises of 4 $LiNbo_3$ (Lithium Niobate) Mach zehnder modulators (MZMs). MZMs are driven through multiplexed optical signal and data sequence with sequence length of 2^{14}-1 generated by PRBS sequence generator as shown in Fig. 1. MZMs are biased at 6 volts.



(a)



(b)

Fig. 2. (a) Spectrum of multiplexed optical signal (b) Spectrum of optical signal after PDM-QPSK Modulator

Four MZMs form two pairs of IQ modulators. Single IQ modulator modulates the data signal into two components named as I (In-phase) and Q (Quadrature) component. A phase shift of π/2 is applied between I and Q components. Two pairs of IQ modulators generate I and Q components for X and Y polarizations. The WDM Optical System is created on optisystem software.

First dual tone generator is driven by sinusoidal signal of 80 GHz frequency. So, each of the three optical signals is converted into two frequency-shifted copies at ±80 GHz from the original lasers frequencies. Six channels are created by first dual tone generator, which are applied to second dual tone generator. Second dual tone generator is driven by sinusoidal signal of 40 GHz frequency. Frequency shifted copies of ±40 GHz are obtained of six channels. So, total twelve channels (sub carriers) are generated which are 80 GHz apart. Fig.2(c) shows spectrum of twelve sub carriers. It can be seen that subcarrier frequencies are in the range of 192.98 THz to 193.86 THz.

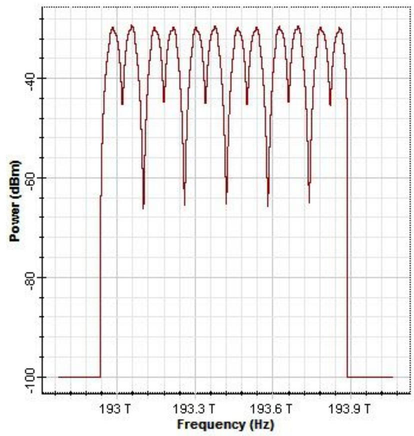


Fig.2.(c) Spectrum of twelve sub carriers

B. FIBER SPAN

Optical signal containing twelve sub carriers propagating through large effective area fiber (LEAF) as shown in Fig. 3. Transmission of the signal is carried out through 100 km fiber span with effective area of 80 μm^2.

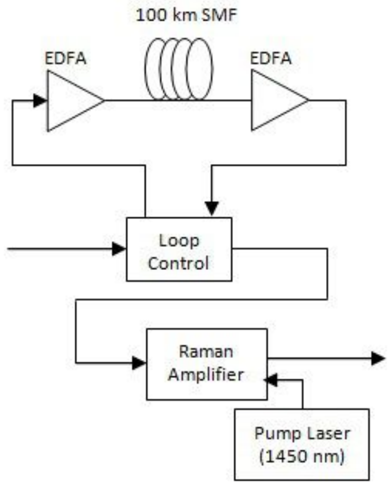


Fig. 3. Fiber span

Two erbium doped fiber amplifiers (EDFA) are used to provide pre and post amplification of optical signal. For long distance communication, recirculating loop is arranged in design, which repeats 100 km fiber span multiple times based on requirement. Gain of the EDFAs placed in each span compensates the attenuation of fiber. Raman amplifier is used at the end to provide distributed amplification of signal and ultimately maintains the signal to noise ratio throughout the fiber length. Parameters of fiber are listed as in table I.

TABLE I. PARAMETERS OF FIBER

Parameter	Value
Reference wavelength	1550 nm
Length	100 km
Attenuation	0.185 dB/km
Dispersion	20 ps/nm/km
Dispersion slope	0.075 ps/nm^2/km
PMD co-efficient	0.05 ps/sqrt(km)
γ	1.31W^{-1}km^{-1}

C. RECEIVER SECTION

For recovery of individual sub carrier, rectangular filter is placed at the receiver side with the bandwidth of 40 GHz. Fig. 4 shows the structure of single channel PDM-QPSK receiver with DSP.

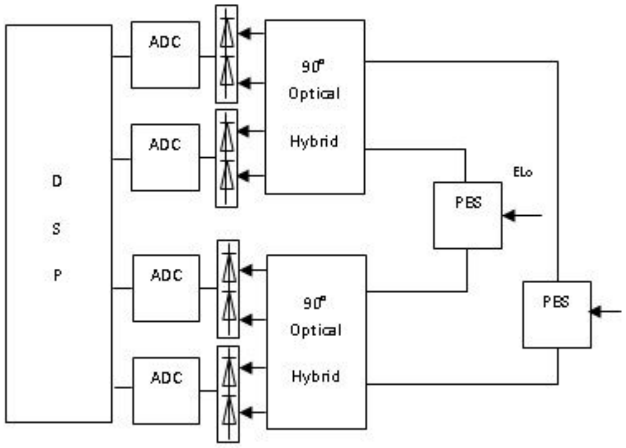


Fig. 4. Single channel PDM-QPSK Receiver

Fig. 5 shows the separation of single channel at 192.98 THz from received 12 channels (sub carrier) at receiver.

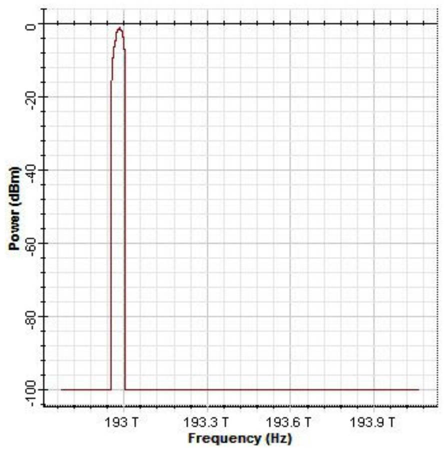


Fig. 5. Single channel at 192.98 THz separated from 12 channels using rectangular filter

Signal is coherently detected at the receiver which recovers the phase information of signal after influence of impairments in fiber [8]. Four output signals from optical coherent PDM-QPSK receiver are I and Q components of the two polarizations (X and Y), which contain the full information of transmitted signals.

Signal is further processed in DSP [9]. Dispersion and nonlinearity are compensated in electric domain by DSP. Q-factor criterion for the performance evaluation of optical transmission systems are frequently used in combination with BER or SER measurement. It enables an efficient representation of relevant noise statistics [10]. Q-factor is defined as:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 - \sigma_0} \tag{1}$$

Error vector magnitude (EVM) describes the effective distance of the received complex symbol from its ideal position in the constellation diagram [11, 12]. The EVM is calculated as follow:

$$EVM\ rms[\%] = \sqrt{\frac{\frac{1}{N}\sum_{n=1}^{N}\left|S_{Rx,n} - S_{Tx,n}\right|^2}{\frac{1}{N}\sum_{n=1}^{N}\left|S_{Tx,n}\right|^2}} \tag{2}$$

In equation (2), $S_{Tx,n}$ and $S_{Rx,n}$ represent the nth transmitted and received symbols, respectively, and N is the number of symbols.

III. RESULTS AND DISCUSSION

First, the system performance of WDM optical system at 100 km for launch power from -4 dBm to +5 dBm is investigated. Fig. 6 shows the Q factor performance of 5th channel (193.3 THz) at different launch powers.

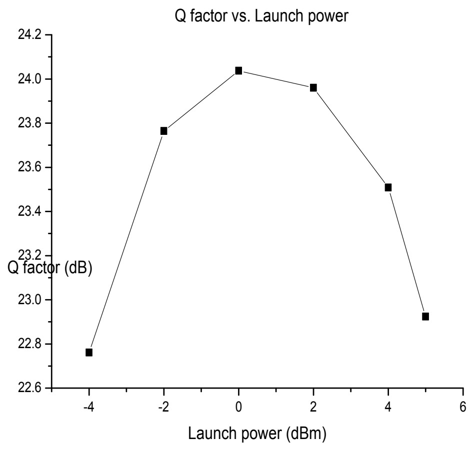


Fig. 6. Q-factor vs. Launch power

The graph shows that higher value of Q-factor is obtained at 0 dBm power level. At this power level fiber nonlinear impairment compensation is better.

We have initially evaluated the performance of WDM optical system without applying any coding scheme at 100 km transmission distance. Gray coding and differential coding are applied on same WDM optical system to verify the performance in terms of symbol error rate (SER), Q factor and error vector magnitude (EVM). Transmission distance of 100 km is considered for sack of simplicity and comparative evaluation of three cases.

Table II shows values of Log of estimated SER for WDM optical system without coding scheme, with gray coding and differential coding for 12 different channels. Q factor and EVM values are compared for these three cases in table III and table IV respectively.

TABLE II. COMPARISON OF LOG_{10} OF ESTIMATED SER WITHOUT CODING, WITH GRAY AND DIFFERENTIAL CODING SCHEMES FOR 100 KM

Channel number (freq. in THz)	Without coding	Gray coding	Differential coding
1(192.98)	-66.1663	-78.8524	-103.838
2(193.06)	-57.7181	-61.4618	-126.948
3(193.14)	-44.707	-50.929	-100.31
4(193.22)	-42.8132	-48.4185	-106.505
5(193.3)	-38.3059	-39.2939	-98.7921
6(193.98)	-34.982	-36.5571	-103.958
7(193.46)	-34.0177	-35.4663	-98.3562
8(193.54)	-41.48	-42.7084	-133.069
9(193.62)	-45.6827	-53.0772	-94.7162
10(193.7)	-58.8341	-64.0458	-103.812
11(193.78)	-58.7933	-71.1004	-123.652
12(193.86)	-63.9013	-59.4319	-128.562

Log of Symbol error rates are varying from channel to channel due to imperfect gain equalization of EDFA in WDM optical system. Log of Estimated SER is found lower in channel 2 and channel 8 as compared to other channels due to variations of fiber nonlinearities from channel to channel as shown in Fig.7. Similar results are also observed in terms of Q factor and EVM from Fig. 8 and Fig. 9 respectively.

TABLE III. COMPARISON OF Q-FACTOR WITHOUT CODING, WITH GRAY AND DIFFERENTIAL CODING SCHEMES FOR 100 KM

Channel number (freq. in THz)	Without coding	Gray coding	Differential coding
1(192.98)	24.80999	25.54118	26.74839
2(193.06)	24.21493	24.446	27.62808
3(193.14)	23.10186	23.61742	26.5969
4(193.22)	22.91325	23.39466	26.8595
5(193.3)	22.42857	22.47246	26.52999
6(193.98)	22.03357	22.15302	26.75318
7(193.46)	21.91175	22.01912	26.51072
8(193.54)	22.77552	22.8409	27.83422
9(193.62)	23.19555	23.79991	26.34538
10(193.7)	24.29794	24.62684	26.74719
11(193.78)	24.29529	25.08661	27.51291
12(193.86)	24.6584	24.29794	27.68348

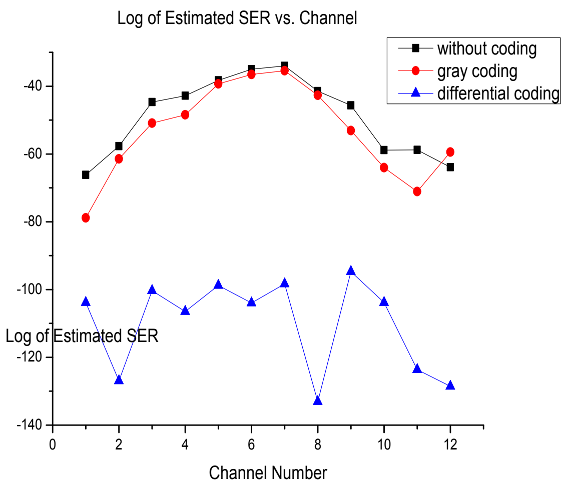


Fig. 7. Log of Estimated SER vs. Channel

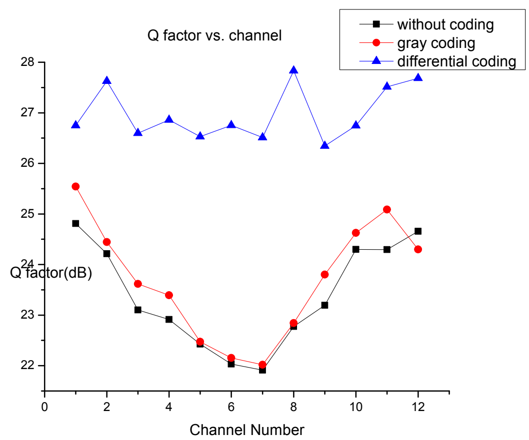


Fig. 8. Q factor vs. Channel

Table II shows the comparison in terms of Log of symbol error rates of twelve channels for three different cases, which is also plotted in Fig. 7. WDM Optical system with differential coding exhibits lower symbol error rates than other two cases. Differential encoding removes the possibility of burst errors due to cycle slips.

An improvement in the range of 2 dB to 5 dB is observed in Q factor for WDM optical system with differential coding in comparison with other two cases. Fig. 8 highlights the better performance of WDM optical system with differential coding. Differential coding is highly preferred scheme for forward error correction (FEC) to enhance the system performance.

TABLE IV. COMPARISON OF EVM WITHOUT CODING, WITH GRAY AND DIFFERENTIAL CODING SCHEMES FOR 100 KM

Channel number (freq. in THz)	Without coding	Gray coding	Differential coding
1(192.98)	0.076053	0.068887	0.059957
2(193.06)	0.078211	0.074508	0.057066
3(193.14)	0.085871	0.079507	0.060614
4(193.22)	0.086864	0.080234	0.059751
5(193.3)	0.090163	0.085697	0.061918
6(193.98)	0.09261	0.088692	0.060904
7(193.46)	0.094456	0.089786	0.061907
8(193.54)	0.08785	0.082758	0.057248
9(193.62)	0.085061	0.077046	0.060963
10(193.7)	0.07901	0.07219	0.060218
11(193.78)	0.077688	0.069635	0.056707
12(193.86)	0.07698	0.074238	0.0564

Low value of error vector magnitude (EVM) indicates better system performance [11]. Table IV clearly shows that EVM performance is enhanced for differential coding as compared to gray coding and without coding schemes. Differential coding shrinks EVM around 26% to 35% for respective channel in comparison with other two cases. EVM values for WDM optical system with differential coding seems to be lowest as shown in Fig. 9.

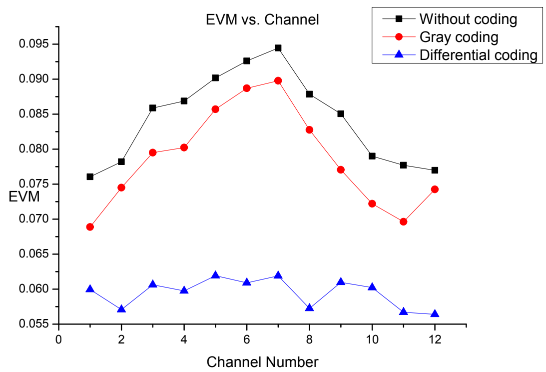


Fig. 9. EVM vs. Channel

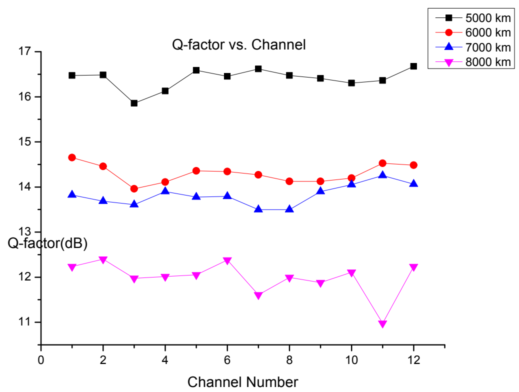


Fig. 10. Q factor vs. channel (5000 km to 8000 km)

Plot of twelve channels vs. Q-factor considering the distances of 5000 to 8000 km in step of 1000 km for WDM optical system is shown in Fig.10. Q-factor for transmission distance from 5000 km to 7000 km is above 13 dB as shown in Fig. 10. WDM optical system with differential coding can reach long distance upto 8000 km for which minimum Q factor is 10.977 dB. This value of Q factor is above the required value of 8.53 dB per channel at BER of 3.8 x 10^{-3} [8].

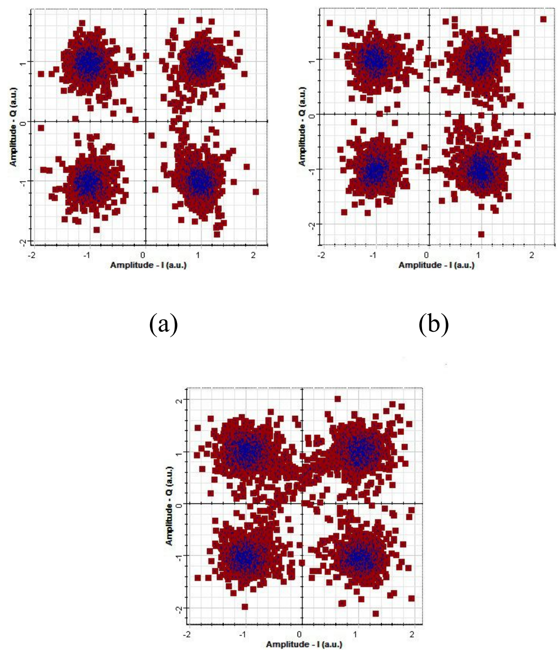


Fig. 11. Constellation diagram of channel 5 (193.3 THz) at (a) 6000 km (b) 7000 km and (c) 8000 km

Constellation diagram of WDM optical system with differential coding at three different link lengths of 6000 km, 7000 km and 8000 km for channel 5 (193.3 THz) is shown in Fig. 11. Four separate points related with symbols of bit patterns (00, 01, 11 and 10) are clearly visible for 6000 km, 7000 km and 8000 km transmission distances from constellation diagrams of Fig. 11(a) , (b) and (c) respectively. WDM optical system with differential coding gives satisfactory performance at 1.92 Tbps data rate up to a distance of 8000 km.

IV. CONCLUSION

In this paper we have presented a design of 12 x 160 Gb/s (1.92 Tb/s) PDM-QPSK WDM optical system. The performance of the system is evaluated and compared by considering no coding, with gray coding and with differential coding for 100 km transmission distance by extensive simulation. System with differential coding outperforms system with gray coding and without coding, because differential coding removes the possibility of burst errors due to cycle slips. Q factor of WDM optical system with differential coding is improved in the range of 2 to 5 dB. Spectral efficiency of 2 b/s/Hz is achieved by keeping

80 GHz channel spacing at the data rate of 160 Gb/s of each subcarrier. Transmission distance for PDM-QPSK WDM optical system with differential coding can be extended up to 8000 km keeping the Q factor above the FEC limit (BER value 3.8 x 10^{-3}).

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