New Method For Modeling and Design Optical SDM Transmission System Using Long Haul FMF with PDM/DWDM Techniques Enabling QPSK Modulation Format

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Abstract:

This paper presents the modeling and design of ultra high capacity Space Division Multiplexing (SDM) transmission system. Polarization Division Multiplexing (PDM) and Dense Wavelength Division Multiplexing (DWDM) techniques are also proposed in this system to increase total system data rate. For the ultra-high capacity need of SDM, Few Mode Fiber (FMF) was proposed as SDM best technology for obtaining ultra-high bit rates with long haul transmission. The description and design of 8-DWDM channels over 7 modes SDM/PDM system was explored as future of ultra-high capacity optical network. A long-haul transmission of 1080 Km recorded for 8-WDM channels-7modes-SDM/PDM system by using QPSK modulation format. The total bit rate achieved by our designed system is 4.48 Tb/s at 40Gb/s. Channel estimation techniques were proposed to enable the transmitter pre-shaping design for the linear effects mitigation by using different DSP algorithms. The presence of linear and nonlinear losses limits the acceptable range of input power that produce the required BER for our proposed system from -4dBm to 4dBm.

Keywords: Space Division Multiplexing (SDM), Polarization division multiplexing (PDM), Dense Wavelength Division Multiplexing (DWDM), Few Mode Fiber (FMF), Quadrature Amplitude Modulation (QPSK).

الخلاصـــة

تقدم هذه الورقة تشكيل وتصميم نظام الأرسال ذو القدرة العالية جدا باستخدام تقنية مضاعفة تقسيم الفضاء (SDM). وتم استخدام تقنية الاستقطاب المزدوج (PDM) لمضاعفة القنوات وتقنية دمج الأطوال الموجية المتعددة الترددات (DWDM) أيضا في هذا النظام من أجل زيادة معدل بيانات النظام. من اجل الحصول الى قدرة فائقة لنظام (SDM)، تم تصميم نظام النقل(FMF) كأفضل تقنية في نظام (SDM) للحصول على أنظمة سعة فائقة. قمنا تصميم وتوصيف تقنية DWDM مع ثمان قنوات مضاعفة بتقنية PDM ومرحلة على سبعة قنوات فضاء نظام SDM. باستخدام تقنية التضمين (QPSK) تمكنا من الحصول على اعلى مسافة ممكنة لنظام (SDM) ذو الثمان قنوات فأعلى طول تم الحصول عليه هو (1080 كم) والذي يعتبر من الاطوال البعيدة المدى. تم الحصول على مستوى عالي جدا لنقل البيانات باستخدام الانظمة المصممة حيث ان القدرة الكلية باستخدام نظام (SDM)ذو الثمان قنوات فمقدار القدرة الكلية يقدر ب(4.8 تيرا هيرتز). وقد استخدمنا مختلف تقنيات (DSP) لتعويض الخسائر الخطية الحاصلة بين القنوات.

الكلمات المفتاحية: تقنية مضاعفة تقسيم الفضاء(SDM)، تقنية الاستقطاب المزدوج (PDM) ، تقنية دمج الأطوال الموجية المتعددة الترددات (DWDM) ، نظام النقل(FMF)، تقنية التضمين (QPSK) .

1. Introduction:

The limited capacity of single-mode fiber (SMF) has been shown to be restricted by fiber nonlinearities (Essiambre *et.al.*,2010). One hopeful approach to moreover enhance the capacity of fiber-based transmission systems is Space Division Multiplexing (SDM) (Richardson *et.al.*, 2013). SDM can be achieved using fiber ribbons, multicore (MC) fibers or few-mode fibers (FMF) (Nikolay Karelin *et.al.*,2015). Afterwards, this paper focuses on solutions for realizing reliable and efficient mode multiplexing for MDM over FMF and investigates optical devices and subsystems for FMF-based long-haul networks. In the following sections, three essential building blocks for MDM: Few mode fiber system, FMF modal and impairments, and digital signal processing (DSP) for FMF will be briefly introduced.

1.1 FMF System Architecture:

At the FMF system, there is high mode-coupling and deferential mode group delay (DMGD) among modes (Randel *et.al.*,2013). At the end of DEMUX, the received channels are detected by coherent detection, with additional multi input multi output (MIMO) DSP to decrease the distortion and crosstalk of signals, such as DMGD and CD (Ezra ,2010). Optical add/drop multiplexers can be applied in SDM system, to dynamically drop or add important spatial- channels at each node of network to be applied on the all optic dynamic- routing systems(Xuan He,2014). The MDM optical network generally contains few-mode fiber, transmitter/receiver arrangement, and multiplexer/demultiplexer of modes as explained in the figure (1).

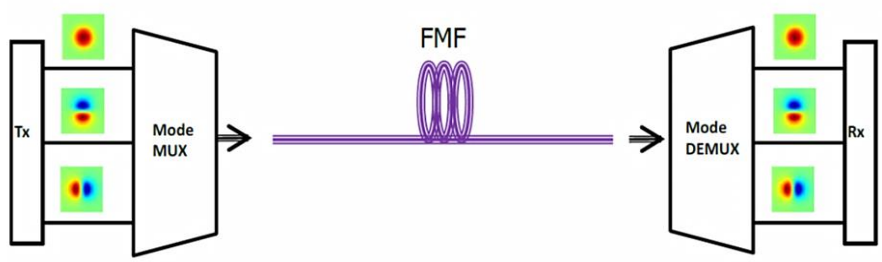
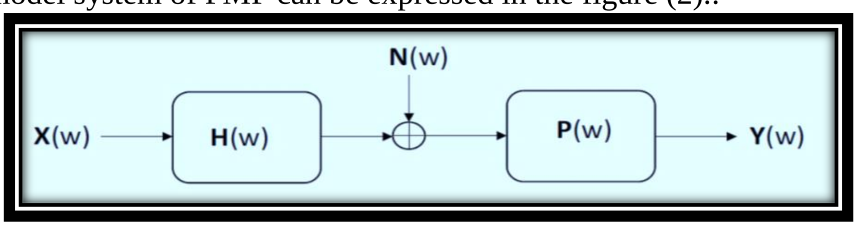


Figure (1): Schematic diagram of an MDM transmission system [Xuan He,2014]

1.2 Modeling and impairments of FMF transmission system:

The model system of FMF can be expressed in the figure (2).:



Figure(2): Link-model of FMF system [Xuan He,2014]

Y(w) will be expressed as the below equation:

$$\boldsymbol{Y}(w)= (\boldsymbol{H}(w)\cdot \boldsymbol{X}(w)+ \boldsymbol{N}(w))\cdot \boldsymbol{P}(w) \quad \text{.......} \quad (1)$$

where **Y**(w) corresponds to the output signals vector in frequency-domain [**Y**1(w), **Y**2(w), … **Y**M(w)]T, T is interval of symbol and *M* is the number of modes, while the angular-frequency is *w*. **Y***M(w) performs the output signal in frequency domain on M mode.

Also**, X**(w) represents the vector of M input signals in frequency-domain, and **X***M(w) act as the input signal in frequency-domain in mode #*M*.

The frequency-domain illustration of propagation matrix is **H**(w). The **H**(w) that has M number of modes in FMF system is presented as follows:

$$\mathrm{H(w)} = \begin{bmatrix} \mathrm{H}_{11}(\mathrm{w}) & \mathrm{H}_{12}(\mathrm{w}) & \ldots\ \mathrm{H}_{1\mathrm{M}}(\mathrm{w}) \\ \mathrm{H}_{21}(\mathrm{w}) & \mathrm{H}_{22}(\mathrm{w}) & \ldots\ \mathrm{H}_{2\mathrm{M}}(\mathrm{w}) \\ \mathrm{H}_{\mathrm{M}1}(\mathrm{w}) & \mathrm{H}_{\mathrm{M}2}(\mathrm{w}) & \ldots\ \mathrm{H}_{\mathrm{MM}}(\mathrm{w}) \end{bmatrix} \quad (2)$$

so **H**ij(w) represents the impulse-response of frequency-domain, that describes mode-coupling losses for #j mode channel on #i mode channel.

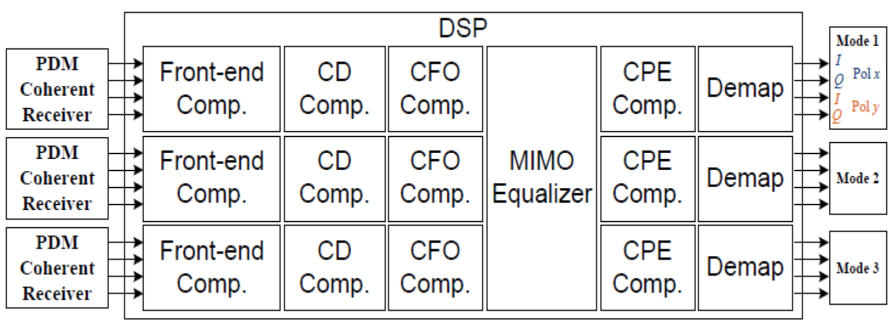
The impulse-response of frequency domain is found by the system losses, containing, MDL, MDG, DGD, CD, and other losses.

The frequency-domain labeling of Amplified Spontaneous Emission (ASE) noise is N(w), that produced by amplifiers in transferring link. By using long transmission system, due to many amplifiers used in the link of transmission, the performance of system generally determined by ASE noise (Xuan He,2014). Passband filter of frequency domain is P(w), that can be used to move the ASE added on the channel power-spectrum. The P(w) bandwidth must be slightly larger than bandwidth of modulated signal, so no Inter Symbol Interference (ISI) is produced by tight-filtering.

1.3 Coherent Detection for FMF system:

One of the most important factors that enables high capacity MDM systems to be realized in lab trials. Coherent-detection is applied for FMF systems, to detect signals of modes after propagation and DGD, CD, and phase-noise will be electrically compensated by DSP. optical coherent receivers and high-speed real-time oscilloscopes are utilized for detecting and sampling the received signals (Ezra ,2010).

Front-end impairments, chromatic dispersion (CD), timing offsets and carrier frequency offset (CFO) can be compensated by DSP too[(Kuschnerov *et.al.*,2009). Carrier phase estimation (CPE) is implemented after the implementation of Multiple-Input Multiple-Output (MIMO) equalizer in time or frequency domain (Viterbi,1983). Figure 3 gives the design of DSP enabling coherent receiver with block for recovering three spatial modes after Polarization Division Multiplexing (PDM) coherent receivers. The most two important DSP techniques will be discussed below.



Figure(3): DSP block for recovering 3 spatial modes [van Uden,2013].

i. Adaptive MIMO equalizer for DMGD compensation

In early MDM demonstrations (Ryf *et.al.*,2012)the time-domain data-aided (DA)-Least-Mean-Square (LMS) algorithm is used for initializing the taps of the MIMO equalizer. After convergence, decision-directed (DD) LMS or Constant Modulus Algorithm (CMA) is employed. To recover optical PDM signals over N spatial modes, the MIMO equalizer requires a 2N*2N FIR filter (Haoshuo Chen,2014). There is large computational complexity, as a large number of taps for each filter are required for compensating the accumulated DGDs. Recently, time domain equalizer (TDE) was applied in optical communication (Bai *et.al.*,2012). Block-by block processing and fast

Fourier Transform (FFT) implementation result in tremendous reduction in computational complexity (Goldsmith,2005]. Figure (4) shows MIMO equalizer with a wide equalizer window to handle DGD.

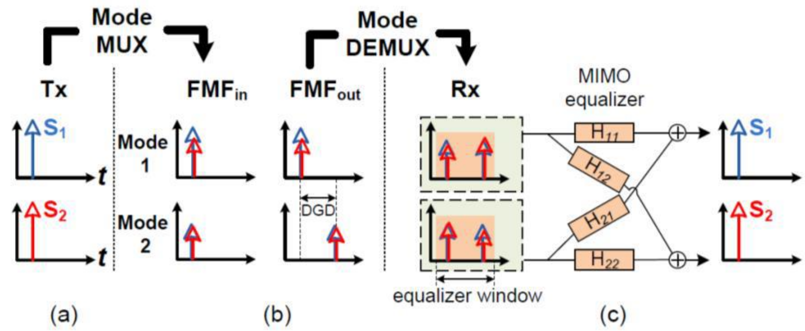


Figure (4): (a) Transmitted signals; (b) mode coupling induced by mode MUX with the DGD between two modes after FMF transmission and (c) MIMO equalizer with a wide equalizer window to handle DGD(Randel,2013).

Generally, adaptive MIMO equalizer has been designed to powerfully mitigate the high DGD and crosstalk, so as a result detecting the channels on variant modes(Xuan He,2014).

2. Dispersion Compensation

The Chromatic Dispersion (CD) can suppose each negative and positive rates (Jagannathan,1996).Coupling 2 fibers with inverse sign CD corresponds to mitigation for the overall losses across the jointed two fibers length (Kuschnerov,2009). To perform one high-order filter for equalizing both PN and residual CD, the accomplishment of the adaptive filter will decrease with the increased value for delay of the filter. As a result, the function is achieved by several steps, among them the one-tap NLMS filter for phase evaluation and the second is a multiple-tap LMS filter for residual dispersion compensation (Jagannathan,1996). The dispersion compensation setup in a fiber-link is seen in figure (5).

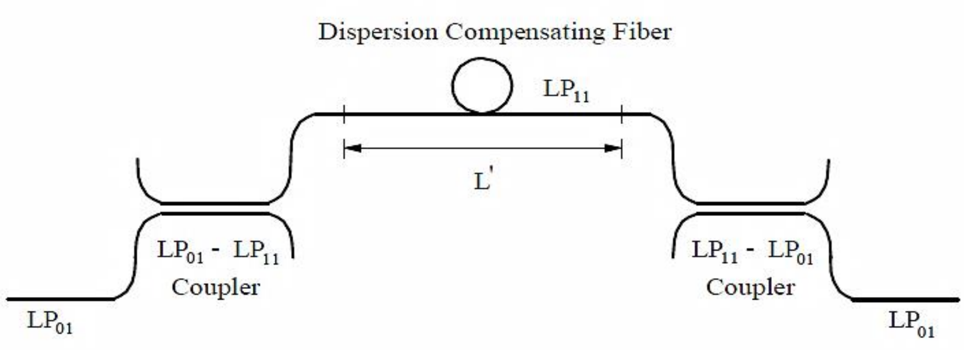


Figure (5): The dispersion compensation setup in a fiber-link [Jagannathan,1996].

2. WDM/SDM/PDM Transmission system using FMF :

The most important purpose of SDM technology is to demonstrate degrees of magnitude enhance the capacity of optical systems by taking the advantage of many available paths of spatial signals (Haoshuo Chen,2014). In spite of the fact that increasing the number of space modes for FMFs is not so complicated, FMF have some unfavorable problems regarding the high number of modes in space paths (Richardson,2013). One of these problems is the detention factor and as a result the curvature losses at the larger number of modes will be higher than little number of modes(Filipe Marques Ferreira,2014).On the other hand, MUX and DEMUX of a higher modes number are sophisticated and mainly produce additional distortions. With a view to demonstrate larger capacity for near future SDM systems, the number of spatial signals per fiber have to be further enhanced from MCFs and FMFs achieved until now.

Figure (6) shows the models developed in the general simulation setup for WDM-FMF systems. At the transmitter 2*M signals are modulated with data streams and mapped into two polarizations (using a polarization multiplexer) and M orthogonal spatial guided modes by the FMF (using a MMUX).

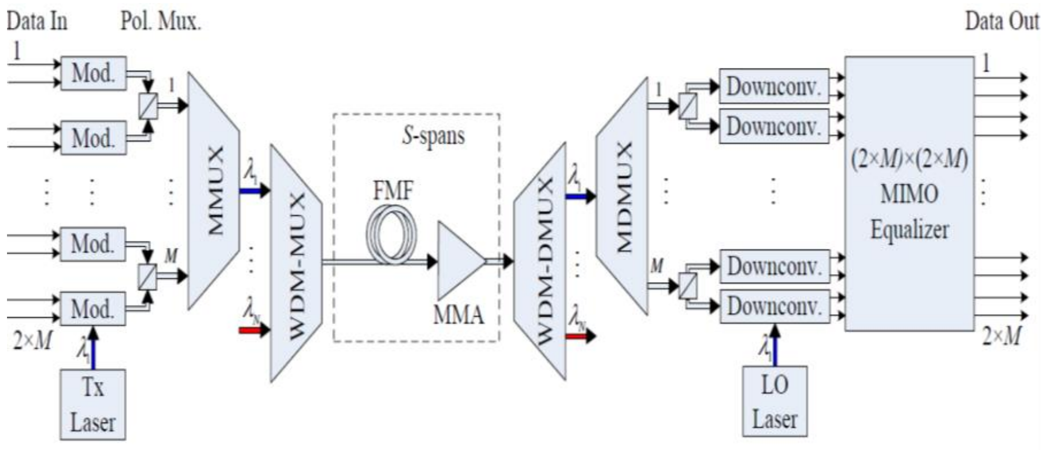


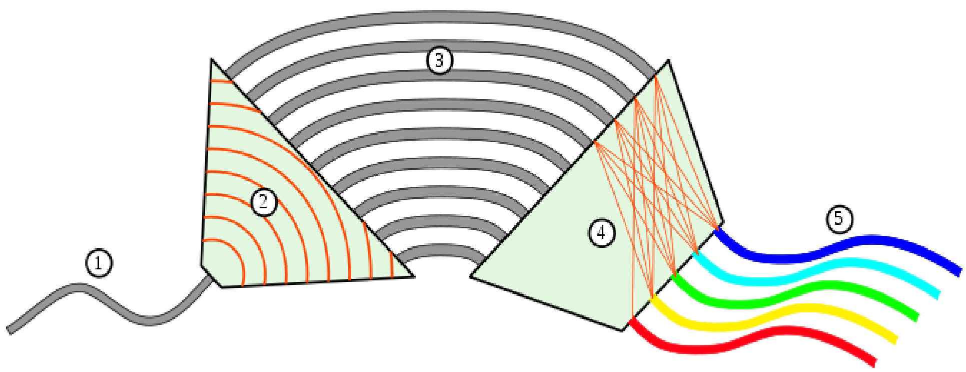
Figure (6): Long-haul MDM-WDM-FMF system setup [Filipe Marques Ferreira,2014]

Here, N signals at different wavelengths are combined by a WDM multiplexer (WDM-MUX), as in a conventional SMF system. As signals propagate through S spans of fiber with length L, total span loss is compensated by a MMA. Different wavelengths are isolated by a WDM de-multiplexer (WDM-DMUX) in the receiver. The signal at each wavelength is separated into M spatial modes and two polarizations using a MDMUX and a polarization demultiplexer, respectively.

The signal in each mode is mixed with a local oscillator (LO), down converting it to baseband. After sampling, DSP-MIMO compensates for the transmission impairments (such as: chromatic dispersion, DMD and linear XT), separating the 2*M multiplexed data signals (Filipe,2014).

❖ Arrayed Waveguide Grating (AWG):

Arrayed waveguide grating is perform routing for different channels to various ONUs. Recently, the most used multiplexer is array waveguides as they used in large purposes of optical systems of WDM channels, like routing, multicasting, and multiplexing (Fonseca *et.al.*,2001). Figure (7) shows an AWG structure .



Figure(7): Arrayed Waveguide Grating (AWG) structure(Online page,2010)

3. System description

In this section, system description of an integrated DWDM transmitter for space division multiplexing is illustrated. We demonstrated DWDM system by transmitting the signal over different wavelengths with 50GHz channel spacing then interleaved into different types of spatial modes.

AWG used for multiplexing and demultiplexing the incoming wavelengths in each spatial mode to be modulated and dual polarized by Tx-mQAM PolMux module. Each wavelength is modulated at 20GHz or 40 GHz with a dual-polarization 16QAM or QPSK modulation formats. Multi-mode coupler used to combine input single-mode optical signals (spatial modes) into a multimode optical output signal.

Ultra-high capacity eight DWDM- SDM PDM systems with seven spatial and polarized dimensions (fiber modes) are presented in this section. The block diagram of 8 DWDM channels–7 modes SDM/PDM is presented in figure (8).

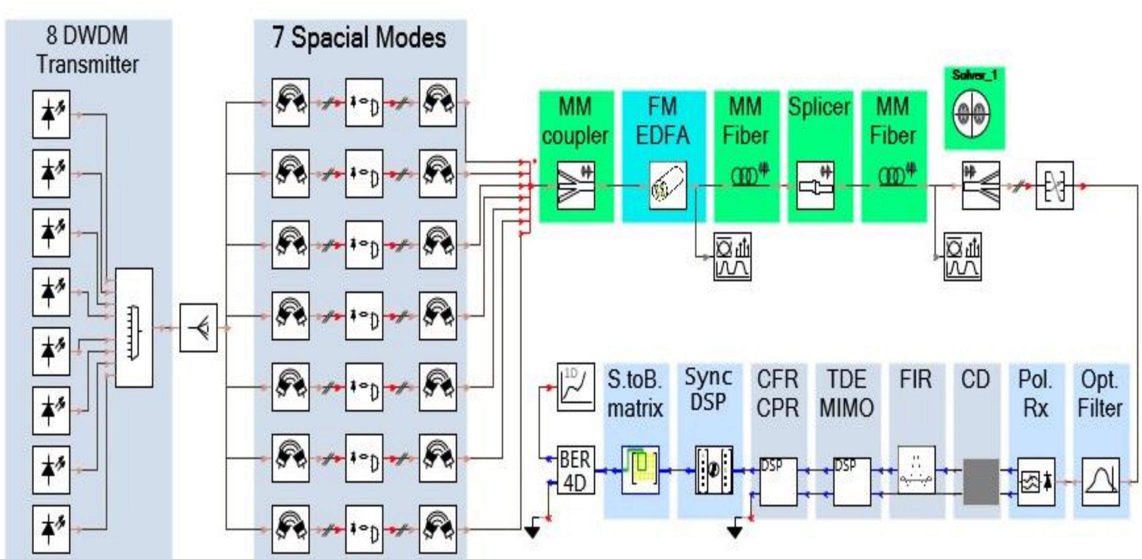


Figure (8): 8 DWDM channels–7modes SDM/PDM system

By using polarization division multiplexing technique and 7 spatial modes for 8 channels, the total bit rate of system in ideal case become 4.48 THz (8Ch.*7 modes*40 GHz*2 polarization states). The description of 8DWDM -7spatial modes SDM/PDM System can by divided into three parts:

1.Transmitter Section:

The simulated transmitter section of 7modes SDM system is shown in figure (9). Eight signals produced with different emission frequencies to be multiplexed by DWDM multiplexer. The transmission structure of 8DWDM -7modes SDM system consists of two parts, 8-DWDM channels transmitter and 7spatial fiber modes. The characterization of each part is shown below:

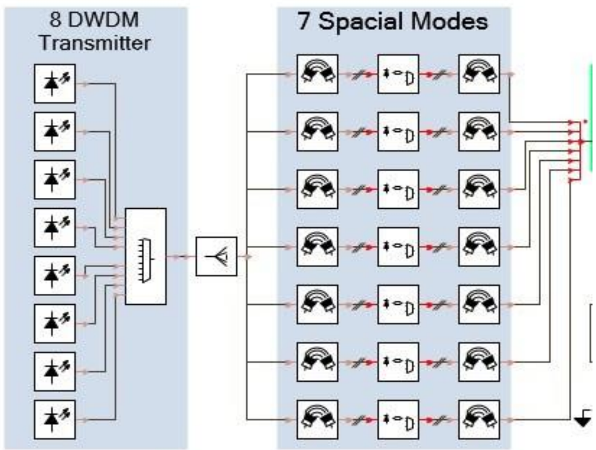


Figure (9): Transmitter section of 8DWDM -7modes SDM PDM System

A.DWDM Transmitter:

This part of transmitter section used for multiplexing the incoming eight optical signals generated by LaserCW modules by using dense wavelength division multiplexing. The table of DWDM multiplexer parameters is shown below:

Table (1) DWDM multiplexer parameters description

Parameter	Value	Units
Channel spacing	50 GHz	GHz
Bandwidth	160 for QPSK	GHz
Insertion loss	2	dB
Filter type	BandPass	
Transfer function	Gaussian	
Gaussian Order	3	
Center freq. Filter 1	192.925e12	
Center freq. Filter 2	192.975e12	
Center freq. Filter 3	193.025e12	
Center freq. Filter 4	193.075e12	
Center freq. Filter 5	193.125e12	
Center freq. Filter 6	193.175e12	
Center freq. Filter 7	193.225e12	
Center freq. Filter 8	193.275e12	

B. Spatial Dimensions (Fiber Modes):

The output signals of power splitter distributed equally into the seven spatial cores where array waveguides used to demultiplex the combined wavelengths. The description of AWG parameters is shown in table (2). The demultiplexed optical signals modulated and dual polarized by the same way as single channel system but an array of DP-mQAM Transmitter module used.

Table (2) Parameters description of AWG

Parameter	Value	Units
Frequency spacing	50	GHz
Number of input/output ports	1/8 for Mux and 8/1 for Demux	
Frequency of the first channel	192.925	THz
Frequency of the last channel	193.275e12	THz
Reference channel frequency	193.1e12	Hz
Passband type	Gaussian	
Model type	Data sheet	
Insertion losses	0	w

This array modulated the incoming optical 8 signals with 20GHz or 40 GHz bit rate with specified modulation technique. Then, the eight polarization-multiplexed optical signals with quadrature modulation multiplexed again by array waveguide. Next, the seven spatial modes become ready to be transmitted over the few-mode fiber. The block diagram of DP-mQAM transmitter array is with an array to process the 8 channels.

2. Optical fiber channel

In this section the propagation of seven spatial modes into multi-mode fiber (MMF) illustrated. MM splicer added to increase the transmission distance. Multimode ideal coupler used to couple 7 single-mode optical modes into a multimode optical fiber. The modal fields are approximated by linear polarized (LP) modes. The supported LP modes of multimode coupler(MMC) and FMF are (LP01, LP11a, LP11b, LP21a, LP21b, LP02 and LP31a) modes. The table of coupling matrix is shown in table (3).

The same EDFA amplifier array model used in single channel, used here to amplify the seven spatial modes. The EDFA acted as gain control amplifier producing high output power with a gain of (14, 14.5, 14.5, 14.75, 14.75, 14.8, 15) dB for (LP01, LP11a, LP11b, LP21a, LP21b, LP02 and LP31a) LP modes respectively, and a noise figure of 4 dB. The same block diagram of FM-EDFA array module is used in 8-DWDM system. Multimode fiber module also used to simulate channel transmission in few mode fiber by considering attenuation and group velocities of the seven fiber modes. Different lengths of FMF tested to evaluate system performance and define maximum reach of the designed system.

Table (3): Parameters description of Multimode coupler

Coupling Matrix			
Port Number	ModeID	Magnitude	Phase(deg)
1	0	1	0
2	1	1	0
3	2	1	0
4	3	1	0
5	4	1	0
6	5	1	0
7	6	1	0

The modal fields and propagation constants calculations are performed by a separate mode solver module. The parameter description of mode solver shown in table (4) .

Table (4): Parameters description of mode solver for 8DWDM/SDM system

Parameter	Value	Units
Refractive Index	1.4	
Supported modes	(0, 1) (1, 1) (2,1) (0,2) (3.1)# LP01, LP11a,LP11b,LP21a,LP21b,LP02,LP31a	
Attenuation	0.2e-3	dB/m
DGD	0,0.05e-12,0.1e-12,0.15e-12,0.2e-12	s/m
Intra mode GDD	5e-15	s/m
Dispersion	20e-6	s/m^2
Dispersion slope	0.075e-12	s/m^3
PMD	0.05e-12/31.62	s/m

Few-mode fiber in 8DWDM system has an attenuation of 0.2e-3 dBm/m and dispersion of 20e-6 s/m^2 and the slope of dispersion is 0.75e-12 s/m^3. The differential group delay values are (0, 0.05e-12, 0.1e-12, 0.15e-12, 0.2e-12) for (LP01, LP11a, LP11b, LP21a, LP21b, LP02 and LP31a) LP modes respectively, and intra mode group Delay (GDD) of 5e-15 s/m. Polarization mode dispersion (PMD) of multi-mode fiber is 0.05e-12/31.62 s/m.

Table (5): Parameters description of multimode splicer

Coupling Matrix			
Input mode	**Output mode**	**Magnitude**	**Phase(deg)**
0	0	1	0
0	1	0	0
0	5	0	0
1	1	1	0
1	2	0	0
1	0	0	0
2	2	1	0
2	3	0	0
2	1	0	0
3	3	1	0
3	4	0	0
3	2	0	0
4	4	1	0
4	5	0	0
4	3	0	0
5	5	1	0
5	6	0	0
5	4	0	0
6	6	1	0
6	0	0	0
6	5	0	0

3. Receiver section

The receiver section of 8DWDM 7modes SDM/PDM system is presented. The block diagram of the receiver section is illustrated in figure (10). A bus selector module used to select the path for data traveling between optical channel and receiver section. The module can be used to easily send a signal to the desired wire of selected mode to be detected.

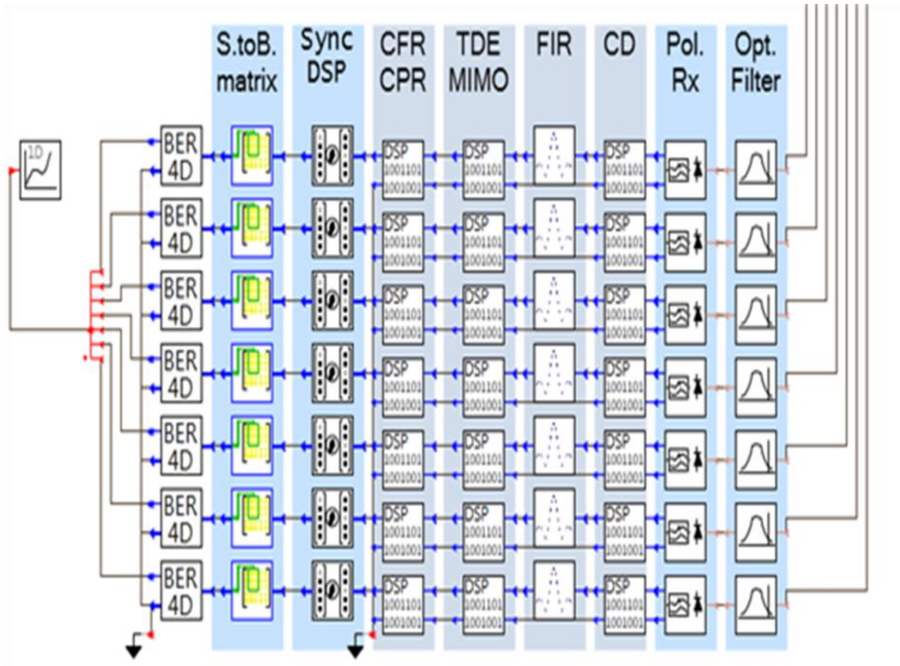


Figure (10): Block diagram of Receiver section

After bus selector using to choose modes to be decoded, an optical filter used to band pass the required channel to be processed in the selected mode with Gaussian transfer function. Optical filter parameters description shown in table (6). Then, the received polarized mode signals passes through polarization-diversity digital coherent receiver where ADC also performed, as presented in figure (11).

Table (6): Optical filter parameters description

Parameter	**Value**	**Unit**
Filter type	Band pass	
Transfer function	Gaussian	
Filter order	3	
Noise bandwidth	2e12	Hz
Noise resolution	10	GHz

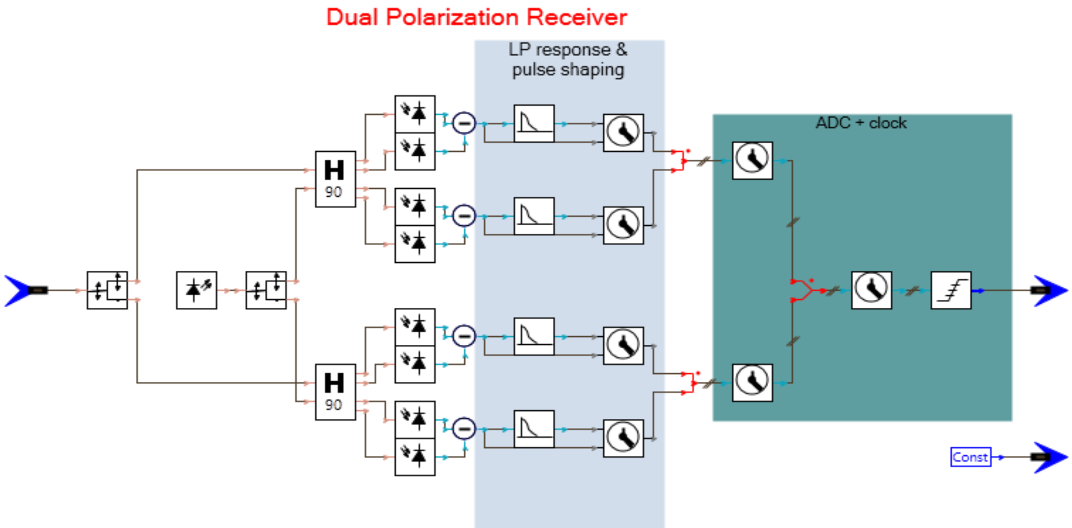


Figure (11): Block diagram Dual polarization receiver

Dual polarization &ADC receiver parameters description shown in table(7).

Table (7): Dual polarization &ADC receiver parameters description

Parameter	Value	Unit
Filter type	Low pass filter	
LPF transfer function	Bessel	
Filter order	4	
ADC Sampling Rate	2*Bit rate	Hz
ADC Resolution	8	Bit

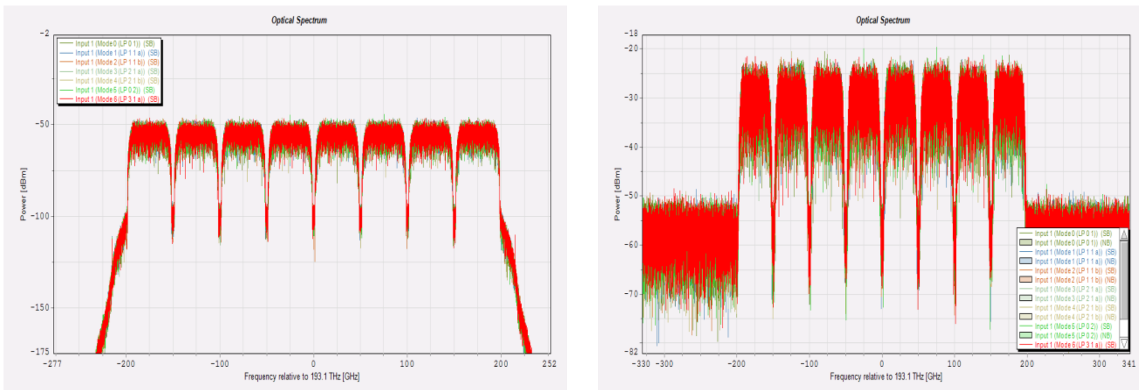
We eliminated chromatic dispersion linear losses by using electrical CD compensating DSP module. Then, we demonstrated finite impulse response (FIR) filter used as Matched filter to decrease losses of channel. FIR consists of symbol to bit matrices, raised cosine filter, and bit to symbol matrices to output the filtered bits in a symbol mode by using commutator and matrix for symbol reshaping.

4. Results

The results obtained by our proposed system are classified in three sections:

i. Spectrum Result:

Figure (13) shows the RF scope analyzer of 8DWDM 7 modes SDM PDM QPSK system before and after 1000km transmission distance at 40 Gb/s. By using seven modes and dual polarization state the total bit rate of our designed system become 4.48 Tb/s.



(a) (b)

Figure (13): The spectrum of optical scope for 8-channels-7 modes SDM/DWDM/PDM QPSK signal (a) before and (b) after 1000 km transmission distance

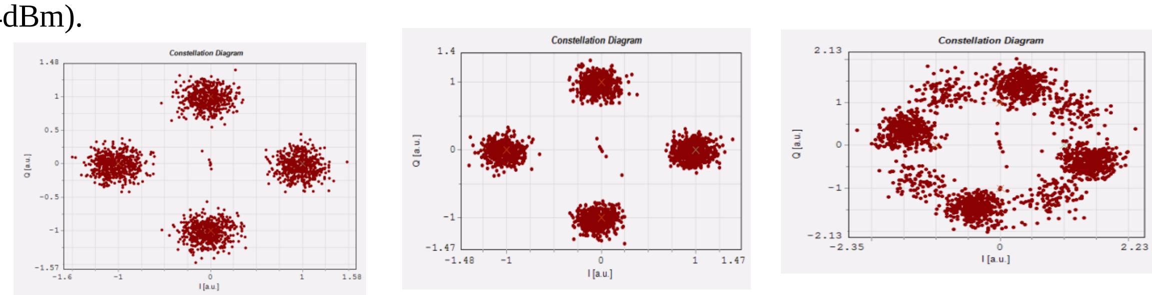
On the other side , as the power decreased and the signal shape distorts due to losses, many compensators required to obtain the required signal at the receiver.

ii. Diagrams of Received Electrical Constellation :

Similar techniques that used in single channel QPSK system can be used in DWDM-QPSK system. The following cases of constellation results will be discussed to study the performance of system:

1. Input Power:

The received constellation diagrams for 1000Km transmission of QPSK system with different input power are shown in figures below. As indicated in single system, better performance achieved by using QPSK system as compared with 16QAM system. The range of acceptable launched power for QPSK system is between (-4dBm) and (4dBm).



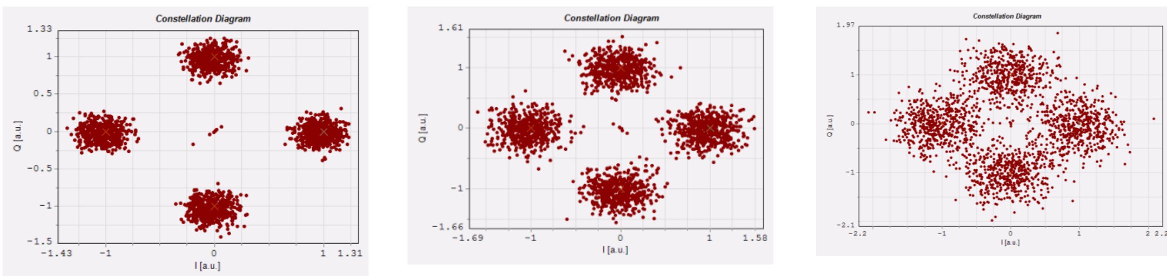
(a) (b) (c)

Figure (14): Received constellation diagram of channel 4X of LP31a mode with a. -4dBm b. 0dBm c.5 dBm at 1000Km

2.Transmission length

The received constellation diagrams for 0dBm input power of QPSK system with different length are shown in figure below. The transmission tests were achieved for a DWDM central channel (channel four). As expected, more transmission reach obtained using QPSK system as compared with 16QAM format. The designed system also supports long haul transmission .

Also, we added one ideal splicer to connect two multi-mode fibers each one support half the transmission length to increase the capabilty of long haul transmission.



(a) (b) (c)

Figure (15): Received constellation diagram of channel 4 of LP31a mode with a. 100 Km b. 700 Km c. 1200 Km at 1dBm

iii. Maximum reach measurements

To distinguish the effective linear and non-linear transmission achievement of 8-DWDM channels SDM/PDM-QPSK system, the maximum reach was measured .as .a .function of the input .power .per .channel at Figure (16). The results are summarized in table (10).

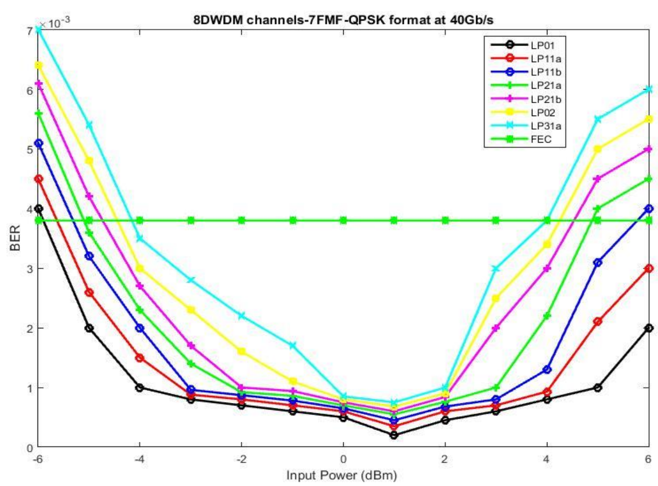


Fig.(16): Input power vesus BER for 8 channels 7modes SDM/DWDM/PDM-QPSK

The best realization of 8 channels-7 modes SDM/PDM-QPSK system and the most extreme achieve results were also measured as function of length of the few mode fiber at 40Gb/s and are appeared in figure (17).

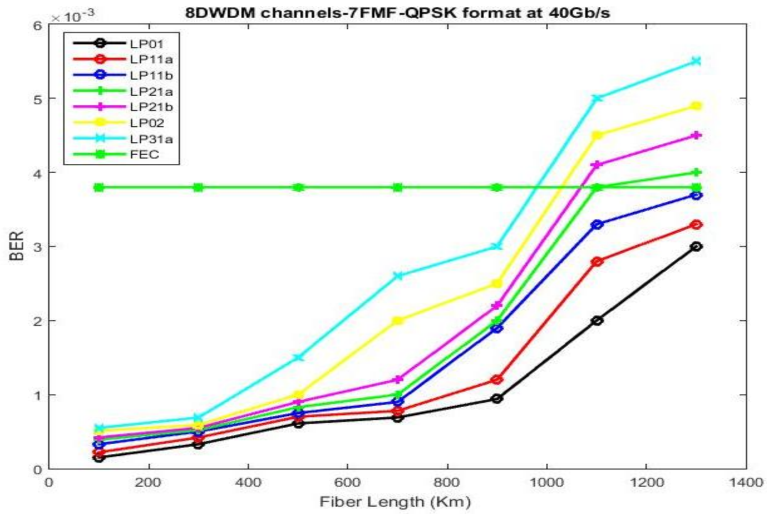


Figure (17): Diagram of LP modes specifying BER versus length for 8 channels-7modes SDM/DWDM/PDM-QPSK system at 40 Gb/s.

Table (11) Ideal Input Power and Maximum reach of 8 channels over 7modes SDM/PDM-QPSK system at 20 and 40Gb/s.

8 channels 7modes SDM/DWDM/PDM-QPSK system		
Bit rate (Gb/s)	Maximum Distance (km)	Ideal Input Power (dBm)
20	1220	-1
40	1080	1

5. Conclusions

In this paper, we successfully designed powerful simulation system for space division multiplexing. The system analyzed and discussed to explain its performance under different bit rates using QPSK modulation format.

We presented 8 DWDM channels over 7 modes FMF system achieving a total bit rate of (4.48 THz).The presence of linear and nonlinear losses limits the acceptable range of input power that produce the required BER for our proposed system from -4dBm to 4dBm.

At 40 Gb/s the existence of the additional 8-WDM channels in the case of QPSK decreased the maximum achievable reach to 1080 Km which is also considered a long haul distance.

Several problems in the design of FMF transmission system including modal dispersion, DGMD, crosstalk and other losses must be compensated. We illustrated different DSP algorithms: TDE MIMO equalization and optimization of DMG in multimode EDFA, CD compensating equalizer for dispersion compensating, CMA algorithms for carrier power and frequency recovery.

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