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Design of high capacity 5.76 Tbits/s SDM-PDM-Nyquist superchannel WDM hybrid multiplexing in 3.1% Germania doped MMF

MD Redowan Mahmud Arnob, Sabiqun Nahar, and Mohammad Nasir Uddin

***Abstract*—To dispatch the goal of walking towards the 4th Industrial Revolution, one of the main key materials that require alterations and enhancements is data communication and transmission. To keep up with the augmented rise in demand for data, fiber optics communication and networks commence a significant role in the transfer of data at high speeds. This article exemplifies the expediency analysis of 5.76 Tbits/s SDM-PDM-Nyquist superchannel WDM hybrid multiplexing technique over a multimodal transmission link up to 10 km using C-band carrier frequencies. This system is designed to carry 48 channels of data that can be produced using 8 C-band carrier frequencies, 2 polarization states, and 3 LP modes through 3.1% Germania doped over pure silica step-index multimode fiber. The system exhibits a satisfactory performance (log BER -9.35, faithful Q-factor 6.09, extinction ratios 7.78, minimum OSNR 46.5 dB) up to a distance of 10 km. Each channel receives a satisfactory amount of power after the dual-stage amplification process in the transmission medium with an ultra-high spectral efficiency of 137% and a high bandwidth-distance product of 385 MHz.km.**

***Index Terms*— Nyquist Superchannel WDM, Space Division Multiplexing, Polarization Division Multiplexing, Forward Error Correction**

I. Introduction

THE data traffic of society has become a matter of fact that to be concerned for this jam-packed radio frequency spectrum prior to the insufficient capacity to reinforce the overcrowding demand of data. The idea of optical fiber communication has become the most conspicuous key to achieving a higher optical spectrum and greater bandwidth. There are several solutions to cope with this ever-increasing demand for data. Optimization of subcomponents, introduction to new modulation techniques, and lastly designing new multiplexing systems will increase the channel capacity of the fiber optics communication system. Introducing new techniques might make the communication system more expensive and hence it will be wiser if the existing systems are modified to saturation level before proposing new techniques [1-4]. The communication architecture in the optical domain allows us to share different category information for both long and short-distance communication. Along with the long-haul communication planning using SEA-ME-WE 6, short-distance communications in data centers, server firms, and research institutes are also required to be swift and efficient [5]. Due to this reason, high-capacity transmission links are designed with the reinforcement of several hybrid multiplexing techniques, different modulation formats, and efficient optoelectronic devices [6]. Some optical fibers are capable of transmitting light in different guided modes, which creates a new generation of multiplexing systems like spatial division multiplexing (SDM). Besides lights might have different polarization states and they do not interfere with each other when they are transmitted through a single cable and this phenomenon gives rise to another new generation multiplexing technique known as polarization division multiplexing (PDM) [7,8].

Some researchers have proposed various hybrid-multiplexing techniques like Islam in [9] designed an OTDM-DWDM hybrid compressed network for long-haul communication and reached a channel capacity of up to 240 Gbits/s. The researcher in [10] designed a hybrid OFDM-WDM-PON covering a distance of 120 km using 4-Ary QAM with a channel capacity of 3.52 Tbits/s. Earlier than that, Pang in [11] also designed MIMO-OFDM gigabit fiber, with polarization division multiplexing on a single mode fiber span reaching a transmission capacity of 1.59 Gbits/s covering 22.8 km. Zhang in [12] also did a similar work where he used PAM modulation technique over SMF and successfully reached 40 km distance with a transmission capacity of 550 Gbits/s. Besides Morant in [13] reached a capacity of 1.2 Gbits/s designing PDM-OFDM hybrid system with NRZ modulation reaching up to 25 km. The hybrid multiplexing techniques are not just incorporated with single or multimode fiber optics, they are also linked with free space optical transmission and inter-satellite communication. Upadhyay in [14] designed an

MD Redowan Mahmud Arnob was with the Department of Electrical & Electronic Engineering, American International University-Bangladesh, 408/1, Kuratoli, Khilkhet, Dhaka 1229, Bangladesh. He is now with the Dept. of Information Display, Kyung Hee University, Seoul 02447, Republic of Korea (e-mail: mdredowanmahmudarnob@gmail.com).
Sabiqun Nahar was with the Department of Electrical & Electronic Engineering, American International University-Bangladesh, 408/1, Kuratoli, Khilkhet, Dhaka 1229, Bangladesh. She is now with the Dept. of Information Display, Kyung Hee University, Seoul 02447, Republic of Korea (e-mail: sabingodhuly@gmail.com).
Mohammad Nasir Uddin is with the Department of Electrical & Electronic Engineering, Faculty of Engineering, American International University-Bangladesh, 408/1, Kuratoli, Khilkhet, Dhaka 1229, Bangladesh (e-mail: drnasir@aiub.edu).

alternate mark inversion (AMI) in 120 Gbps WDM-PDM system with FSO link up to a distance of 8 km. Moreover, Chaudhary in [15] worked on 6×20 Gbps Hybrid WDM-PI inter-satellite communication system covering a long-haul distance of up to 1000 km under the influence of transmitting pointing error. The research goals are not limited to enhancing the channel capacity of a particular communication link only, but also to ensure the stability and superlative performance of the system. A typical WDM/SDM hybrid system might carry hundreds of parallel channels in wavelength, time, and space domains but they do not exhibit equal performances due to different gains from optical amplifiers at each channel, which leads to loss and power variation at each spatial channel. To achieve an error-free performance of the system, the worst channels are required to be quoted and analyzed. By taking adaptive measures for those channels the overall data rate can be maximized which results in high spectral efficiency and bulk transmission rate [16].

In this research, the PDM-SDM-WDM hybrid technique has been introduced with multimode fiber and this simulative analysis was done in the software "Optisystem". In this work, 48 independent channels with 8 different wavelengths are multiplexed with 3 different modes (Fig 1) along with two different angles of polarization. Each channel carried a 120 Gbit/s data rate for 100 GHz channel spacing that exemplifies the Nyquist superchannel and successfully achieved a 5.76 Tbit/s net transmission rate [17, 18].

II. Proposed Architecture

The proposed hybrid technique of optical fiber link interoperating 48-channel (X & Y polarization) of the PDM, 3 modes in spatial division multiplexing and Nyquist superchannel from WDM transmission system. These 48 distinct channels with 120 Gbit/s operating at 100 GHz channel spacing, which is the combination of 8 different wavelengths. This 100 GHz channel spacing ensures the proper utilization of bandwidth. The spectral ranges from 1550 nm to 1555.6 nm and the symbol rate remained at 83*109 symbol/s according to the Nyquist superchannel criteria [19-22]. Fig.2 described the transmission side where each signal splits through dual-polarization angles such X-Polarization and Y-Polarization. These two polarized signals are then divided into 3 different LP modes with a power splitter to maintain constant power. These dual-polarized signals have 3 different modes then combined with a polarization combiner. Polarization beam combiner (PBC) combined those same LP modes with two different polarization signals to minimize dispersion. Fig.3 represents the multimode fiber length and amplification process that is a dual-stage. Fig.4 explains the receiving side. In the transmission side from Fig 2, the data of each channel are converted into electrical signals by a non-return-to-zero (NRZ) modulator. The optical career of a certain frequency and polarization state is split into 3 equal parts by a power splitter which is converted into an optical modulated single by the Mach Zehnder interferometer (MZI). The multimode generator produces 3 linearly polarized modes LP_{01}, LP_{11}, LP_{-11} as shown in Fig 1, The same modes of these 2 different polarized signals are then again merged in the polarization beam combiner (PBC) and these signals are sent into the multiplexer [23,24].

The multiplexer intercorporate all the wavelengths and send them into a multimode fiber link. The whole process has gone through a 2-stage amplification medium over an 8 m length of Erbium-doped multimode fiber (EDMF). On receiving side, the polarization beam splitter detects the polarization state and then splits the corresponding mode before coupling it with a spatial receiver. The PIN photodiode (Dark Current=10 nA, Responsivity=1A/W) converts the optical signal back to electrical, and the Low Pass Bessel filter (LPBF) clips the undesired electrical noises from it producing a total of 6 outputs for each frequency and 48 outputs for the entire system. Hence, this proposed system is capable of transmitting 5.76 Tbits/s (8-frequencies×2-polarization states×3-LP modes×120 Gbits/s) of data.

The laser power is a very important measurement parameter which is can be defined as the energy per pulse in a given pulse duration time. The laser power fluctuations are less significant in Continuous wave (CW) lasers, but it is also important to observe their attenuation pattern over large distances. The equation below shows how the laser power is calculated in several pieces of literature.

$$Laser\ Power(W) = \frac{Energy\ per\ pulse\ (J)}{Pulse\ Width\ (s)};$$

Moreover, the Bit error rate (BER) is one of the most propounded and vital ways to assess the quality of the digital transmission system. This is the ratio of the number of error bits and the total number of bits. The lesser the values of BER, the system reliability or confidence is more. The signal-to-noise ratio, distortion, and jitters are some factors that affect the bit error rate. The acceptable BER range nowadays ranges from 10 E-9 to 10 E-12. The equation below can be used to calculate BER for a given system.

$$BER = \frac{No.of\ error\ bits}{Total\ No.of\ bits};$$

The Spectral Efficiency for a fiber optic system is the maximum amount of data that can be transmitted for given bandwidth with a minimum transmission error. In other words, it is the maximum number of bits of data that can be transmitted over a number of users per second, without compromising the quality of the data. The equation below illustrates how spectral efficiency can be calculated.

$$Spectral\ Efficiency = \frac{Data\ rate\ (bps)}{Channel\ bandwidth\ (Hz)};$$

The bandwidth-distance product (BDP) for a fiber optic link can be expressed as the product of the length of the fiber span and the maximum data rate over the optical fiber link. The following equations were used to compute the following parameters of the SDM-PDM-Nyquist WDM system [25].

$$BDP(MHz.km) = BW(MHz) * Distance\ of\ the\ Tx\ link\ (km);$$

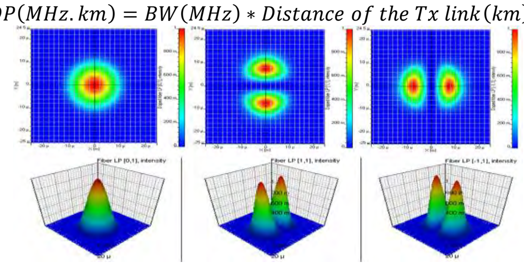

Fig 1: Different LP modes, LP_{01}, LP_{11}, LP_{-11}

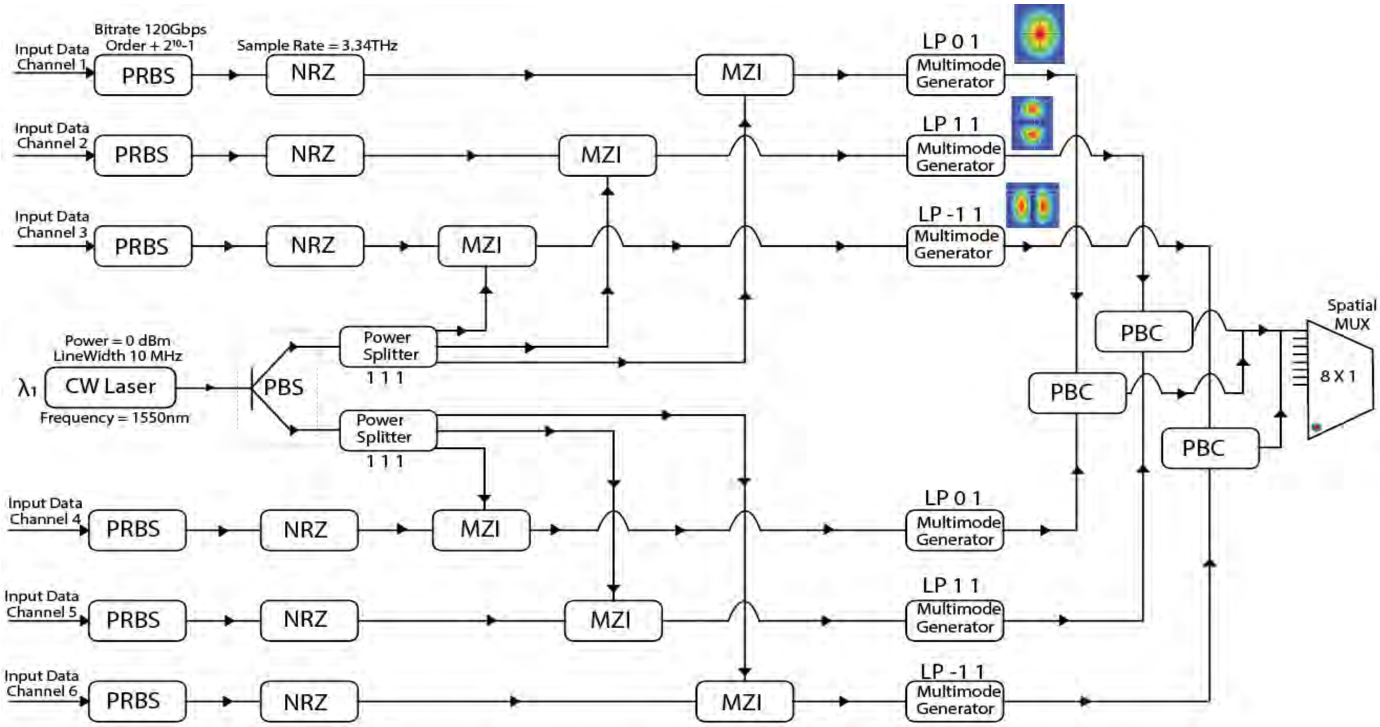

Fig 2 Block diagram for the design of first 6 channel of frequency 1550 nm on the transmission side

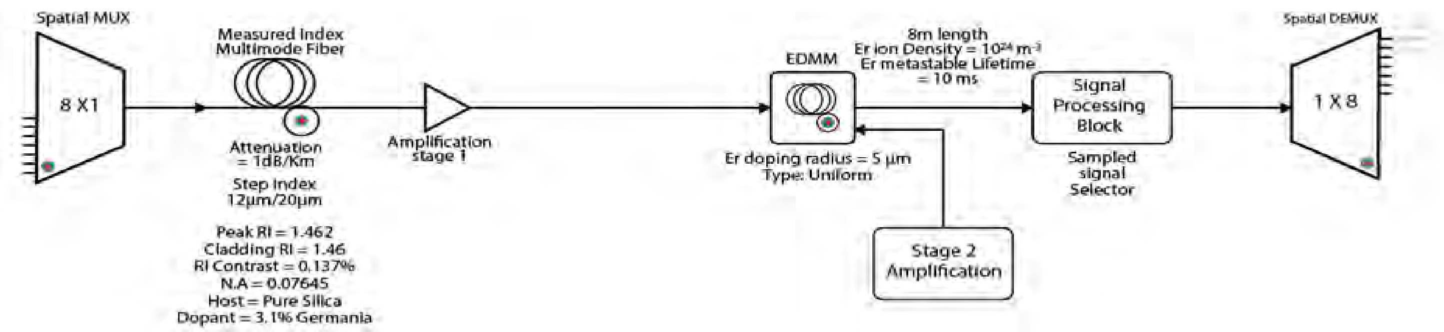

Fig 3 Multimode transmission link, amplification and signal processing units

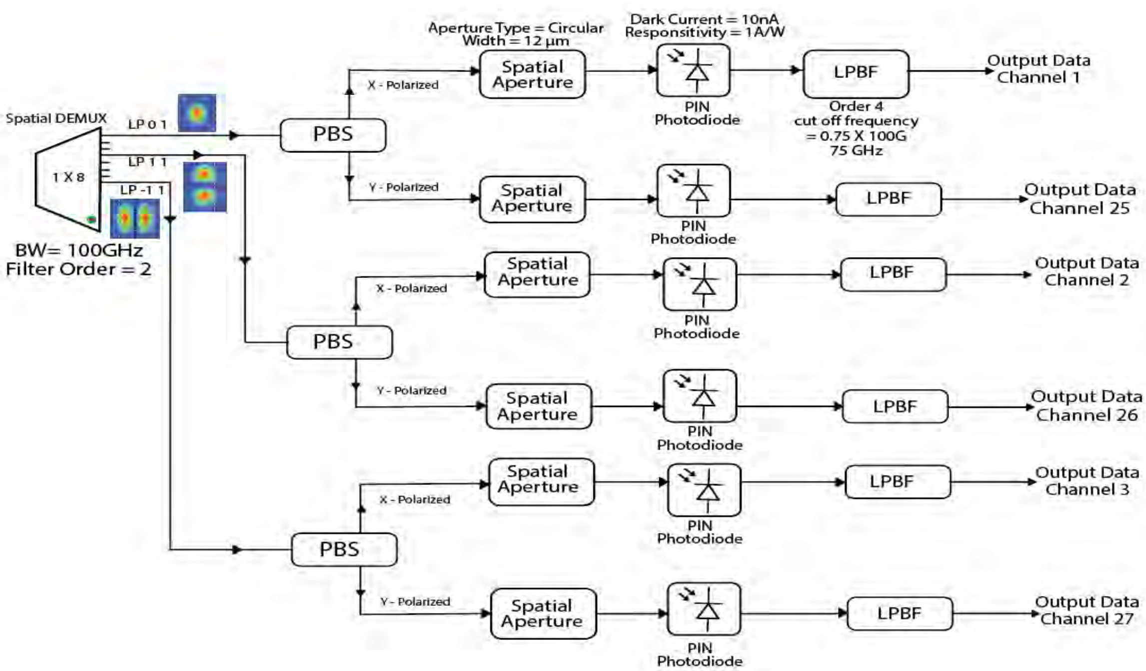

Fig 4 Block diagram for the design of first 6 channel of frequency 1550 nm on the receiving side

III. RESULTS AND ANALYSIS

A. ***RESULTS FROM THE OUTPUTS OF OPTICAL SPECTRUM ANALYZER:*** In order to check the fairness of the signal at distances up to 5-25 km, the outputs from the OSA were observed in Channel#1 which is more likely to get distorted being the side most channels receiving the least amplification gain in the entire spectrum from 1550 to 1555.6 nm. The gain was mainly provided at the median position of the spectrum and hence it can infer that the channels at both far ends will show declined performance, which was the main reason for selecting this channel for analysis. As the distance increases, it can be seen that the optical spectrum for 1550 nm remained sharp and symmetric on the sides of the spectrum. The effectivity of the noise power which increases with distance was found to be negligible since the side mode suppression ratio (SMSR) is relatively much higher even at longer transmission distances. The spectral efficiency, which is the ratio of net throughput (120 Gbits/s) and the channel bandwidth (0.7/8 THz) for this system, was found to be 137%. Fig 5 shows the output from the optical spectrum analyzer for Channel #1(λ=1550 nm) at a distance of 10 km.

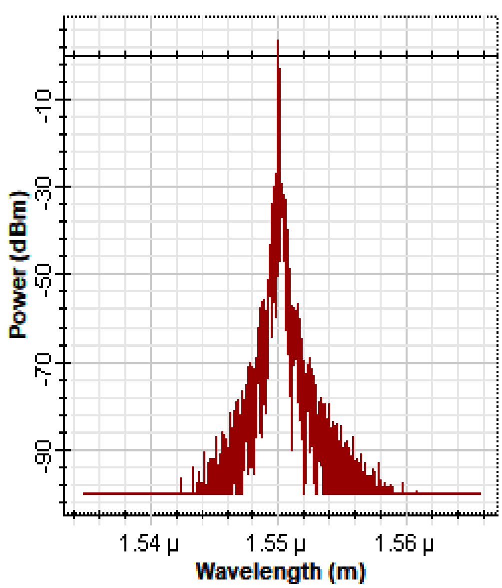

Fig 5 The spectral diagram from the output of OSA for Channel#1 at a transmission distance of 10 km

After the two stages amplification process, the power received at each channel was found for a transmission distance of 5-25 km. There is a smooth declination of power with the distance for all channels. All the X-polarized 24 channels with 3 spatial modes are displayed here, among them $LP_{0,1}$ mode contains maximum power whereas $LP_{-1,1}$ channel show relatively less coupled power which requires individual amplification. Channel 22 ($LP_{0,1}$) at a distance of 5 km shows a maximum power of 8.48 dBm, whereas channel 3 ($LP_{-1,1}$) shows a minimum power of 0.35 dBm at a transmission distance of 25 km.

B. ***VARIATION OF LOG BER, EXTINCTION, AND Q-FACTOR WITH DISTANCE FOR HYBRID SDM-PDM-NYQUIST SUPERCHANNEL WDM:*** Several parameters like BER, Q-Factors, extinction ratio were calculated from the simulated model in order to evaluate the system performance in Nyquist frequencies. The graph in Fig 6 shows how the condition of the minimum value of BER gets downturned with increasing transmission distance. The Log BER vs transmission distance graph was plotted for the channel spacing of both 50 GHz and 100 GHz, adjusting the symbol rate each time to keep it consistent with the channel spacing as per the criteria of Nyquist WDM. It can be observed from Fig 6 that for each value of transmission distance, the system design with 100 GHz channel spacing shows better performance than the one with 50 GHz since they have a lower value of BER.

Figure 7 shows how the extinction ratio decreases with the transmission distance for the channel spacing of 50 GHz and 100 GHz. The supremacy of the performance of a 100 GHz channel spacing system can be seen for all transmission distances. The Q-factor also decreases with the increase of transmission distance, which is shown in fig 8. The system with 100 GHz channel spacing shows a greater value of Q-factor than the one with 50 GHz channel spacing. To check the individual performance of each channel, the Q-factor for each channel was calculated and it can be observed that channel 1 shows the best performance for all the distances below 10 km, whereas channel#15 shows a better performance than any other channel above 10 km.

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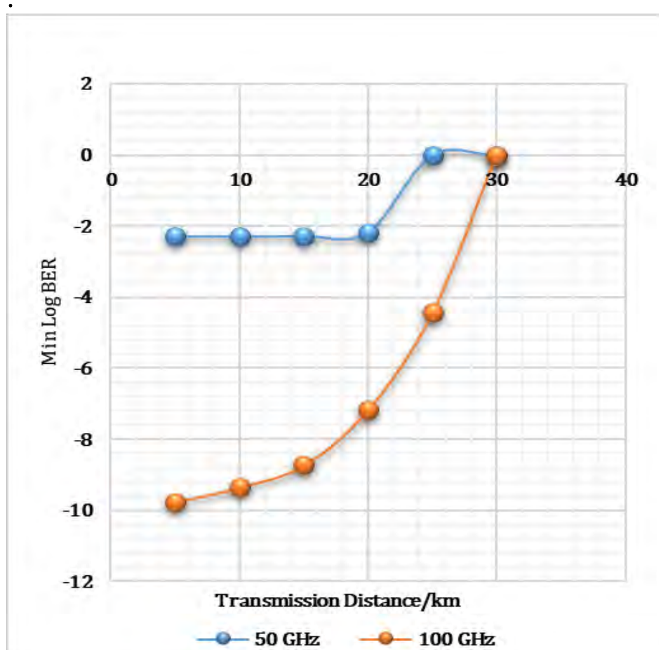

Fig 6 Variation of Min Log BER with Transmission distance for Channel #1 with channel spacing of 50 GHz and 100 GHz

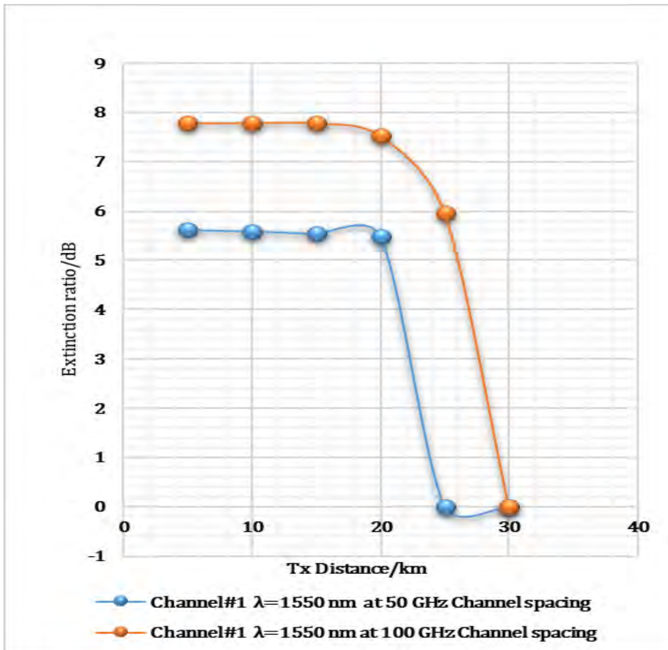

Fig 7 Variation of Extinction Ratio with Tx distance for Channel #1

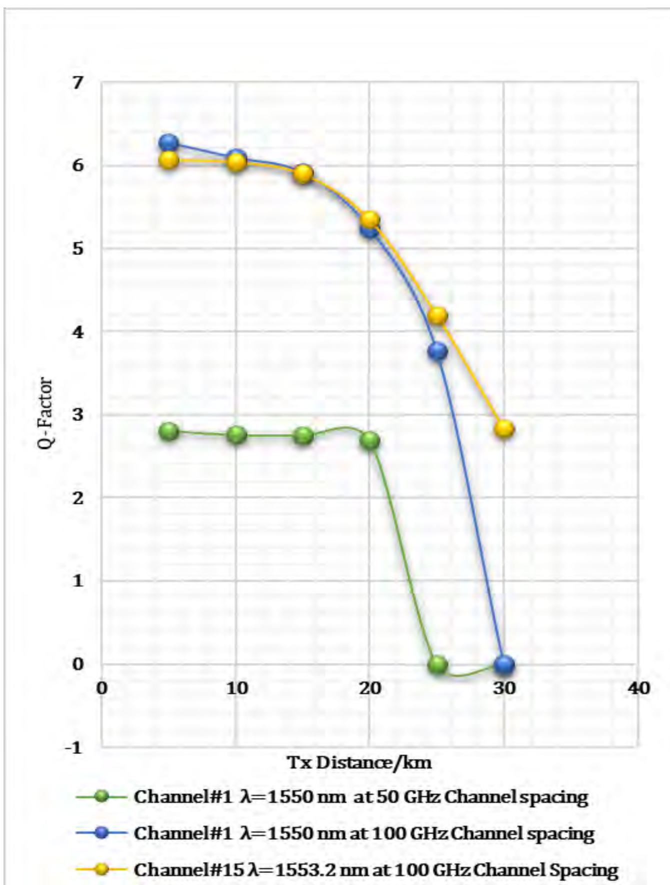

Fig 8 Variation of Q-Factor with Tx distance for Channel #1 and Channel#15

C. ***ANALYSIS FROM ENCIRCLED FLUX ANALYZER AND MULTIMODE FIBER PROPERTIES:*** To analyze the multimode fiber properties and how they provide feasibility to the system, can be evaluated by several types of analysis like Encircled flux properties, differential mode delay analysis, and bandwidth-distance product analysis. Few multimodal parameters such as launch conditions and link losses of the system give better results at distances lower than 15 km for a particular channel. The results from the encircled flux analyzer (Fig 9) satisfy the requirement of the IEC 61280-4-1 standard for this system since the maximum radial intensity appears at the 8µm radius of the MMF where the core radius is 12 µm. That means the maximum radial intensity lies within the core boundary ensuring minimum losses in the core-cladding interfaces.

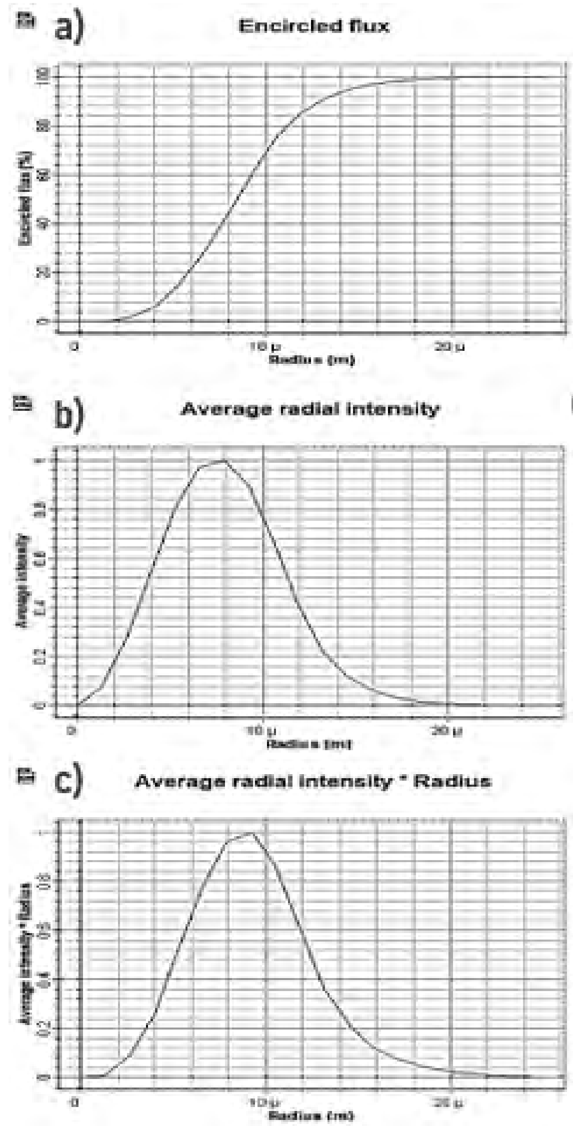

Fig 9 Outputs from encircled flux analyzer of channel 1, a) Encircled flux (%) vs radius, b) Average radial intensity vs radius, c) Average radial intensity-radius product vs radius

Differential mode delay (DMD) is a common problem when a laser source is coupled with multimode fiber. When DMD takes place a single laser source might excite a few modes evenly inside the multimode fiber. These modes might follow

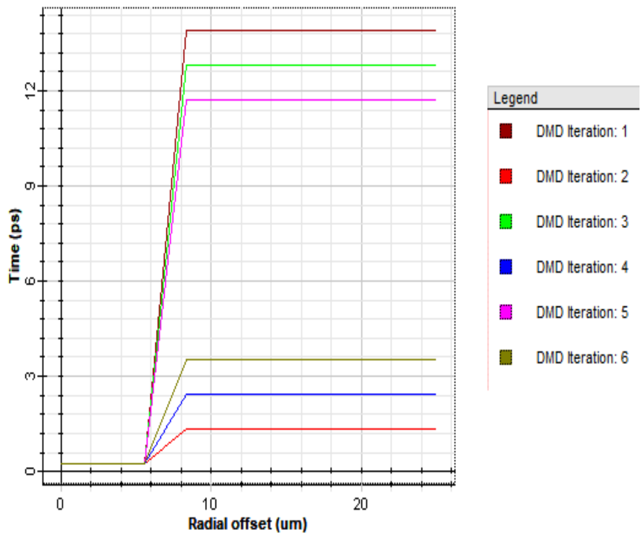

Fig 10 Differential Mode Delay (ps) vs radial offset(µm) for transmission distance of (5-30) km in 5 km intervals

different pathways having different lengths causing transmission dispersion. Due to DMD, a distinct pulse might reproduce into two independent pulses which interfere with each other making it difficult to retrieve the original data. Fig 10 shows the DMD time in ps vs the radial offset of the fiber in µm for a transmission distance of 5-30 km in a 5 km interval. The DMD is relatively lower near the core of the fiber and it increases at a 5.5µm radial distance. It can be observed that for different distances the DMD pattern is different. The DMD has the least impact at the transmission of 10 km.

The bandwidth-distance product (BDP) for this system remained significantly higher near the core and their performance degraded with the increase in radial distances. The modes near the core are less likely to interfere with each other producing a distinct pattern. Away from the core, the different pathways of lights are difficult to separate hence decreasing the bandwidth. The system performs best at a 10 km transmission distance and the performance falls as it increases. Figure 11 shows the Bandwidth-distance product vs the radial offset for different transmission distances from 5 to 30 km. All these things can be consolidated to check the suitability of the fiber design.

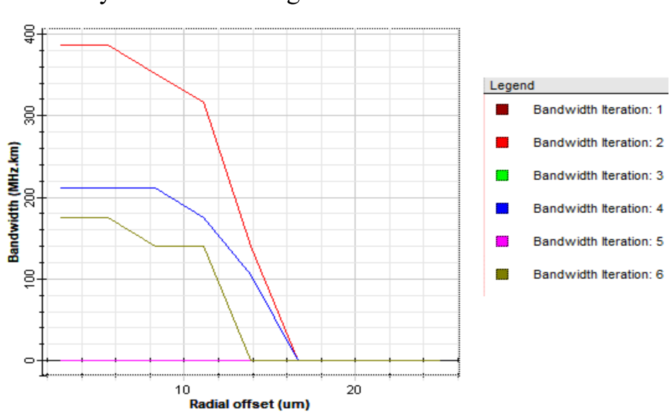

Fig 11 Bandwidth-Distance (MHz.km) product vs radial offset(µm)

D. *OPTICAL SIGNAL-TO-NOISE RATIO AND FORWARD ERROR CORRECTION (FEC):*

The OSNR variation for channel 1(highest OSNR) and Channel 43 (lowest OSNR) are illustrated in Fig 12 showing the most superior and inferior performances respectively. The increase in transmission distance leads to a decrease in OSNR. Moreover, the deviation in both channels' OSNR rises with the transmission distance which discriminates the quality of outputs for each channel at larger transmission distances.

Figure 13 displays the relationship between the minimum Log BER and OSNR of the system. According to the IEEE standard the forward error correction (FEC) limit corresponding to Min Log BER -3, the minimum OSNR was found at 58 dB and 27.8 dB for channels 1 and 43 respectively. Using this information and the information in fig 12, the maximum transmission distance for this system was found to be 27 km and 30 km for channel 1 and channel 43 respectively.

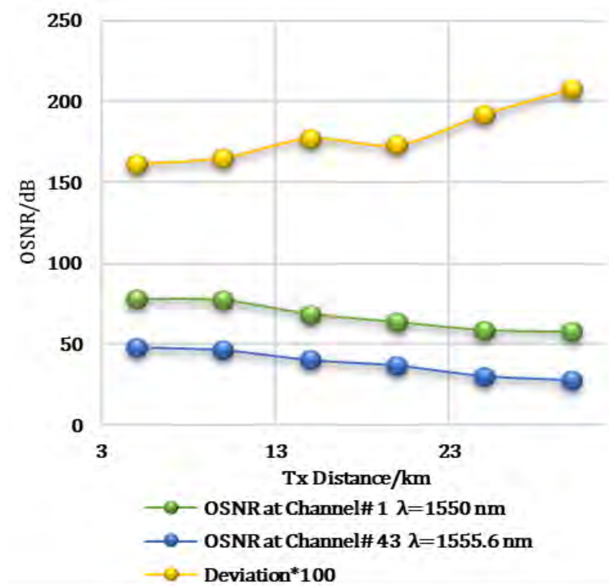

Fig 12 Variation of OSNR with Tx distance for Channel 1, and Channel 43

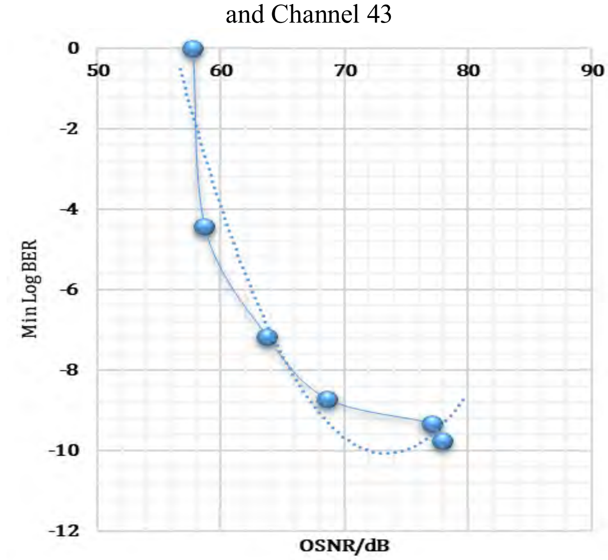

Fig 13 Relation between Min Log BER and OSNR for observing FEC limit

The condition of the eye diagram of channel 1 deteriorates with the increase in transmission distance from 5 to 30 km is presented in figure 14. There is a distinct eye-opening and the eye height appears to be clear up to 20 km and the eye-opening diminishes after that. Factors like Min BER, Extinction ratio, Q-factor, FEC limit, and Min OSNR are taken into consideration to conclude that, 10 km will be the optimal distance for this particular system.

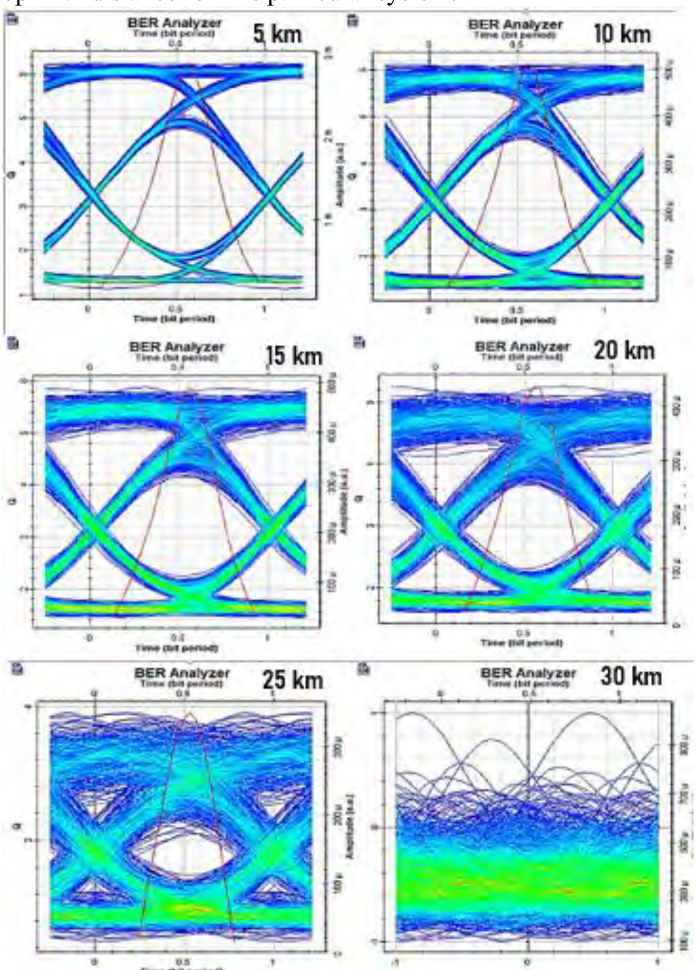

Fig 14 Eye diagram for 6 transmission distances, i.e. (5-30) km

IV. Conclusion

This research represents the feasibility analysis of high-speed 5.76 Tbits/s SDM-PDM-Nyquist superchannel WDM hybrid multiplexed system over a 3.1% Germania doped over pure silica 12µm/20µm step-index multimode fiber carrying 48 independent channels of bitstreams of data over a transmission distance up to 10 km. The channel spacings were kept at 100 GHz keeping it 1.2 times the symbol rate of the system according to the Nyquist superchannel WDM criterion, which ensures proper utilization of bandwidth and prevents intersymbol interferences between the adjacent channels. These 48 channels are deployed over the C-band spectral range of 5.6 nm (1550 nm to 1555.6 nm), with 2 different polarization angles (0° or 90°) and 3 linearly polarized modes ($LP_{0,1}$ or $LP_{1,1}$ or $LP_{-1,1}$) with an overall spectral efficiency of 137% and the Bandwidth-distance product of 385 MHz-Km. The minimum Log BER, Q-factors, and extinction ratios observed at a 10 km distance were satisfactory, with a clear eye-opening at each channel. The differential mode dispersion after doping 3.1% Germania remained adequately minimum in the core and a maximum radial intensity appeared at the 8µm radius of the MMF, which is assembled within the core of MMF (core radius 12µm). The minimum OSNR for the system was found at 46.5 dB which is far greater than the threshold OSNR of 27.8 dB obtained from the FEC limit analysis.

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MD Redowan Mahmud Arnob received his B.Sc. and M.Sc. degrees in Electrical and Electronic Engineering from American International University-Bangladesh in 2020 and 2022 respectively. He majored in photonics communications during his master's program and studied different hybrid multiplexing techniques like SDM-PDM-WDM. Currently, he is a Graduate Research Assistant at Advanced Display Research Center (ADRC), Kyung Hee University and he is undertaking his post-graduation program in Dept. of Information Display. He received "Thesis Submission Scholarship" and "Ministry of Education" scholarship from the government of the Republic of Korea. His interested areas of research are oxide thin-film transistors, flexible AMOLED displays, semiconductor device physics, and perovskite materials. He can be contacted at email: mdredowanmahmudarnob@gmail.com and on LinkedIn: linkedin.com/in/redowan-arnob-75498a18b.

Sabiqun Nahar received B.Sc. and M.Sc. degrees in Electrical and Electronic Engineering from American International University-Bangladesh in 2020 and 2022 respectively. She completed her Bachelor's degree with a major in Renewable energy and received the academic award Cum Laude and also achieved Dean's award for best poster presentation in the course of the capstone project and thesis program in her Bachelor's degree. She is currently undertaking her post-graduation program in "Information display", at Kyung Hee university. She was granted with thesis submission scholarship and ministry of education scholarship from the government of the Republic of Korea. Besides she is working as a graduate research assistant at Advanced Display Research Center (ADRC), Kyung Hee University studying LTPS thin-film transistors for AMOLED flexible displays. Her research interest includes Thin-film transistor engineering, Flexible LTPS TFT, TCAD simulation, and Semi-Conductor Device Physics. She can be contacted at email: sabingodhuly@gmail.com and on LinkedIn: linkedin.com/in/sabiqun-nahar-godhuly-b9373919a.

Mohammad Nasir Uddin received a B.Sc. degree in Electrical and Electronic Engineering from Khulna University of Engineering and Technology, KUET in 2003 and an M.Sc. Engineering in Computer Networks from Middlesex University, United Kingdom (UK) in 2006 and a Ph.D. degree from Kyushu University, Japan in 2015. Currently, he is the head of the graduate program in the EEE department at American International University-Bangladesh. He received Monbukagakusho scholarship from Japan Govt. to peruse his Ph.D. at Kyushu University, Opto-electronics (Hamamoto) Laboratory, Japan. He has received numerous awards including Merit Award during his M.Sc. at Middlesex University, UK, the 2013 IEEE Excellent student award from Japan, Deans Plaque for his outstanding research during his Ph.D. His current research interest includes Active MMI Laser Diode, High-Speed Optical Communication, Wireless Communication, and Optical Sensor network. Dr. Uddin is a member of the Institute of Electrical and Electronics Engineers (IEEE), a member of the Institute of Electronics, Information, and Communication Engineers (IEICE), Japan, and LIFE FELLOW of the Institute of Engineers, Bangladesh (IEB). He can be contacted at email: drnasir@aiub.edu and on LinkedIn: linkedin.com/in/nipu98325.