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## 40 Gbps NRZ/RZ Data Transmission over 100 km SMF and 100 m FSO in Four Channel WDM-PON System

Rajesh Dey<sup>1</sup>, Binoy Das<sup>2</sup> and Ardhendu Sekhar Patra<sup>3,\*</sup>

<sup>1</sup>Dept. of Physics, Chunaram Gobinda Memorial Government College, Purulia, West Bengal, India

<sup>2</sup>Dept. of Physics, J. K. College, Purulia, West Bengal India

<sup>3</sup>Dept. of Physics, Sidho-Kanho-Birsha University, Purulia, West Bengal, India

\*Corresponding Author. E-mail address: ardhendu4u@yahoo.com

Received: 16.10.2025; Accepted: 12.12.2025; Published online: 31.12.2025

DOI: <https://doi.org/10.54280/jse.255109>

**Abstract:** We have proposed and demonstrated a four channel WDM-PON architecture to transmit 40 Gbps RZ/NRZ data over 100 km SMF and 100 m FSO. Fiber-FSO link with FBG as a dispersion compensation module is investigated. Outstanding eye diagrams and impressive BER value  $\sim 10^{-30}$  is observed for RZ format with 0.5 duty cycle. FSO attenuation was 0 to 50 dB/km. Our proposed system is suitable to transmit high data rates over long-haul transmission system.

**Key words:** WDM-PON; NRZ; RZ; SMF; FBG; FSO.

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### 1 Introduction

According to a recent report (DD News, 22 March 2025), the average monthly data consumption per user in India reached 27.5 GB in 2024 with compound annual growth rate (CAGR) 19.5% over the past five years. The rapid expansion of the 5G device ecosystem is a major contributor to this growth. Meeting this mounting demand necessitates the provision of large bandwidth and high data rates. Optical fibre (transmission bandwidth approx. 1260 to 1675 nm, G. Keiser pp 378) [1] enabled communication system combined with wavelength division multiplexing (WDM) technique is a promising solution to address this demand [2-5]. A simple point-to-point link utilizing a single optical source wavelength does not fully exploit the large bandwidth capacity of optical fiber. In contrast, the WDM technique permits the simultaneous transmission of multiple information-carrying wavelengths onto the same fiber,

thereby utilizing efficiently the full spectral capacity of the fiber. WDM supports simultaneous and independent transmission of different data rates across multiple channels in various formats, making it suitable for long-haul undersea links, terrestrial backbones, metropolitan networks, and fiber-to-the-premises (FTTP) systems as well as cable TV distribution, military and aerospace communication, smart grid infrastructure, and high-frequency trading networks [6-8]. Linear dispersion in optical fiber is a primary limitation in distortion-less optical transmission. Dispersion causes temporal broadening of signal pulses, which results in inter-symbol interference (ISI), an increase in bit error rate (BER), and a reduction in eye opening [9-11]. Fiber Bragg Grating (FBG) is a widely adopted solution to mitigate the dispersion effect and hence to improve the system performance [12-14]. FBG provides dispersion compensation by inducing an opposite dispersion effect, thereby reducing pulse spreading within the fiber. In

recent years, wireless communication has revolutionized modern standards of living. Its unprecedented mobility, flexibility, and accessibility have made it possible to overcome both geographical and socioeconomic barriers. Radio frequency (RF) technology is well established in wireless communication systems; however, the requirement for spectrum licensing and inherent bandwidth limitations pose significant challenges to its deployment [15]. In contrast, free-space optical (FSO) communication is license-free and offers high bandwidth, enhanced security, and strong immunity to electromagnetic interference, making it a promising alternative for wireless communication [16-17]. But, the performance of FSO systems is highly vulnerable to environmental conditions along the propagation path.

In this paper, a hybrid optical fiber-FSO system comprising 100 km of single-mode fiber (SMF) and a 100 m FSO link is theoretically investigated using OPTISYS-TEM 14. The proposed system success-

fully transmits four WDM channels carrying an aggregate data rate of 40 Gbps. In the receiving section FBG is employed as dispersion compensation module (DCM) and performance of the system is investigated for both NRZ and RZ formats. For the RZ format, duty cycles of 0.25, 0.5, and 0.75 of the time slots are considered. This SMF-FSO-WDM-PON system with FBG as a dispersion compensation module improves the signal integrity over long distances. The system performance is analyzed in severe real world atmospheric conditions for 0 to 50 dB/km FSO attenuation and achieved BER  $10^{-30}$  with clean eye diagram using RZ format with 0.5 duty cycle. This study has been able to show the feasibility of a long-haul, high capacity, low-cost access network, combining the strengths of optical fiber and FSO channels along with effective dispersion management.

## 2 Simulation Set-up

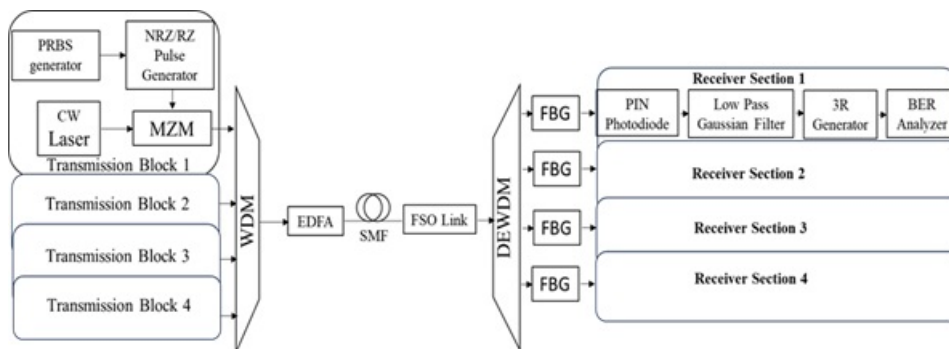


Figure 1: Block diagram of the proposed 4 channel fiber-FSO communication system.

Figure 1 shows the proposed hybrid fiber-FSO optical communication system. In the transmission part four channels, transmission block 1 to transmission block 4 are multiplexed using  $4 \times 1$  WDM system. Each block consists of one pseudo random bit sequence (PRBS) generator, one RZ pulse generator, one continuous wave (CW) laser source and one Mach-Zehnder modulator (MZM). CW laser of these four blocks 1 to 4 emits 193.1 THz, 193.2

THz, 193.3 THz and 193.4 THz respectively. In each block the carrier wave is modulated at MZM by 10 Gbps data rates which is generated by PRBS generator and NRZ/RZ pulse generator. The modulated optical signal is amplified by Erbium doped fiber amplifier (EDFA) of 5m length. After amplification the modulated signal is launched into the fiber backbone and transmitted over 100 km of SMF followed by a 100 m FSO link. The

SMF exhibits a chromatic dispersion of 16.75 ps/nm/km and an attenuation of 0.2 dB/km. A  $1 \times 4$  DEMUX system is used to separate the four channels.

At the receiver end, each channel is passed through an ideal FBG serving as a DCM to counteract the effects of chromatic dispersion. The DCM employed has a bandwidth of 100 GHz and provides a dispersion of  $-1000$  ps/nm. The compensated optical

signal is then detected by a photodetector (PD), where it is converted into an electrical signal using a PIN photodiode. The electrical signal is further filtered by low pass gaussian filter and analyzed by BER analyzer to detect the transmission performance. Figure 2 shows the layout of our proposed system in the Optisystem software.

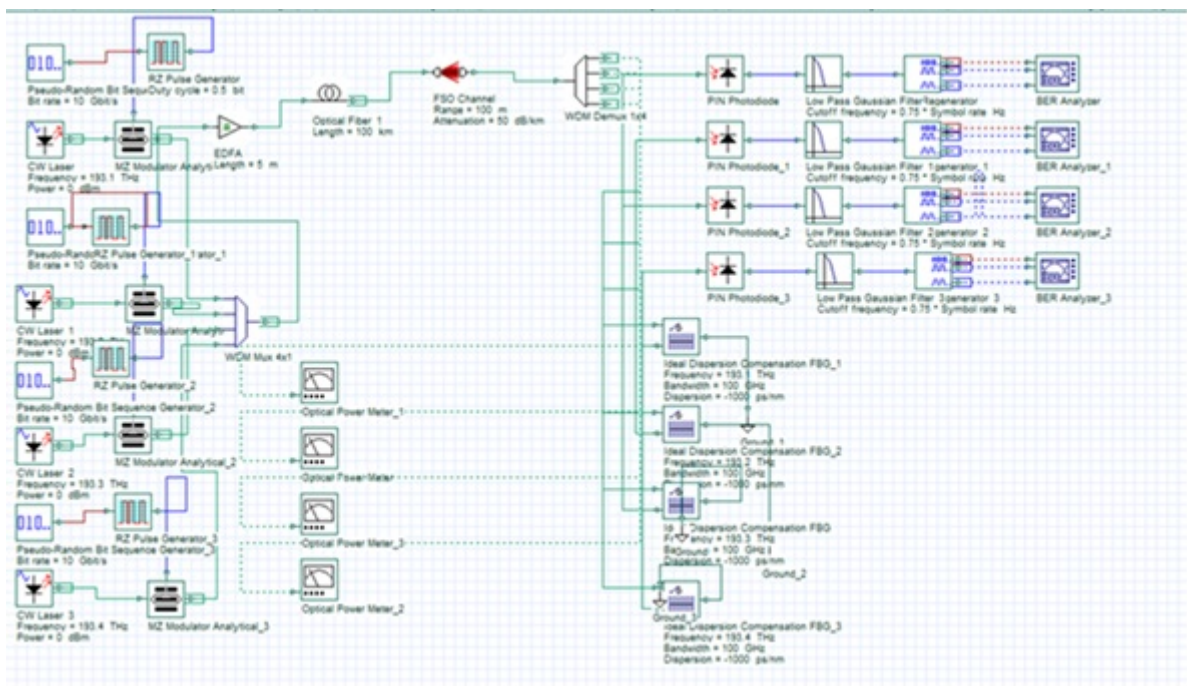


Figure 2: Layout of our proposed system in optisystem 14.

### 3 Result and Discussion

In this configuration four different CW light wave is modulated by 40 Gbps ( $4 \times 10$  Gbps) data and multiplexed to transmit through a SMF.

Figure 3 illustrates the electrical baseband signal of different duty cycles, 0.25, 0.50, 0.75 and 1.0 (NRZ) of the time slots in timescale. The variation in duty cycle directly affects pulse width and temporal separation between symbols. Shorter duty cycles offer better tolerance to disper-

sion and ISI by providing narrower pulses, whereas larger duty cycles improve spectral efficiency but may increase vulnerability to dispersion. The modulated signals are transmitted through 100 km SMF followed by 100 m FSO link. Figure 4(a) to 4(d) have shown the eye diagram for different duty cycles.

The clear eye openings validate that the proposed architecture is suitable for the simultaneous transmission of four channels in long-haul communication.

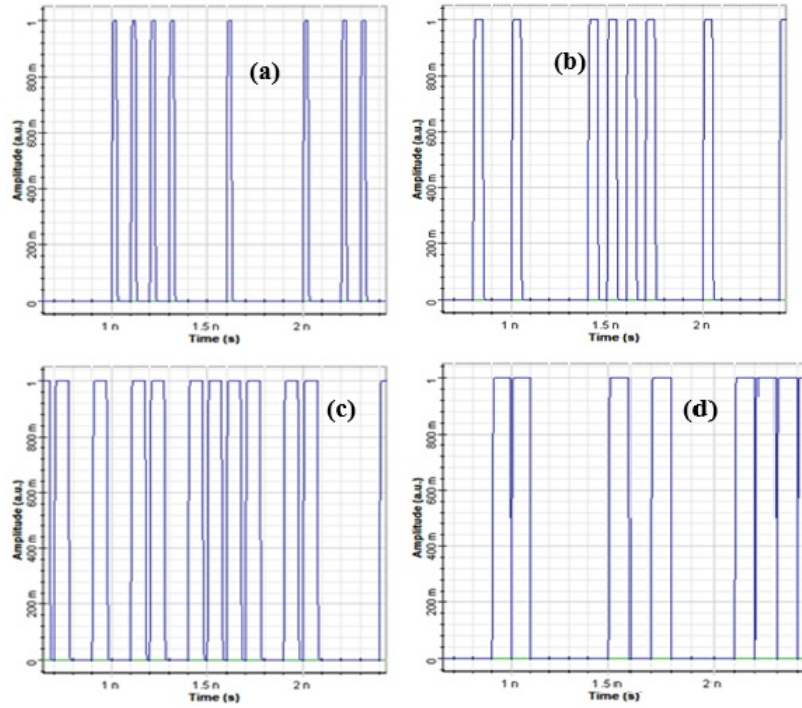


Figure 3: Electrical Oscillator view of the electrical signal of duty cycles (a) 0.25 (b) 0.5 (c) 0.75 (d) 1.00.

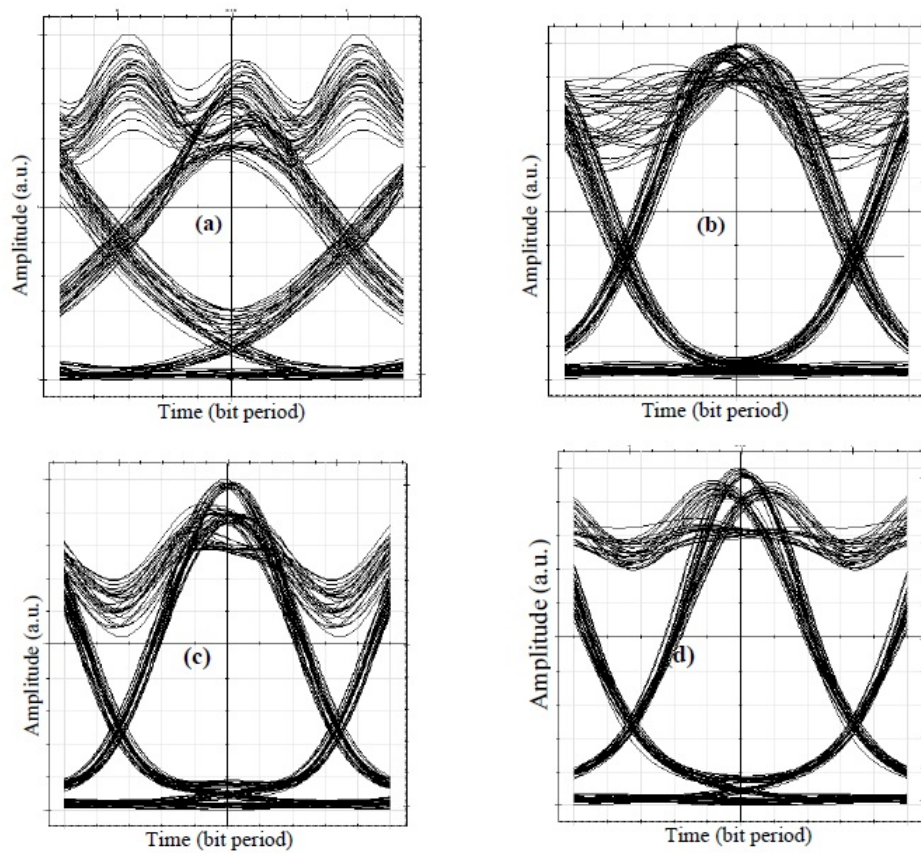


Figure 4: Eye diagram after 100 km SMF and 100 m FSO for the duty cycles (a) 0.25, (b) 0.5, (c) 0.75 and (d) 1.0.

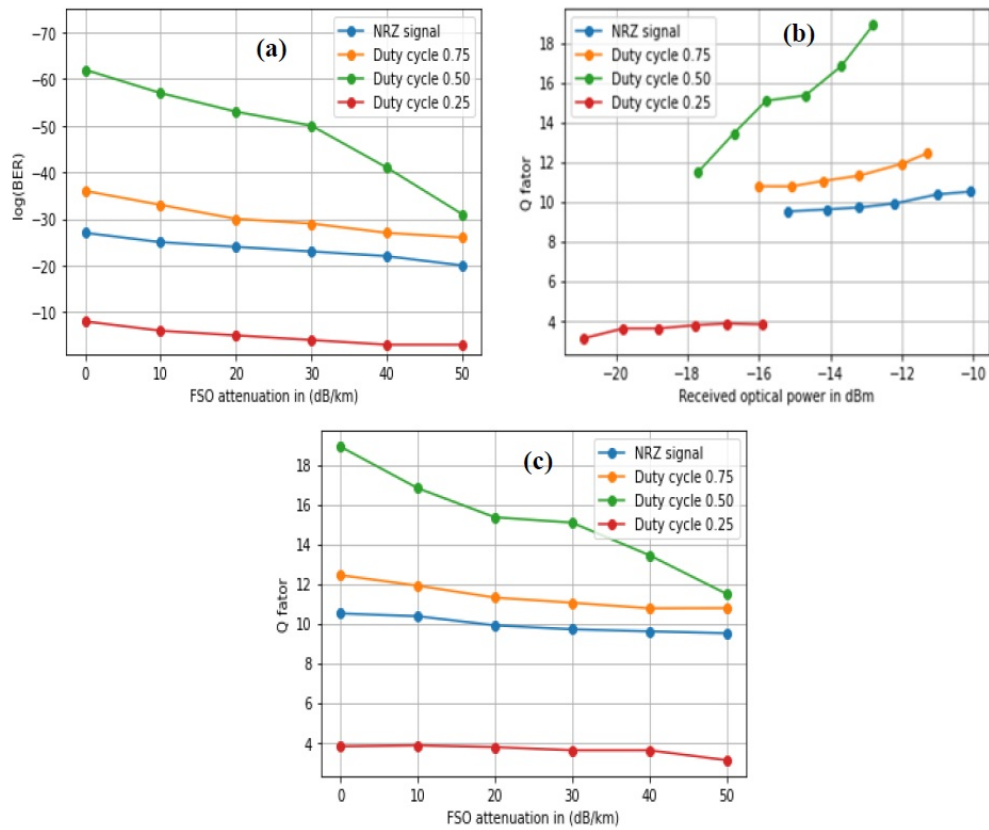


Figure 5: (a) BER values for different FSO attenuation, (b) Q factor vs Received optical power, (c) Q factor for different FSO attenuation.

FSO is highly dependent on weather condition. Bad weather conditions like haze weather, heavy rain, fog etc degrades the performance of FSO as high attenuation of data transmission takes place. Figure 5(b) shows the variation of Q-factor with respect to the received optical power in dBm. It is observed that the RZ format with a 0.5 duty cycle achieves the highest Q-factor

compared to other coding formats. Furthermore, Figures 5(a) and 5(c) reveal that the 0.5 duty cycle RZ format consistently better performance than other formats under FSO attenuation levels ranging from 0 dB/km to 50 dB/km. At 50 dB/km attenuation low BER value shows the feasibility of our proposed architecture. The system parameters are tabulated in the table 1.

Table 1: The specifications of the system parameters

| System parameters |                               | Values                      |
|-------------------|-------------------------------|-----------------------------|
| PRBS generator    | Bit Rate                      | 10 Gbps                     |
|                   | Order                         | 7                           |
| CW Laser          | Frequency                     | 193.1 Hz to 193.4 Hz        |
|                   | Power                         | 0 dBm                       |
|                   | Linewidth                     | 1MHz                        |
|                   | Extinction ratio              | 60 dB                       |
| MZM               | Length                        | 5 m                         |
| EDFA              | Core radius-                  | 2.2 $\mu\text{m}$           |
|                   | Er Doping radius              | 2.2 $\mu\text{m}$           |
|                   | Er metastable lifetime        | 10 ms                       |
|                   | Numerical aperture            | 0.24                        |
| Optical Fiber     | Reference WL                  | 1552.52 nm                  |
|                   | Attenuation                   | 0.2 dB/km                   |
|                   | Dispersion                    | 16.75 ps/nm/km              |
|                   | Dispersion slope              | 0.075 ps/nm <sup>2</sup> /K |
|                   | Differential group delay      | 0.2 ps/km                   |
| FSO               | Transmitter aperture diameter | 5 cm                        |
|                   | Beam divergence               | 2 mrad                      |
|                   | Receiver aperture diameter    | 20 cm                       |
| PIN diode         | Dark current                  | 10 nA                       |
| FBG               | Dispersion                    | -1000 ps/nm                 |
|                   | Bandwidth                     | 100 GHz                     |

Table 2: Comparing our findings with previous studies

| Recent Work (Ref.)                         | Ref. 18               | Ref. 19                | Ref. 20                  | Ref 21               | Proposed Work       |
|--|-----------------------|------------------------|--------------------------|----------------------|---------------------|
| 1. Data rate                               | 10 Gb/s               | 10 Gb/s                | 12.5 Gb/s                | 20 Gb/s              | 40 Gb/s             |
| 2. Q-Factor                                | 8.964                 | 7.22                   | 6.712                    | 18.46                | 19                  |
| 3. Modulation formats                      | NRZ, DB and MDB       | OQPSK/DPSK             | PAM-4                    | NRZ                  | RZ/NRZ              |
| 4. Minimum BER $\leq 10^{-9}$              | $1.3 \times 10^{-19}$ | $5.59 \times 10^{-13}$ | $9.5321 \times 10^{-12}$ | $59 \times 10^{-57}$ | BER $\leq 10^{-30}$ |
| 5. Dispersion compensation techniques used | FBGs (4 cascaded)     | CFBG                   | FBG                      | CFBG                 | FBG                 |

## 4 Conclusion

A 40 Gbps fiber-FSO hybrid system employing WDM has been proposed and theoretically investigated to efficiently utilize the spectral bandwidth of optical fiber. The architecture demonstrates the capability of simultaneously transmitting four channels at 10 Gbps each over 100 km of SMF and a 100 m FSO link. At the transmission point RZ format with 0.5 duty cycle shows excellent performance than other formats. Even under severe FSO attenua-

tion of 50 dB/km, the system achieves a very low BER,  $\sim 10^{-30}$  and high Q factor for 0.5 duty cycle, confirming its practicality in adverse weather conditions. Impressive eye diagram, low BER value and high Q factor establish its suitability for long-haul communication system.

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