A Simple and Cost-effective Design for Simultaneous Transmission of Point-to-point and Broadcast Services in WDM-PON

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Abstract

A simple and cost-effective design of centralized light source wavelength division multiplexing passive optical network (WDM-PON) is proposed, which supports simultaneous transmission of point-to-point data and broadcast services. 10 Gbit/s differential quadrature phase shift keying (DQPSK) downstream data and superimposed 2.5 Gbit/s inverse return-to-zero (IRZ) broadcast service are simultaneously transmitted from optical line terminal (OLT) in downstream channels without pulse carving, whereas a 2.5 Gbit/s on-off keying (OOK) data signal is used for upstream signal using re-modulation of downstream signal power, no additional laser is used at optical network unit (ONU). Simulation results show that downstream transmissions of 10 DQPSK point-to-point channels with IRZ broadcast service and upstream transmission of 10 OOK channels, using 100 GHz channel spacing and high extinction ratio (ER), can be successfully achieved over a distance of 20 km with low transmission power penalties and improved receiver sensitivity. It is also evident from results that proposed simple technique has good tolerance against transmission nonlinearities and can be implemented as a cost-effective solution in future WDM-PON networks.

Keywords: *WDM-PON, DQPSK, IRZ, OOK, centralized light source, extinction ratio (ER), broadcast service*

1. Introduction

According to Cisco forecast project, during the years of 2011 to 2016, it is estimated that explosive growth of global internet traffic will reach up to peta (10^{15}) bytes per minute including video content of millions (10^{6}) of minutes per second [1]. This is the key driving force that shifted the technology trends towards the deployment of high capacity next generation access (NGA), to cope with future broadband applications and bandwidth demands. At present, it is expected that nearly 50% of broadband customers and 80% to 90% of local loop customers can shift on NGA [2]. Passive optical networks (PONs) are considered as the most promising candidates for next-generation access (NGA) systems due to low cost, simple operation & maintenance (O&M) and high bandwidth provision. To provide broadband access services, various standards of time division multiplexed PONs (TDM-PONs) have been introduced such as ITU G.983 for ATM PON (APON) and Broadband PON (BPON), ITU G.984 for Gigabit PON (GPON), IEEE 802.3ah and IEEE 802.3av for Ethernet PON (EPON) as an its upgrade version 10GEPON. As compared to TDM-PON, wavelength division multiplexing passive optical networks (WDM-PONs) are recognized as a best solution to meet the high bandwidth demands in access network with security and scalability [3]. The WDM-PON architecture based on optical line terminal

(OLT) at central office (CO) having several independent wavelength channels, which are connected with number of optical network units (ONUs) in a point-to-point configuration. Moreover, each ONU can access not only full bit rate of a channel but also different bit rates of same channels as per requirement. Further, no severe problem power-splitting losses, inherently transparent to the channel bit rate and multiple wavelengths over the same fiber provide scalability in the network [4]. Despite of these advantages, the high cost of ONU due to the wavelength-specific architecture was a challenge, which requires separate optical sources for every wavelength at ONU, consequently network cost is increased. Therefore various colorless *(i.e.*, wavelength-unspecific) ONU based WDM-PON techniques have been proposed, which reduces the system costs [5]. In this regard modern electronic devices based ONU techniques, such as Fabry-Perot laser diode (FP-LDs) in [6], semiconductor optical amplifier (SOA) in [7], Reflective semiconductor optical amplifier (RSOA) in [8], have been reported to avoid wavelength-specific ONUs design. However, performances of these techniques are mitigated due to the limitations of novel devices, low extinction ratio or low receiver sensitivities. Besides of these schemes another approach has been introduced using re-modulation of downstream signal at ONU to generate upstream without additional laser source and complex circuitry in [9]. This technique not only reduces system cost but also decreases management complexity of operation, administration and maintenance. Therefore, we have also implemented a simple and efficient centralized laser source based re-modulation techniques to achieve colorless ONU architecture for cost-effective design. In which downstream signal power is used as a carrier for re-modulation of intensity modulated upstream at ONU.

For further efficient bandwidth utilization in proposed WDM-PON, point-to-point downstream data as well as broadcast data/video service can be transmitted simultaneously at OLT over downstream channel. In this regard various techniques have been reported such as subcarrier multiplexing (SCM) in [10-13], selective-broadcast schemes in [12-15], Fabry-Perot laser diode (FP-LDs) as a broadband source in [16, 17], wavelength re-use with Red/Blue (R/B) filter based technique in [18] and time interleaved phase re-modulation approach in [19] for broadcast service transmission. However, SCM based scheme can be influenced by dispersion induced penalty, inter RF channel crosstalk and at least 3 dB loss in optical power budget also it requires broadband linear transmitter and receiver [20]. Further, in the selective-broadcast techniques, receiver sensitivity is remained poor, even though system is amplified by EDFA. When FP-LD broadband source is used limitation of data rate can be observed. Also, complex wavelength re-uses architecture and separate fiber for broadcast data is not a cost-effective solution. Similarly time interleaved approach has more power penalties and low receiver sensitivity. Hence, above cited schemes reduce their effectiveness due to various limitations such as design complexity, additional equipments, low extinction ratio, poor receiver sensitivity, data rate limitation, transmission losses and power penalties. Therefore, in order to provide simultaneous broadcast service in WDM-PON networks, the most critical issues are to reduce the system cost, increase transmission capacity, and improve system reliability.

In this paper we proposed and demonstrated simple and cost-effective design of centralized light source WDM-PON, which supports simultaneous transmission of point-to-point data and broadcast data/video services. A DQPSK signal of 10 Gbit/s data rate is used as downstream and a 2.5 Gbit/s IRZ signal is superimposed on it as a broadcast service at OLT and transmitted over the downstream channel without pulse carving and EDFA amplification. At ONU a 2.5 Gbit/s OOK data signal is used as a upstream signal after re-modulation of downstream signal power as a carrier, therefore no additional laser is required at ONU. Simulation results verify that 10 DQPSK downstream channels with IRZ broadcast service and 10 OOK upstream channels, using ITU-T grid 100 GHz channel spacing at high extinction ratio (ER), can be error-freely transmitted over a distance of 20 km with lower transmission power penalty and improved receiver sensitivity. In this paper, first part is introduction, second part explains working principles, third part describes simulation setup, fourth part covers performance analysis of transmission, and finally conclusion in the end.

2. Working Principle of Broadcasting in Proposed WDM-PON

Working principle of proposed simultaneous transmission of point-to-point and broadcast service in WDM-PON is shown in Figure.1 and it will be discussed in detail in subsections.

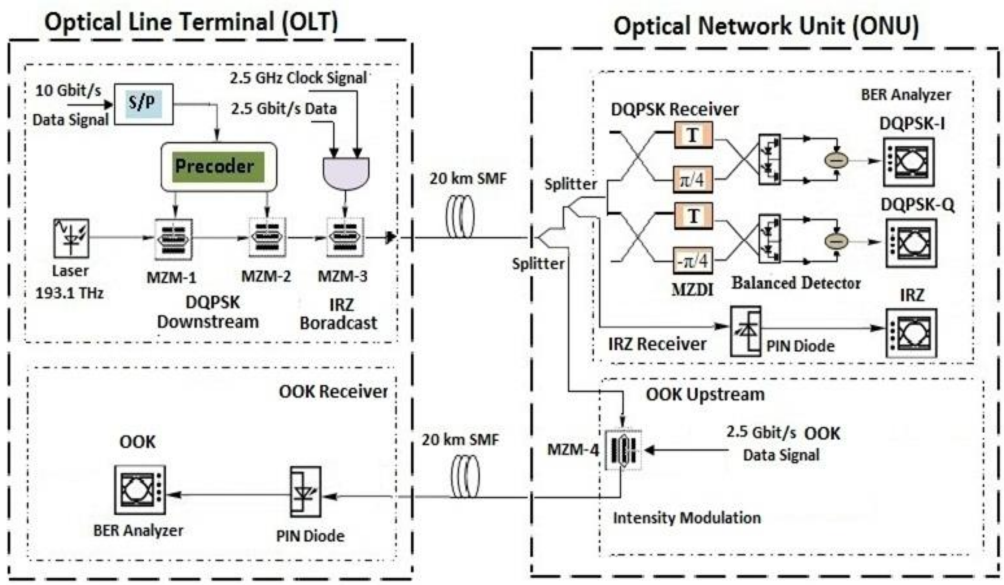

Figure 1. Working Principle of Proposed Simultaneous Transmission of Point-to-Point and Broadcast Service in WDM-PON

2.1. Point-to-point WDM-PON with Simultaneous Broadcast Services

In centralized laser source architecture, the main laser source is used at OLT as an optical source for 10 Gbit/s DQPSK downstream signal generated by phase modulators (*i.e*. Mach-Zehnder modulators MZM-1 & MZM-2) and precoder circuit. Then DQPSK signal power works as carrier in MZM-3 to superimpose IRZ broadcast service, in this way both services are simultaneously transmitted in downstream channel over distance of 20 km single mode fiber (SMF). At the ONU side, received signal is split in two parts via optical power splitter then first part of the signal is further split for the DQPSK receiver and IRZ receivers for demodulation of downstream point-to-point data and IRZ broadcast data/video service. The second part of the received signal is fed into an upstream data transmitter, where downstream signal power is used as a carrier for re-modulation of OOK upstream data via intensity modulator MZM-4 and transmitted back towards OLT via 20 km SMF. DQPSK receiver is based on a pair of Mach-Zehnder delay interferometer (MZDI) and balanced detectors, whereas IRZ and OOK receiver are based on a single PIN diode. Bit-error rate (BER) Analyzer can be used after receiver to analyze the performance of transmission.

2.2. Differential Duadrature Phase Shift Keying (DQPSK)

Differential quadrature phase shift keying (DQPSK) is very popular transmission technique for multi-level, spectral efficient and high data rate transmission. Due to four-level phase modulation and approximately constant envelope in intensity, DQPSK modulation provides better performance against nonlinear effects, reduces the cost of electric drive components and improves the flexibility towards polarization mode dispersion (PMD). Also transmission capacity of DQPSK system is twice than DPSK at the same symbol rate. As compared to OOK modulation, DQPSK provides better performance against nonlinear effects and much improved receiver sensitivity due to balanced receiver design [21].

In DQPSK transmitter, instead of phase of a symbol, encoding of symbol information depends upon change of phase from a symbol to its next. Consequently at receiver, only detection of symbols phase change is needed rather than actual phase of the symbol, due to this local carrier synchronization is not required, which was difficult to achieve at optical frequencies and critical issue in QPSK systems [22]. Therefore, DQPSK transmitted signal can be expressed as in equation (1).

$$x(t) = A\cos(2\pi f_c t + \theta(k)), \quad kT \le t < (k+1)T \tag{1}$$

$$\theta(k) - \theta(k-1) = \begin{cases} \pi & \text{if } (I(k), Q(k)) = 00 \\ 3\pi/2 & \text{if } (I(k), Q(k)) = 10 \\ 0 & \text{if } (I(k), Q(k)) = 11 \\ \pi/2 & \text{if } (I(k), Q(k)) = 01 \end{cases}$$

Where fc represents carrier frequency, θ(k) is the phase of carrier in the time interval (kT, (k+1)T) and the (I(k), Q(k)) denotes the kth symbol of transmitted signal. For the DQPSK downstream transmission, 10 Gbit/s binary data electrical stream is generated by pseudo random binary sequence (PRBS) then signal is passed through serial to parallel conversion (S/P) and precoder. In DQPSK, precoder is used to avoid iterative decoding and hardware complexity with accuracy at receiver for demodulation and detection. After the precoding, signal is split into two 5 Gbit/s streams with four binary patterns (00, 10, 11, 01) for the in-phase (I) and quadrature-phase (Q) parts of the DQPSK signals, related to four phases (π, 3π/2, 0, π/2). Precoder output equation is shown in equation (2a) and (2b), where Ii and Qi are output, Ui and Vi are inputs for I and Q phases of the precoder, ⊕ is binary or modulo-2 addition and the i-1 indicates previous value.

$$I_i = \overline{(Q_{i-1} \oplus I_{i-1})(U_i \oplus I_{i-1})} + (Q_{i-1} \oplus I_{i-1})\overline{(V_i \oplus I_{i-1})} \tag{2a}$$

$$Q_i = \overline{(Q_{i-1} \oplus I_{i-1})(U_i \oplus I_{i-1})} + (Q_{i-1} \oplus I_{i-1})\overline{(U_i \oplus I_{i-1})} \tag{2b}$$

To achieve this, π and π/2 phase difference is set in the two phase modulators using in series configuration instead of parallel combination as was in [23]. Carrier wave laser is used to operate properly biased $LiNbO_3$ MZM-1 and MZM-2, to produce phase modulated optical DQPSK signal. At DQPSK receiver, received signal is split into two parts and passed through two MZDIs for realizing the coherency and optical signals cancellation with delay T and phase shifts π/4 and -π/4. To produce phases in I and Q parts, T = 2/B delay is set in MZDI, where B is the transmission bit rate. Then two balanced detectors are used for separately applying the phase difference in I and Q parts

[21]. DQPSK received signal is multiplied by its delayed version and filtered to obtain a signal which is function of phase difference as per equation (3).

$$x(t)*x(t-T)|_{lpf} = \cos(\theta(t) - \theta(t-T)) \tag{3}$$

Figure 2 shows configuration of DQPSK transmitters using MZMs in parallel and proposed MZMs in series for signal generation. Similarly in Figure 3, configurations of receivers are shown for the MZMs in parallel and series configurations for DQPSK signal reception. The proposed configuration provides improved receiver sensitivity than DQPSK in [23].

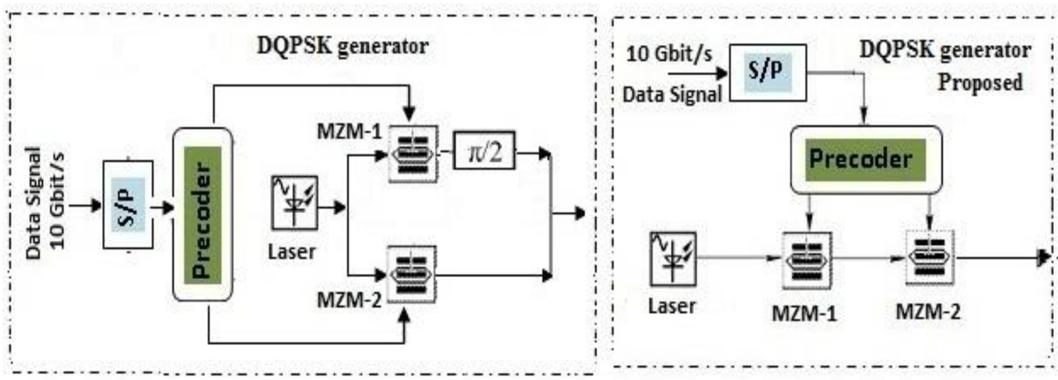

Figure 2. Two Different Configurations of DQPSK Transmitters

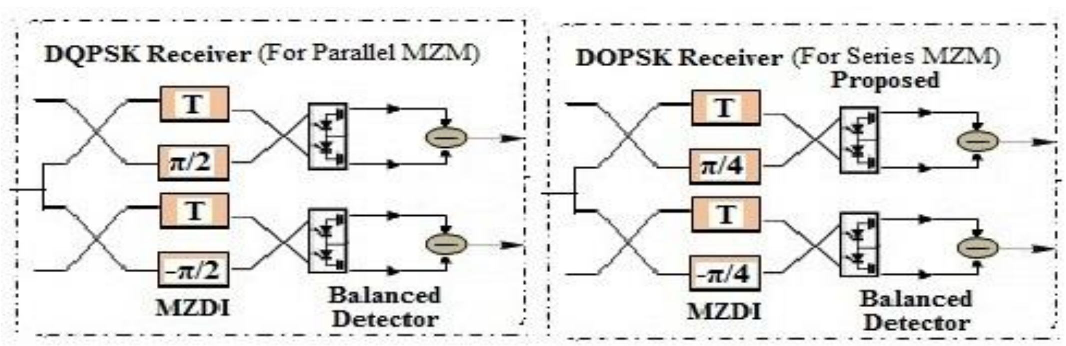

Figure 3. Two Different Configurations of DQPSK Receivers

2.3. Inverse Return-to-Zero (IRZ)

IRZ signal is obtained by inverting the intensity level of return-to-zero (RZ) signal, so it has optical power at both the mark levels and the space levels during each bit period, therefore in this modulation technique signal can maintain high extinction ratio (ER). IRZ pulse allows better integration of phase and amplitude modulation formats. Furthermore, due to separation of the phase and amplitude modulation and with the phase modulation stored in the high and constant power part of the waveform, the amplitude modulation is allowed to use high (ideally infinite) extinction ratio meanwhile phase modulation is hardly affected. IRZ signal can be achieved via properly biased Mach-Zehnder modulator (MZ-MOD) driven by AND gate logic operation of NRZ-shaped radio frequency (RF) signal and clock, optical signal processing can also be used to invert a conventional RZ signal [24]. Moreover, IRZ signal has advantages of cost-effective design to increase transmitter and receiver bandwidth, which is twice as compared to NRZ similarly the optical bandwidth of the IRZ is double than NRZ signals. Moreover, improved receiver sensitivity is obtained by using IRZ modulation format as compared to other RZ formats. Working principle of the IRZ transmitter is shown in Figure 4.

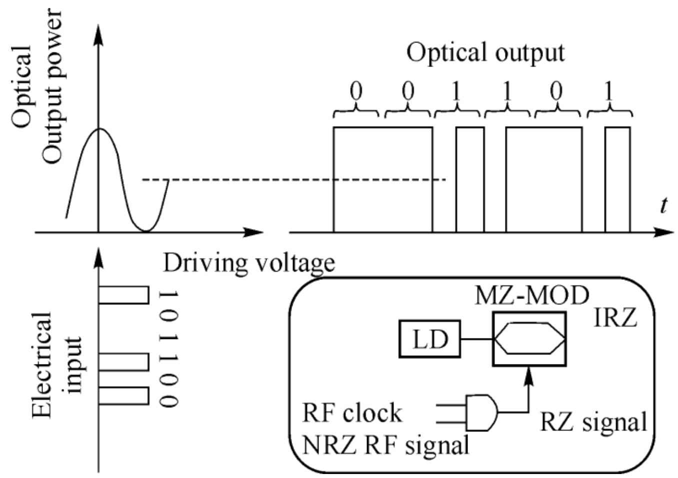

Figure 4. Working Principle of Optical IRZ Transmitter

3. Simulation Setup and Operation

In simulation setup, proposed WDM-PON in Figure 1 has been implemented for 10 DQPSK channels for the downstream transmission, using 10 Gbit/s pseudorandom bit stream (PRBS) data having order 2^7-1. The channels are separated using ITU-T 100 GHz channel spacing, using launch power of 5 dBm, which are generated by distributed feedback (DFB) laser sources ranging from 193.1 THz to 194.0 THz and represented by (λ_1 to λ_{10}). Then 2.5 Gbit/s IRZ broadcast service is superimposed on multiplexed DQPSK point-to-point data and transmitted over 20 km SMF, having following simulation parameter specifications in Table 1.

Table 1. Parameters Used for Simulation

SMF Parameters	Values
Length	20 km
Dispersion parameter	16.75 ps/(nm.km)
Dispersion slop	0.075 ps/(nm^2.km)
Attenuation Coefficient	0.2 dB/km
Effective core area	80 um^2
Non Linear index-coefficient	2.6x10^{-20}

Optical spectrum of 10 multiplexed downstream channels is shown in Figure 5a. In the ONU, received signal is split by power splitter in two parts, one part is fed in downstream channel receiver and other one is fed to upstream transmitter. Downstream channel receiver comprises DQPSK receiver as well as IRZ receiver. The upstream OOK data channels are generated by re-modulation of downstream via intensity modulator with high ER, *i.e.*, 30dB. Then upstream data is transmitted back towards OLT via 20 km SMF. The 10 OOK upstream channels are also multiplexed using ITU-T grid 100 GHz channel spacing, as its optical spectrum is shown in Figure 5b. At OLT, a PIN diode is used as an OOK receiver for the demodulation of upstream channel. Dispersion compensation fiber (DCF) can be used to minimize the dispersion effects. Bit error rate (BER) analyzer is used for received signal performance measurement. 7.5 GHz bandwidth low pass electrical Bessel filter is used before BER analyzer for flatten the output signal.

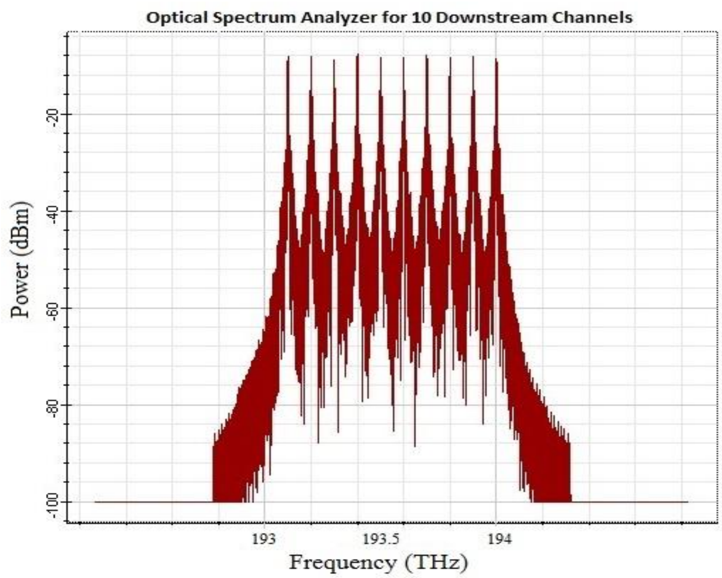

Figure 5(a). Optical Spectrum Downstream Channels

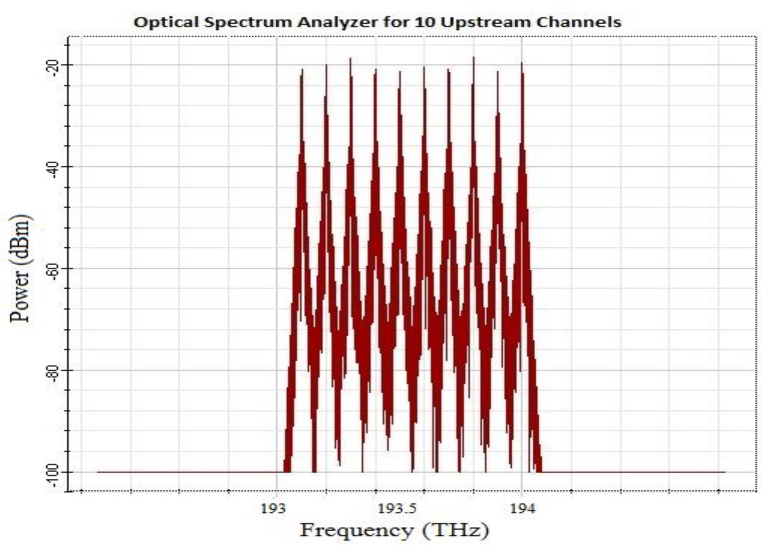

Figure 5(b). Optical Spectrum Upstream Channels

Figure 5. Optical Spectrum of 10 Downstream and 10 Upstream Channels

4. Transmission Performance Analysis

Performance analysis of transmission has been evaluated in OptiSystem 7.0 [25]. Eye diagrams of DQPSK-I, DQPSK-Q, and OOK for channels 4 and 7 are shown in Figure 6, Figure 7 and Figure 8 respectively. Wide and clear eye-openings ensure good tolerance against fiber nonlinearities in both directions of transmission. This section is divided into two parts for discussion in details.

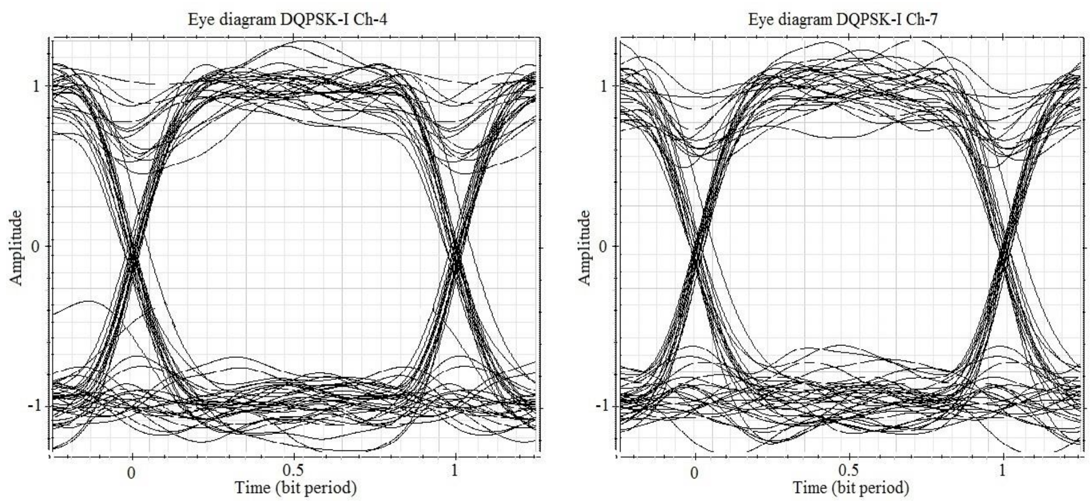

Figure 6. Eye Diagrams of DQPSK-I Channel-4 and Channel-7

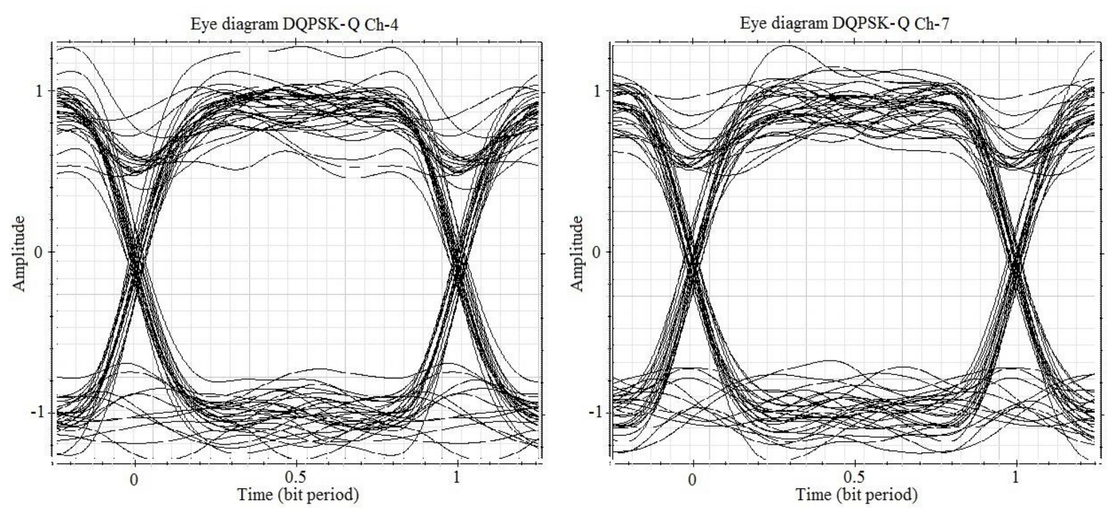

Figure 7. Eye Diagrams of DQPSK-Q Channel-4 and Channel-7

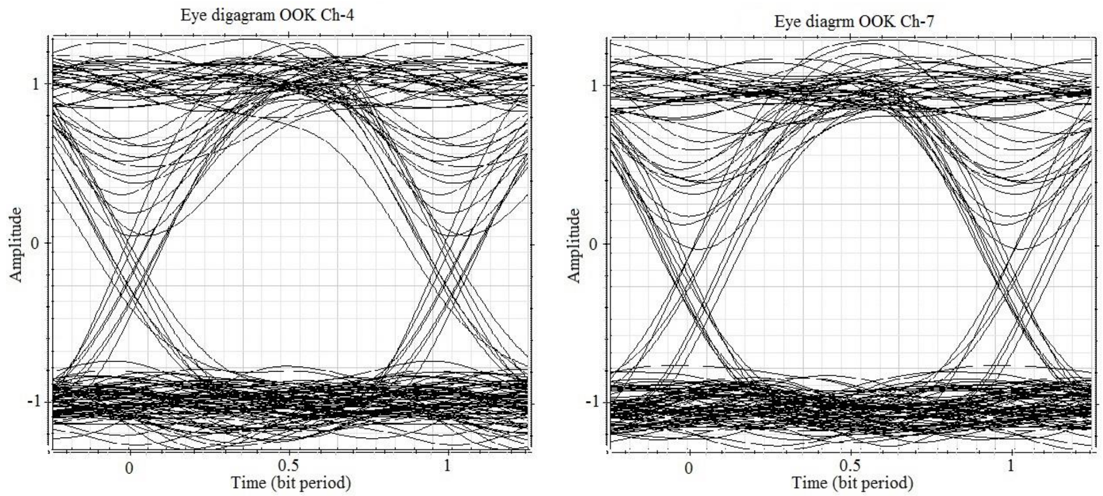

Figure 8. Eye Diagrams of OOK Channel-4 and Channel-7

4.1. Performance Analysis of Simultaneous Point-to-Point and Broadcast Services

Four basic attributes, by which data can be modulated in optical transmission, are intensity, phase, frequency and polarization. Some of these attributes can be modulated in a combined technique but at the cost of some transmission penalty mitigation. Therefore, performance of simultaneous transmission of phase modulated DQPSK point-to-point data and intensity modulated IRZ broadcast data/video service in downstream channel depends upon the optical power of received signal, coupling coefficient of splitter (coupler) and extinction ratio of IRZ signal. Therefore, performance of DQPSK and IRZ signal can be optimized by adjusting these parameters [24]. We evaluated performance by using eye height in BER analyzer, as high BER value, eye height will be smaller and for low BER values eye height will be larger.

Figure 9 shows that the transmission performance of the system in terms of eye height versus optical received power. It can be observed that DQPSK signal is hardly affected when the eye height of IRZ signal is decreased more at low optical received power. As compare to DQPSK, IRZ signal is severely influenced by high BER on very low optical received power, so its eye height completely deteriorated before DQPSK signal.

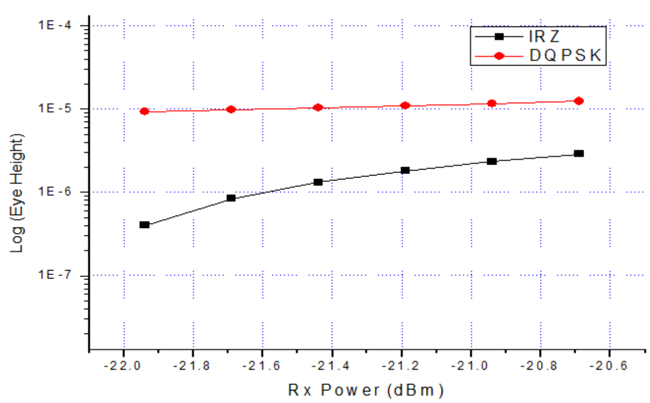

Figure 9. Eye Height vs Received Power for DQPSK and IRZ

System performance in terms of eye height versus coupling coefficient of splitter is shown in Figure 10, it is observed that for low coupling coefficient values IRZ has minimum eye height whereas DQPSK signal has maximum eye height. On the other hand, at higher value of coupling coefficient the results are vice versa. Therefore it is required to set appropriate value of coupling coefficient, such as 0.5 in our proposed scheme where both DQPSK and IRZ signals can provide better performance.

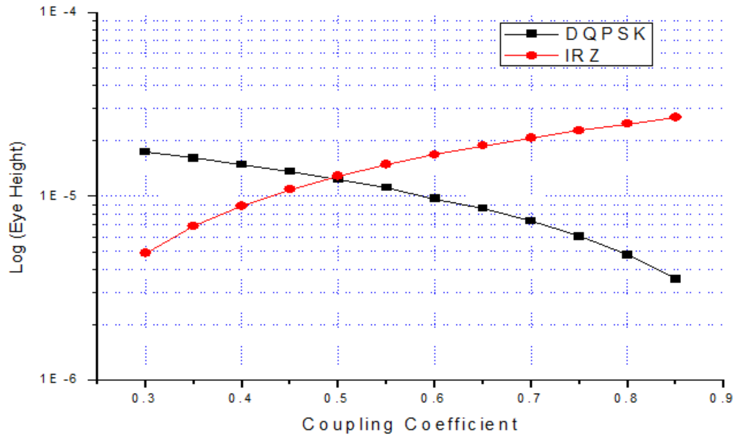

Figure 10. Eye Height vs Coupling Coefficient for DQPSK & IRZ

In Figure 11 performance of system in terms of eye height versus extinction ratio is shown. It is observed that there is negligible effect of extinction ratio on DQPSK signal, thus low extinction ratio can be preferred, however, IRZ signal is highly influenced at low values of extinction ratio so it is necessary to set higher extinction ratio. Therefore an optimal value of extinction ratio such as 30 dB or higher can provide maximum performance for simultaneous detection of DQPSK and IRZ.

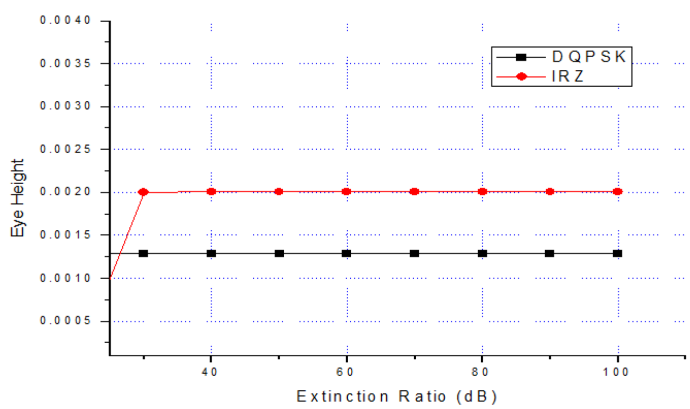

Figure 11. Eye Height vs Extinction Ratio for DQPSK & IRZ

4.2. Transmission Power Penalty in Proposed WDM-PON

To measure transmission power penalty in WDM-PON, received optical power of every channel with respect to bit error rate (BER) is analyzed in back to back (B2B) and after 20km transmission. At required BER *i.e.* $1x10^{-9}$, difference of received optical powers provides power penalty of transmission channel.

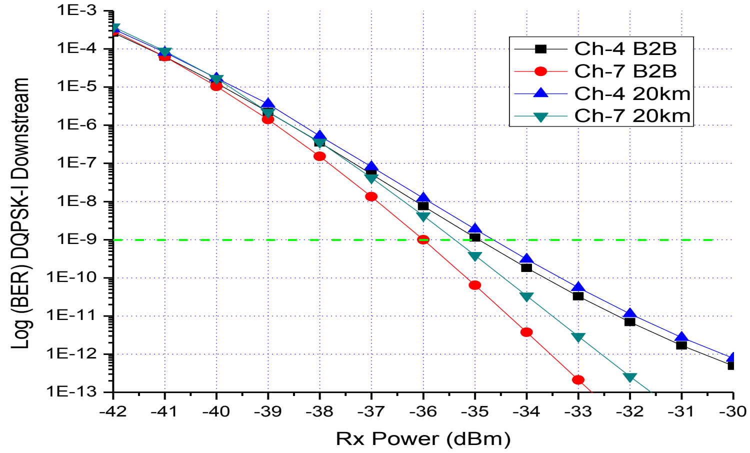

Figure 12. BER versus Received Power of DQPSK-I Ch 4 & 7

Figure 12 shows BER versus received optical power of DQPSK-I for channels 4 and 7 in downstream. We compared these channels over 20 km transmission and back to back (B2B). At required 1×10^{-9} BER, the differences of received optical powers are 0.3 and 0.6 dB respectively, which are the transmission power penalties. Similarly in Figure 13, BER versus received optical power of DQPSK-Q for channels 4 and 7 are shown, it can be observed that transmission power penalties are 0.7 and 0.9 dB respectively.

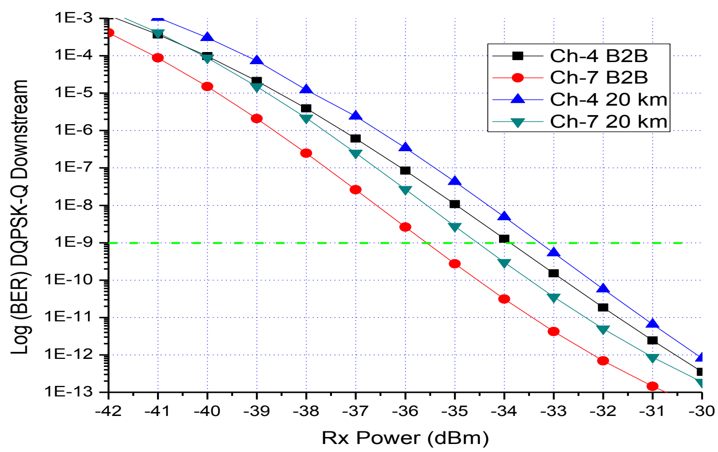

Figure 13. BER versus Received Power of DQPSK-Q Ch 4 & 7

Also in Figure 14, BER versus received optical power of IRZ broadcast data is shown, it can be observed that transmission power penalty is 0.5 dB only. From Figure 15 BER versus received optical power of OOK for channels 4 and 7 are shown, it can be observed that transmission power penalties are 0.5 and 0.4 dB respectively. A comparison of DQPSK signal receiver sensitivity for MZMs in parallel configuration [23] and proposed MZMs in series configurations is shown in Figure 16. It is observed that proposed configuration of DQPSK signal has 17dBm improved receiver sensitivity over 20km transmission at 1×10^{-9} BER.

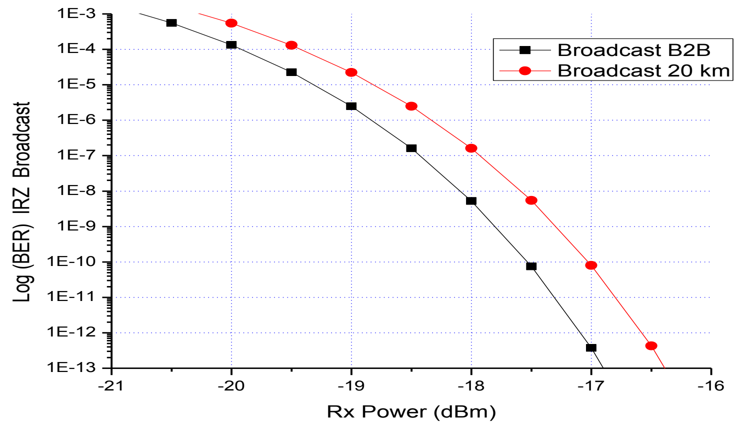

Figure 14. BER versus Received Power of IRZ Broadcast

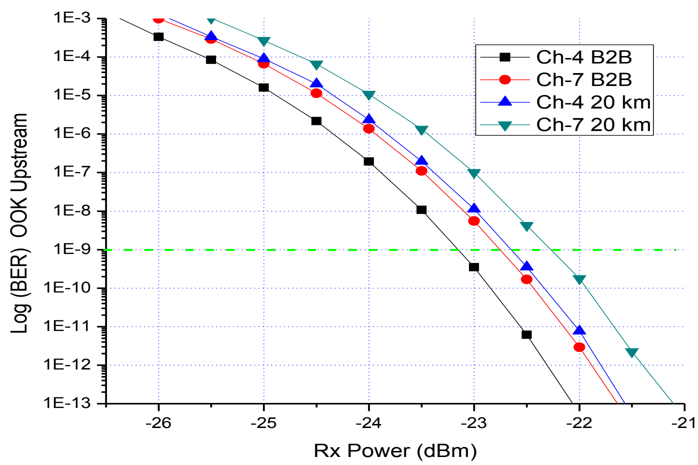

Figure 15. BER versus Received Power of OOK Ch 4 and 7

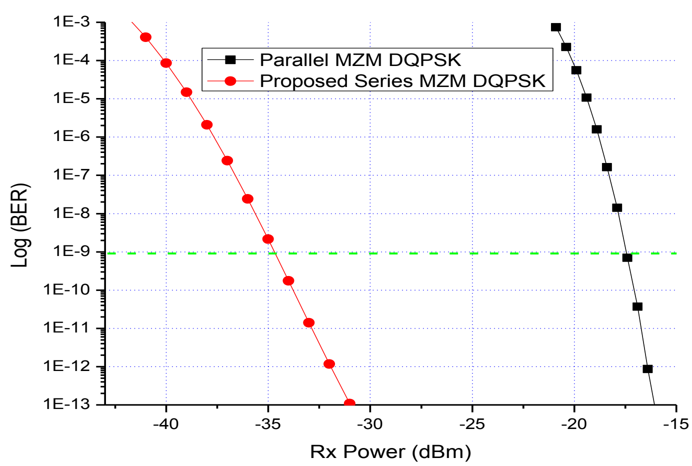

Figure 16. Receiver Sensitivity of Two DQPSK Configurations

Therefore, such low transmission power penalties reflect that proposed technique has very robust performance and high tolerance against transmission nonlinearities. It is important to note that transmission power penalties have been measured without EDFA amplification over 20 km fiber span. Hence, it is evident from above results that error free transmission can be achieved in DQPSK point-to-point data with IRZ broadcast data service in downstream channels and OOK upstream channels and therefore proposed technique can be implemented in future high capacity WDM-PON.

5. Conclusions

We have proposed and demonstrated simple and cost-effective design of centralized light source WDM-PON, having simultaneous transmission of point-to-point data and broadcast data/video services. A DQPSK signal of 10 Gbit/s data rate is used as downstream and a 2.5 Gbit/s IRZ signal is superimposed on it as a broadcast service at OLT and transmitted in downstream channel without pulse carving and EDFA amplification. At ONU a 2.5 Gbit/s OOK data signal is used as a upstream signal after re-modulation of downstream signal power as a carrier, therefore no additional laser is required at ONU. Simulation results verify that 10 DQPSK downstream channels with IRZ broadcast service and 10 OOK upstream channels, using ITU-T grid 100 GHz channel spacing at high extinction ratio (ER), can be successfully transmitted over a distance of 20 km SMF. Further it is also observed that transmission performance analysis has clear and wide eye-openings in eye diagrams, low transmission power penalties and improved receiver sensitivity, therefore robust performance against transmission nonlinearities is ensured in proposed WDM-PON.

Acknowledgements

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