

An AWG based colorless WDM-PON with RZ-DPSK modulated downstream and re-modulation of DL signal for OOK upstream

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Abstract We proposed an arrayed waveguide grating (AWG) based 10 Gbps full duplex wavelength division multiplexing passive optical network (WDM-PON) utilizing a return-to-zero differential phase shift keying (RZ-DPSK) modulation technique for down-link direction and then re-modulation of the downlink (DL) signal for the uplink (UL) direction using intensity modulation technique (OOK) with a data rate of 10 Gbps per channel. A successful cost effective colorless WDM-PON full duplex transmission operation for a data rate of 10 Gbps per channel, with a channel spacing of 60 GHz over a distance of 25 km without any optical amplification and dispersion compensation is achieved within low power penalty.

Keywords wavelength division multiplexing passive optical network (WDM-PON), arrayed waveguide grating (AWG), centralized light source, differential phase shift keying (DPSK), re-modulation

1 Introduction

Video on demand (VoD), multimedia broadcasting, videoconferencing, online user generated video content, high-definition TV (HDTV), e-learning, interactive games, voice over IP, and many other broadband services are increasing at exponential rate in access network [1]. Keeping this trend in sight, one may estimate that users will require more than 30 Mbps of guaranteed bandwidth per user in the near future [2]. These services will put immense pressures on carriers to come up with both innovative and inexpensive solutions regarding higher aggregate bandwidth, service provisioning and long link reach [3].

The rapid deployment of optical fiber is underway at present and passive optical networks (PONs) are replacing existing copper based access systems because of their low cost and simple operation and maintenance. Also these are capable of providing higher bandwidth for broadband subscribers and can offer data rates of upto few Gbps (EPONS, GPONS) or point to point (P2P) or point-to-multipoint (P2MP) links according to Ethernet [4].

Many operators are using EPON and GPON based on TDMA for provisioning of baseband services. These have been widely accepted as the current-generation optical access solutions. However, TDMA PONs have limitations of bandwidth, cost and link reach. On the other hand, wavelength division multiplexing passive optical networks (WDM-PONs) have emerged as alternative technology for fulfilling future requirements in the access network [5,6]. These can offer many benefits such as large capacity, reduced optical path loss, channel independence, format transparency, network security and scalability (the number of channels that can be easily upgraded) and flexibility (several types of channels transmitted at different wavelength that can coexist on the same time) [7–10]. These can serve distances up to 80–100 km without the need for optical amplification [3]. Though these are considered as popular solutions that will revolutionize the access network but the cost of initial deployment and maintenance due to a number of wavelength specific light sources is a deterring factor [11]. Also the high cost involved in wavelength selective components and wavelength specific transmitters at both the optical line termination (OLT) and within each optical network unit (ONU) has reduced the competitiveness of this technology in the current optical transport market [9]. The most critical issue in the implementation of practical WDM-PON networks is the realization of low cost transmitters at subscriber ends [6,12]. Researches have suggested colorless operation

within customer premises equipment (CPE) to reduce both CapEx and OpEx [5].

Several arrayed waveguide gratings (AWGs)-based WDM-PON architectures have been recommended in the recent past [12–15]. AWGs have a very low insertion loss (3 to 4 dB), good crosstalk levels (30 to 35 dB), high fiber-coupling efficiency, and polarization independence. Since the insertion loss is independent of port count, these are appropriate for cost-sensitive WDM-PONs. Other advantages of the AWGs are precisely controlled channel spacing (easily matched to the ITU grid) and simple and accurate wavelength stabilization [16,17]. Besides, these operate at high diffraction orders that lead to wavelength resolution of better than a nanometer despite their small overall size (of the order of centimeters) [18]. One more important benefit is that the AWG based MUX/DEMUX devices are linear phase filters and have intrinsically very small chromatic dispersion [19]. An $N \times N$ AWG multiplexer is appealing in optical WDM networks because it is capable of increasing the aggregate transmission capacity of a single strand optical fiber [20]. Finally, the simple implementation of technology of AWGs reduces network cost and complexity at the remote node (RN) [21].

In this paper, we will make use of the above listed features of AWG in colorless WDM-PON network characterized by remodulation and try to establish seamless communication without any application of power amplifiers or dispersion compensation management.

Section 2 describes the working principle of AWG and gives a description of proposed network architecture. Section 3 presents the simulation setup and demonstrates the colorless nature of the network. Section 4 analyzes the transmission performances of the constructed network. Section 5 concludes our work.

2 Working principle of AWGs and network architecture

2.1 Working principle of AWG

AWG, also known as the phasor (phased array) or waveguide grating router (WGR) is a key device in WDM optical communication systems. It performs functions such as wavelength multiplexing and demultiplexing, wavelength filtering, signal routing, and optical cross-connects. It was first devised by Smith [22]. It is one of the most complex, superbly developed, and commercially successful planar waveguide devices. It is also being used in areas other than WDM, such as signal processing, spectral analysis and sensing.

Figure 1 shows the four basic functions offered by the arrayed-waveguide $N \times N$ wavelength multiplexer. First and second are simple multiplexing and demultiplexing. The third function is add-drop multiplexing (ADM).

This function achieves both demultiplexing and multiplexing simultaneously. One or more frequencies can be dropped and inserted by opening the respective loops. The last function is $N \times N$ full-interconnection. The frequency multiplexed signals input to each of the left-hand-side ports are separated according to frequency and connected to different right side ports. The N demultiplexers, N multiplexers, and N^2 fibers are replaced by a single multiplexer.

AWG is a passive optical device with multiple input/output ports that can perform wavelength-selective optical routing function also. For any given wavelength and input port of an AWG, the output port is selected based on its routing function. The basic routing function of an AWG can be defined as

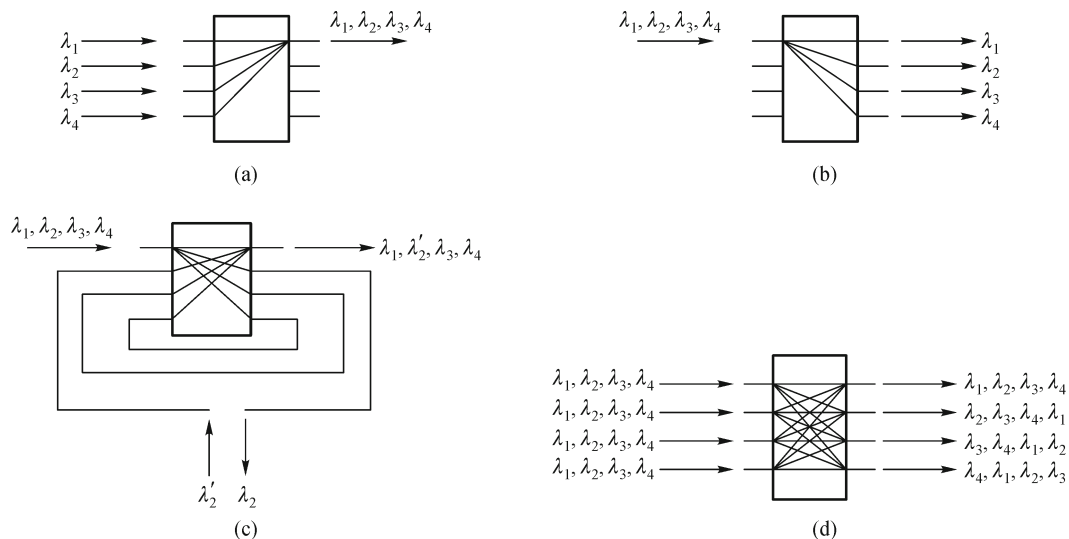


Fig. 1 Basic functions of arrayed-waveguide $N \times N$ multiplexer. (a) Multiplexing; (b) demultiplexing; (c) ADM operation; (d) $N \times N$ interconnect

$$j = 1 + \left(i - 1 + \left\lfloor \frac{f-1}{C} \right\rfloor \right) \bmod M, \quad (1)$$

where i and j are indices of input and output ports and M is the size of the AWG. C and f represent the coarseness and an index to specify wavelength respectively. The basic wavelength λ_{basic} arrives at the output port j , if it enters the input port i . The value of f is equal to one, for a basic wavelength. Coarseness, C , implies that there are C wavelengths having the same routing function, within the same free spectral range (FSR) [21].

Figure 2 shows a schematic representation of the $N \times N$ AWG. It consists of two input and output concave slab waveguides connected by a dispersive waveguide array with the equal length difference (ΔL) between adjacent array waveguides. Optical waveguides consisting of a silica-based cladding and core in the AWG are fabricated on a substrate of silicon. The operating principle of the AWG multiplexers/demultiplexers is described briefly in the subsequent paragraph.

Two slabs have the same function as lenses and arrayed waveguides have the same function as a grating. When optical light is launched into an input waveguide, it spreads out in the first slab and is captured by the arrayed waveguides. After passing through the arrayed waveguides, each beam of optical light interferes constructively or destructively according to the phase condition. The interfering optical light constructively focuses onto one of the output waveguides. AWG is an imaging system that contains finite discrete dispersive elements called arrayed waveguides. Both ends of array have a tapered structure to reduce crosstalk and insertion loss. In the first slab region, input waveguide separation is D_1 , array waveguide separation is d_1 and radius of curvature is f_1 .

The waveguide parameters in the first and the second

slab regions may be different. Therefore, in the second slab region, the output waveguide separation is D , the array waveguide separation is d , and the radius of curvature is f , respectively. The input light at the position of x_1 (x_1 is measured in a counter-clockwise direction from the center of input waveguides) is radiated to the first slab and then excites the arrayed waveguides. The excited electric field amplitude in each array waveguide is a_i ($i = 1, 2, \dots, N$), where N is the total number of array waveguides. After traveling through the arrayed waveguides, the light beams constructively interfere into one focal point x (x is measured in a counter-clockwise direction from the center of the output waveguides) in the second slab. The location of this focal point depends on the signal wavelength because the relative phase delay in each waveguide is given by $2\pi\Delta L/\lambda$.

Let us consider the phase delays or retardations for the two light beams passing through the $(i-1)$ -th and i -th array waveguides. The difference of the total phase retardations for the two light beams passing through the $(i-1)$ -th and i -th array waveguides must be an integer multiple of 2π in order that two beams constructively interfere at the focal point x . Therefore, we have the interference condition:

$$\begin{aligned} & \beta_s(\lambda_0) \left(f_1 - \frac{d_1 x_1}{2f_1} \right) + \beta_c(\lambda_0) [L_c + (i-1)\Delta L] \\ & + \beta_s(\lambda_0) \left(f + \frac{dx}{2f} \right) \\ & = \beta_s(\lambda_0) \left(f_1 + \frac{d_1 x_1}{2f_1} \right) + \beta_c(\lambda_0) (L_c + i\Delta L) \\ & + \beta_s(\lambda_0) \left(f - \frac{dx}{2f} \right) - 2m\pi, \end{aligned} \quad (2)$$

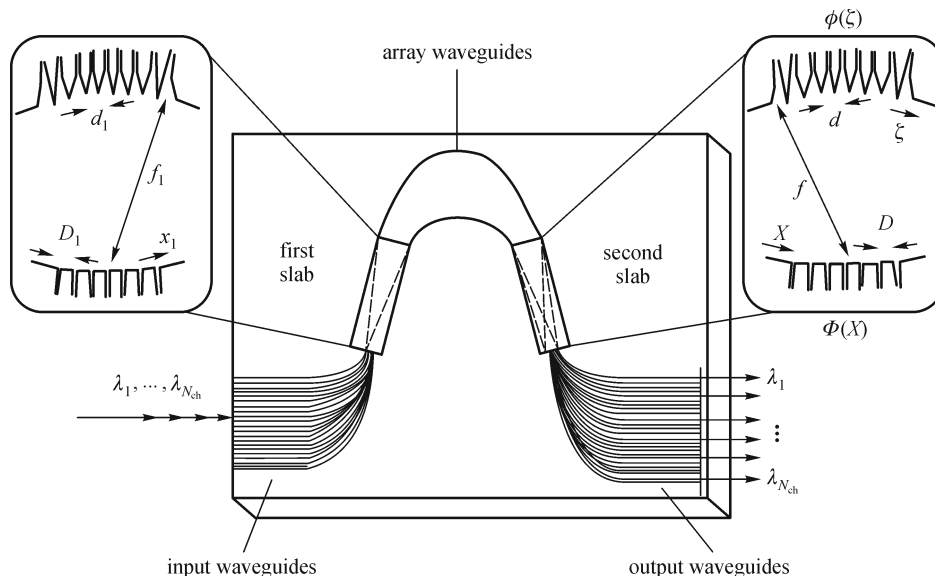


Fig. 2 AWG multiplexer

where β_s and β_c are the propagation constants in slab region and array waveguide respectively, m is the diffraction order, λ_0 is the center wavelength of WDM system and L_c is the minimum array waveguide length. Subtracting common terms from Eq. (2), we obtain

$$\beta_s(\lambda_0)\frac{d_1x_1}{f_1} - \beta_s(\lambda_0)\frac{dx}{f} + \beta_c(\lambda_0)\Delta L = 2m\pi, \quad (3)$$

since

$$\beta = n_{\text{eff}}\frac{2\pi}{\lambda}, \quad (4)$$

or

$$\beta_c = n_c\frac{2\pi}{\lambda_0}. \quad (5)$$

As $\Delta\phi_{\text{AWG}}$ (the phase difference between the adjacent waveguides) can be defined as

$$\Delta\phi_{\text{AWG}} = \beta_c\Delta L = \frac{2\pi\Delta Ln_c}{\lambda_0}, \quad (6)$$

and

$$2\pi m = \frac{2\pi\Delta Ln_c}{\lambda_0}, \quad (7)$$

simplifying it results as

$$\lambda_0 = \frac{n_c\Delta L}{m}. \quad (8)$$

When condition given in Eq. (8) is satisfied for λ_0 , the light input position x_1 and the output position x should satisfy the condition

$$\frac{d_1x_1}{f_1} = \frac{dx}{f}. \quad (9)$$

In Eq. (8), n_c is the effective phase index of the array waveguide. The above equation means that when light is coupled into the input position x_1 , the output position x is determined by Eq. (9). Usually, the waveguide parameters in the first and the second slab regions are the same ($d_1 = d$ and $f_1 = f$). Therefore, input and output distances are equal as $x_1 = x$. The spatial dispersion of the focal position x with respect to the wavelength λ for the fixed light input position x_1 is given by differentiating Eq. (3) with respect to λ as

$$\frac{\Delta x}{\Delta \lambda} \approx -\frac{N_c f \Delta L}{n_s d \lambda_0}, \quad (10)$$

where n_s is the effective index in the slab region and N_c is the effective group index of the effective index n_c of the array waveguide ($N_c = n_c - \lambda dn_c/d\lambda$). The spatial dispersion of the input-side position x_1 with respect to the wavelength λ for the fixed light output position x is given by

$$\frac{\Delta x_1}{\Delta \lambda} \approx -\frac{N_c f_1 \Delta L}{n_s d_1 \lambda_0}. \quad (11)$$

The input and output waveguide separations are $|\Delta x_1| = D_1$ and $|\Delta x| = D$ respectively, when $\Delta \lambda$ is the channel spacing of the WDM signal. Putting these relations into Eqs. (8) and (9), the wavelength spacing on the output side for a fixed light input position x_1 is given by

$$\Delta \lambda_{\text{out}} = \frac{n_s d D \lambda_0}{N_c f \Delta L}. \quad (12)$$

The wavelength spacing on the input side for a fixed light output position x is given by

$$\Delta \lambda_{\text{in}} = \frac{n_s d_1 D_1 \lambda_0}{N_c f_1 \Delta L}. \quad (13)$$

The spatial separation of the m th and $(m+1)$ th focused beams for the same wavelength is obtained from Eq. (3) as

$$X_{\text{FSR}} = x_m - x_{m+1} = \frac{\lambda_0}{n_s d}, \quad (14)$$

X_{FSR} is the free spatial range of AWG. The number of available wavelength channels N_{ch} is given by dividing X_{FSR} with the output waveguide separation D as

$$N_{\text{ch}} = \frac{X_{\text{FSR}}}{D} = \frac{\lambda_0 f}{n_s d D}. \quad (15)$$

2.2 Description of proposed WDM-PON

The proposed WDM-PON network contains continuous light source, return-to-zero differential phase shift keying (RZ-DPSK) transmitter/receiver, AWG, standard single-mode fiber (SMF), intensity modulation technique (OOK) receiver/transmitter and Photo-detector as the basic building elements. The RZ-DPSK transmitter consists of a continuous laser source and two cascaded Mach-Zehnder (MZ) (LiNbO₃) modulators. The first modulator is used to perform the phase modulation and the second MZ modulator (MZM) called the pulse carver, converts the incoming non return-to-zero (NRZ) signals into RZ signals. The schematic diagram of the proposed full-duplex AWG based 4×4 WDM-PON system is shown in Fig. 3. A continuous light source is externally modulated by a LiNbO₃ MZM (LN-MZM) because of its higher response frequency for transmission of high data rate of 10 Gbps. The MZM is operated at its minimum transmission (null) point, with a DC bias of $-V_\pi$ and a peak-to-peak modulation of $2V_\pi$. The transmitted output from second MZM optical modulator would be a periodic RZ-DPSK pulse train. The generated downstream RZ-DPSK signal is then fed to AWG along with other downlink (DL) channels each having a data rate of 10 Gbps. The multiplexed signal is transmitted over a single feeder fiber. The feeder fiber is

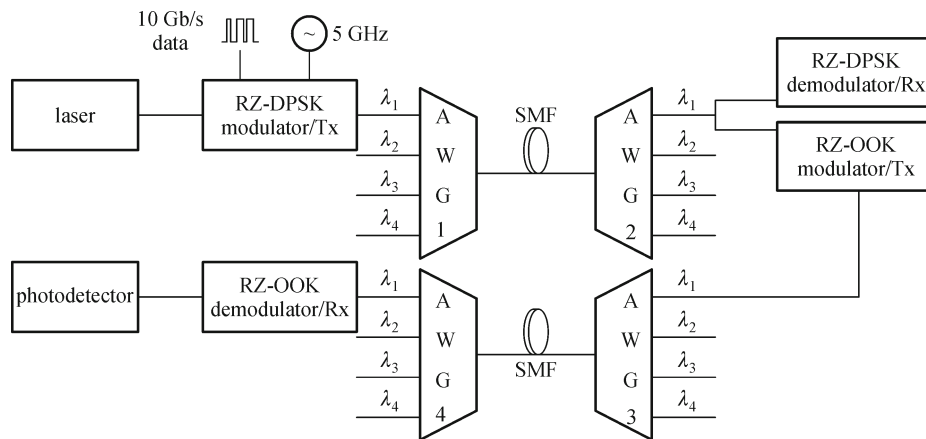


Fig. 3 Schematic diagram of AWG based 10 Gbps RZ-DPSK DL and OOK UL WDM-PON

a SMF of 25 km. At the other end, an AWG is used to demultiplex the downstream signals and send them to their respective ONUs. At each ONU, after a power splitter, half of the downstream phase encoded signal is re-modulated with 10 Gbps data using an OOK to be transmitted back to the optical line terminal (OLT) in order to avoid the cost of a specific laser in each ONU.

3 Simulation setup

The transmission performance of the proposed WDM-PON with four 10 Gbps DL channels and four 10 Gbps uplink (UL) channels over 25 km (feeder + distribution) fiber was evaluated by simulations using Optiwave software Optisystem 7.0. Figure 4 shows the simulation setup for the proposed AWG based WDM-PON system using a centralized light source for DL and UL directions. Four continuous light waves with a launch power of 0 dBm were generated by four distributed feedback (DFB) lasers

at wavelengths 1552.52 nm (λ_1), 1552.04 nm (λ_2), 1551.56 nm (λ_3), and 1551.08 nm (λ_4) for four different channels respectively keeping 60 GHz channel spacing. All channels were modulated independently by a transmitter consisting of two cascaded LN-MZM in series. The first modulator of each transmitter was the data modulator (DM) that performed phase modulation (biased at the null point). So each generated wavelength was first externally modulated by the MZM driven by 10 Gbps 2^7-1 pseudorandom binary sequence data. The output of the first MZM was fed to the second modulator known as the pulse carver, driven by a 5 GHz clock pulse generating about 33% duty-cycle RZ pulses.

The four RZ-DPSK signals thus produced were then multiplexed by a 4×1 AWG MUX on 60 GHz channel grid and transmitted over a 25 km single mode feeder fiber. The SMF in the simulation had attenuation coefficient of 0.2 dB/km, the dispersion parameter of 16.75 ps/(nm·km), the dispersion slope of 0.075 ps/(nm²·km), and the effective area of 80 μm^2 . The nonlinear-index coefficient

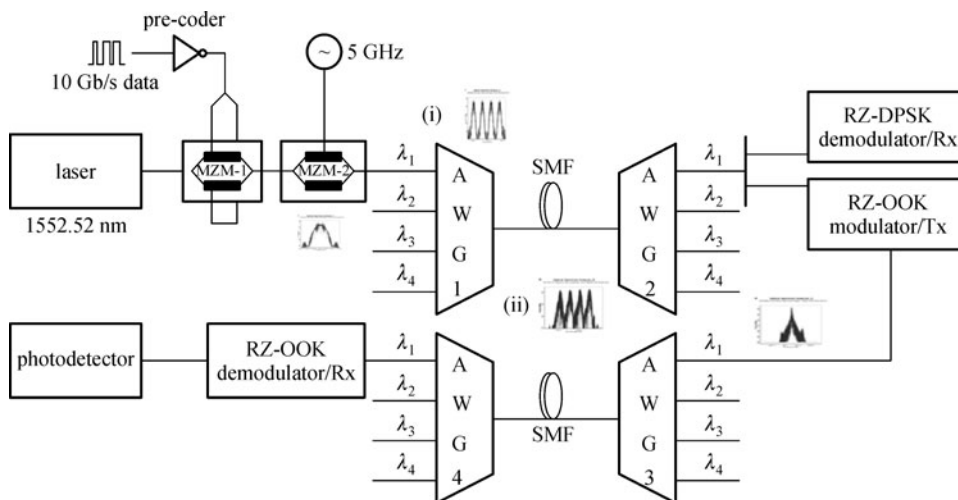


Fig. 4 Proposed AWG based 10-Gbps RZ-DPSK DL & OOK based UL WDM-PON

n_2 of the SMF was $2.6 \times 10^{-20} \text{ m}^2/\text{W}$. The DL multiplexed signal was first de-multiplexed using a 1×4 AWG DEMUX and then transmitted to the corresponding ONU. At the receiving ONU, a 3 dB optical splitter was used to tap half of the optical power for the downstream receiver. A MZ delay interferometric demodulator (MZDI) was used to convert the phase-modulated DPSK signal to an intensity-modulated signal before it was received by a regular direct detection PIN receiver. The other half of the DPSK signal was injected into a MZ intensity modulator (IM) driven by a 10 Gbps upstream data with RZ modulation format. The IM was biased at transmission null point and the driving voltage was set to $2V_\pi$. The re-modulated RZ OOK upstream signal was transmitted back to the OLT through another 25 km of SMF-28 before being received by a direct detection PIN receiver. The PRBS length of the upstream data was set to $2^7 - 1$. A 4th order Bessel low-pass electrical filter (LPF) with cut-off frequency of 12.5 GHz was used as RZ OOK decoder for 10 Gbps upstream data.

As same wavelengths were used for DL and UL transmission, a dual fiber transmission structure in-between OLT and ONU was used to prevent transmission performance limited by Rayleigh backscattering reflections. In the simulation, Pin photo-detector receivers were used at DL and APD at UL side. The general settings of the photo-detector in our simulation were: (i) responsivity is 1 A/W; (ii) dark current is 10 nA. Insets (i) and (ii) in Fig. 4 show four DL multiplexed RZ-DPSK signals and four UL multiplexed RZ OOK signals, respectively.

4 Performance and results

4.1 Results of 60 GHz spacing on AWG-based scheme

The bit error rate as a function of received optical power for both RZ DPSK downstream and RZ OOK upstream channels before and after the transmission are illustrated in Fig. 5.

Figure 6 shows the BER for four DL DPSK channels and four UL OOK channels for a distance of 25 km. The graph displays that DPSK modulated channels have better power sensitivity than OOK channels. Among DPSK, 3rd channel lags behind others, while in UL direction, all the four channels behave nearly in same manner.

Figure 7 shows the BER for four DL DPSK channels and four UL OOK channels for a back to back. All four DPSK channels coincide. Channel 4 for OOK has better receiver sensitivity than that of the remaining OOK channels.

The receiver sensitivity at 10^{-9} BER is around -41 dBm for DPSK channels and -25 dBm for OOK channels and the Average power penalty of the all the four multiplexed DPSK downstream signals is about 0.5 dB after transmission on 25 km in a single mode fiber without any optical

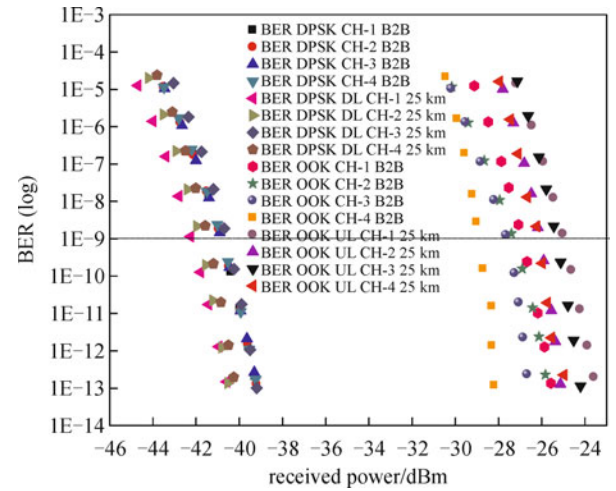


Fig. 5 BER graph for four multiplex channels DPSK DL & OOK UL (B2B & 25 km)

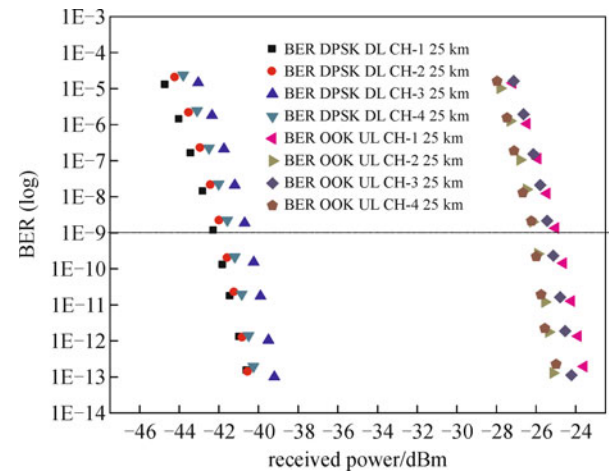


Fig. 6 BER graph for four multiplex channels RZ-DPSK DL & OOK UL for 25 km

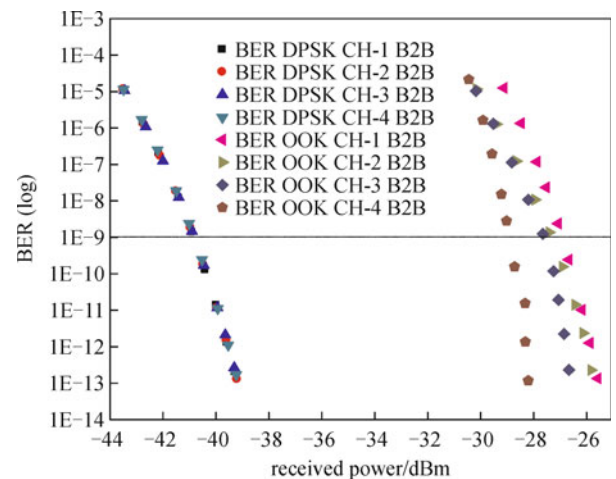


Fig. 7 BER graph for four multiplex channels DPSK DL and OOK UL for B2B

amplification or dispersion management as shown in Fig. 8.

Figure 9 details eye diagrams in conformity with the simulated results.

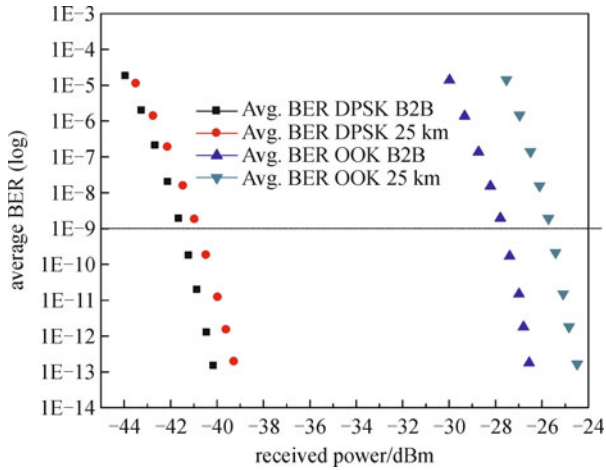


Fig. 8 Average BER graph for four multiplex channels DPSK DL and OOK UL (25km & B2B)

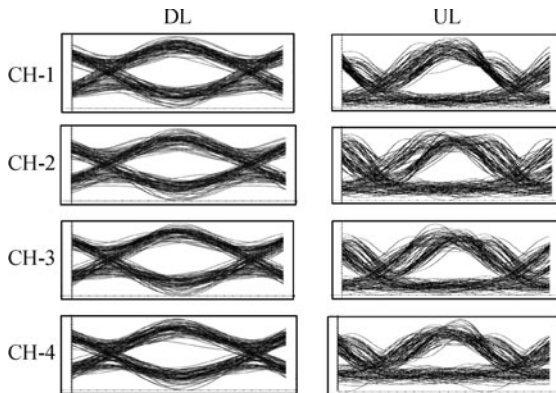


Fig. 9 Eye diagrams

The eyes are clear and wide open. However on the DL side eyes are much clearer. This is due to reuse of wavelengths, cross talk and other noises in the UL side. From the graphs and eye diagrams, we can derive the result that fault free transmission is successfully achieved WDM-PON based on AWG.

4.2 50 GHz spacing on AWG-based scheme

This network was also used to run at 50 GHz channel spacing. All channels except channel 3 at OOK side performed error free. The minimum BER for channel 3 OOK was 4×10^{-9} . The reason for this is the presence of some performance limiting conditions that may be due to signal attenuation, crosstalk from co-propagating channels and beat noise (due to the square-law photodetection

process), laser relative intensity noise apart from signal-dependent shot noise, and thermal noise at the receiver end. However if the power of the laser source is increased from 0 to 5 dBm, then its minimum BER is reduced to 10^{-13} .

4.3 Comparison with scheme based on MUX-DEMUX

When compared with other conventional WDM-PON networks using MUX/DEMUX, this scheme performs better because of its high power sensitivity and lower power penalty. Also there is no need of optical power amplification or dispersion management.

5 Conclusions

AWG based 10 Gbps full duplex WDM-PON system is simulated and analyzed by utilizing a RZ-DPSK modulation technique for down-link direction. In the ONU, the DL signal is re-modulated for the UL direction with a data rate of 10 Gbps per channel. A fault free and inexpensive colorless WDM-PON full duplex transmission operation for a data rate of 10 Gbps per channel over a distance of 25 km is achieved, without any means for signal amplification on the fiber and dispersion compensation management.

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