Front. Optoelectron. 2013, 6(1): 102–107
DOI 10.1007/s12200-012-0276-8

RESEARCH ARTICLE

Impact of Rayleigh backscattering on single/dual feeder fiber WDM-PON architectures based on array waveguide gratings

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Abstract The performance of colorless wavelength-division multiplexing passive optical network (WDM-PON) systems suffers from transmission impairments due to Rayleigh backscattering (RB). A single feeder fiber colorless WDM-PON architecture was modeled, simulated and analyzed at 25 km distance that sustained the noise induced by RB. We analytically compared the performances between single feeder and dual feeder WDM-PON architectures based on array waveguide gratings (AWGs). For single feeder WDM-PON, the high extinction ratios in both return-to-zeros (RZ)-shaped differential phase shift keying (DPSK) downstream and intensity remodulated upstream data signals helped to increase the tolerance to the noise induced by RB. However, a cost effective colorless system in dual feeder WDM-PON architecture was achieved without any optical amplification and dispersion compensation, low power penalty. These results illustrate that single feeder fiber architecture was cost effective in terms of deployment having a power penalty, while dual feeder fiber had lower power penalty thereby with better performance. Simulation results show that downstream and upstream signals achieved error-free performance at 10-Gbps with negligible penalty and enhanced tolerance to the noise induced by RB over 25 km single mode fiber.

Keywords wavelength division multiplexed-passive optical network (WDM-PON), Rayleigh backscattering (RB), differential phase shift keying (DPSK), arrayed waveguide grating (AWG)

1 Introduction

The emergence of broadband multimedia services is increasing exponentially in access networks. These services include multimedia broadcast, video conferencing, high-definition TV, voice over internet protocol VoIP, e-learning and interactive games, etc [1]. In the near future, it is predicted that an individual user will require at least 30 Mbps throughput for the emerging multimedia applications [2]. Different multiplexing techniques are used in a passive optical network (PON) system to achieve multiple access capability because many optical network units (ONUs) are fed by a single optical line terminal (OLT). Some service providers are using time division multiple access (TDMA) technique to provide baseband services as in the case of Gigabit PON (GPON) and Ethernet PON (EPON). The use of TDMA-PON is constrained by its limitations, such as bandwidth, cost and link reach. This has given rise to the use of next generation PON architectures, among which WDM-PON is considered to be the best for satisfying the future bandwidth requirements in access networks [3,4]. Among various access solutions, WDM-PON is considered to be a promising next generation access network solution due to its high bandwidth provision, protocol transparency and flexibility. A WDM-PON network, which is characterized by a centralized light source at the OLT in central office and with data re-modulation using downstream signal received at the optical network unit (ONU), is viable solution for low cost implementation of the upstream transmitter [5]. As the access networks have been revolutionized by the introduction of WDM-PONs, however their competitiveness as access method has been deterred by its high initial and maintenance cost due to a number of wavelength specific light sources [6]. The deployment of wavelength

Received May 25, 2012; accepted July 8, 2012

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specific transmitters and wavelength selective components at both the OLT and each ONU has reduced the application of this technology in the current optical transport market due to high capital expenditure (CAPEX). Hence, cost effective WDM technology is a key solution for the next generation WDM-PONs [7,8].

However, all these schemes utilize dual fiber architecture for full duplex transmission. The introduction of single feeder fiber in WDM-PON can further minimize the deployment cost keeping in view the mitigation of Rayleigh backscattering (RB) phenomenon. To obtain optimum performance of both downstream and upstream transmission, various modulation schemes have been proposed in recent past. To decrease RB inducing cross talk in WDM-PON's multi-wavelength source, shared seeding schemes and pulse broadening technique have been incorporated to cater the induced cross talk in reflective semiconductor optical amplifiers (RSOA) based WDM-PON's [9–11]. A re-modulation approach in WDM-PON is proposed by Xu et al. in Ref. [12]. It is reported that decreasing modulation depth of differential phase shift keying (DPSK) signal will make the upstream signal more robust to RB induced noise to cater the RB scattering.

In this paper, we analyzed the RB phenomenon which is dominant in single feeder fiber WDM-PON system compared to the dual feeder fiber systems. We considered that the question of how well the single feeder and dual feeder WDM-PON systems outperform each other in terms of cost and performance was compared. An intensity re-modulation scheme was proposed, which demonstrated enhanced RB tolerance for a colorless 10-Gbps WDM-PON with single feeder fiber. The tolerance of the upstream signal against the RB induced noise is enhanced by the reduction in modulation depth of the downstream DPSK signal. The rest of the paper structure is divided in four sections. Section 2 describes the working principle and network architecture, Section 3 presents the simulation setup and operation, Section 4 discusses the transmission performance and analysis, and finally Section 5 concludes the paper.

2 Working principles and network architecture

There are two basic components of RB, which interferes with the upstream data signal, when it propagates from ONU to OLT in a conventional single feeder WDM-PON shown in Fig. 1. The first component, the carrier backscattering E_{CB} is generated by the carrier being delivered to ONU. The mathematical expression for E_{CB} is given as below [13,14]:

$$E_{\mathrm{CB}} = E_{\mathrm{C}}B(1-\mathrm{e}^{-2\alpha L}), \tag{1}$$

where E_{C} is the carrier power injected into the fiber, $B = S_{\alpha_{\mathrm{S}}}/2\alpha$ is the fiber scattering co-efficient of $\alpha_{\mathrm{S}}(\mathrm{K}\cdot\mathrm{m}^{-1})$, S is the fiber recapture co-efficient (dimensionless), α_{S} is the attenuation co-efficient and L indicates the fiber length.

The second component, the signal backscattering E_{SB} is generated by the modulated upstream data signal. The back scattered lights re-enters the ONU, where it is re-modulated and reflected toward the receiver at OLT. The mathematical expression for E_{SB} is given as

$$E_{\mathrm{SB}} = E_{\mathrm{C}}B(1-l^2)l^2g^2. \tag{2}$$

The noise in Eq. (2) again will create RB resulting in continuous iterative process. Thus, Eq. (2) develops into

$$E_{\mathrm{SB}} = E_{\mathrm{C}}l^2\sum_{n=1}^{\infty}B^n(1-l^2)^n g^{n+1}. \tag{3}$$

The spectrum of E_{CB} remains the same as the continuous wave (CW) carrier, whereas the spectrum of E_{SB} becomes broaden, as it is modulated twice at ONU. It has been observed that under normal conditions, this expression depends on the squared gain, which may lead to systems limitations.

The proposed WDM-PON architectures based on arrayed waveguide gratings (AWGs) for dual fiber and single fiber are shown as in Figs. 2 and 3, respectively. AWG is a key device in WDM optical communication systems, and is also known as the waveguide grating router (WGR) or the phasar (phased array). It performs functions, such as wavelength multiplexing, demultiplexing, wavelength filtering, signal routing and optical cross-connects, was first devised by Smit [15]. 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. The mandatory elements in the proposed WDM-PON networks contain continuous light source, return to zero differential phase shift keying (RZ-DPSK) transmitter/receiver, AWG, single-mode fiber (SMF), on off keying (OOK) receiver/transmitter and photo-detector. The RZ-DPSK transmitter consists of a continuous laser source and two cascaded Mach-Zehnder ($\mathrm{LiNbO_3}$) modulators. The first modulator is used to perform the phase modulation and the second Mach-Zehnder 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 dual feeder fiber and single feeder fiber AWG based 4 × 4 WDM-PON systems are shown in Figs. 2 and 3, respectively. Accordingly, a continuous light source is externally modulated by a $\mathrm{LiNbO_3}$ 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

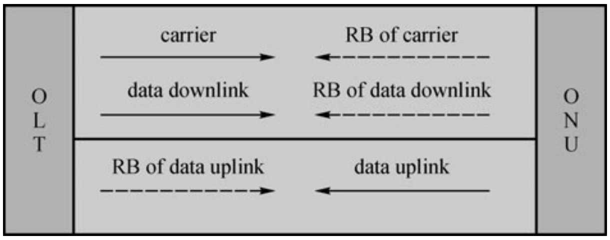

Fig. 1 Path of two back reflection lights in conventional one fiber WDM-PON systems

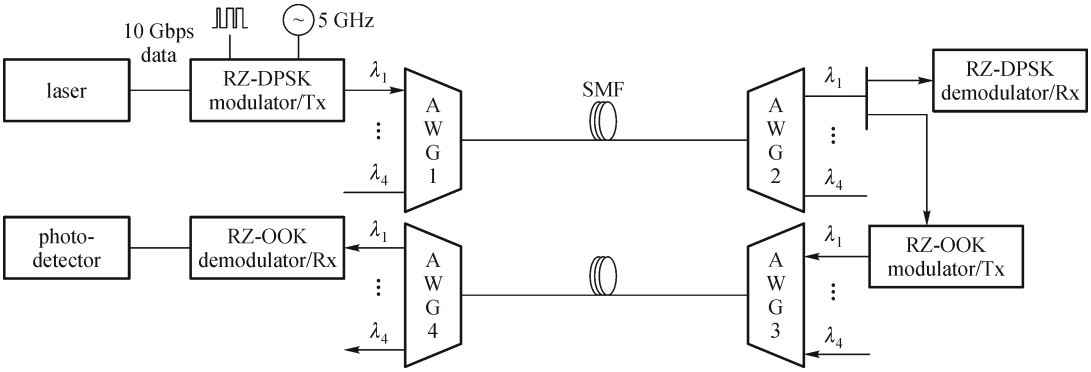

Fig. 2 Schematic diagram of dual fiber AWG WDM-PON system

from second MZM optical modulator would be a periodic RZ-DPSK pulse train. The generated downstream RZ-DPSK signal was then fed to AWG along with other downlink channels each having a data rate of 10 Gbps. The multiplexed signal is transmitted over a SMF of 25 km length. At the other end, 1×4 AWG demultiplexer (DEMUX) is used to de-multiplex 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 intensity modulation technique OOK to be transmitted back to the OLT, in order to avoid the cost of a specific laser in each ONU. The generated upstream signal is transmitted back to the OLT using SMF through a complete path. However, regarding typical OLT configurations, the up- and down-link paths are merged by means of an optical circulator and therefore a possible reflection is strongly attenuated.

3 Simulation setup and operation

To discuss the performance of the proposed WDM-PON systems, we established models for simulation using Optisystem according to network architectures as shown in Figs. 2 and 3 for dual feeder fiber and single feeder fiber arrangements, respectively. The transmission performance of the proposed AWG based WDM-PON with four 10-Gbps downlink channels, and four 10-Gbps uplink channels over 25 km feeder SMF using a centralized light source for both downlink, and uplink directions is realized. Four continuous light waves with a launch power of 0 dBm are generated by four distributed feedback (DFB) lasers at wavelengths 1552.52 (λ_1), 1552.04 (λ_2), 1551.56 (λ_3), and 1551.08 nm (λ_4) for four different channels respectively keeping 60 Hz channel spacing. A transmitter consisting of two cascaded $LiNbO_3$ MZM is used to modulate all channels independently. Phase modulation (biased at the null point) is performed by the first modulator of each transmitter and is referred to as the data modulator (DM). So, each generated wavelength is first externally modulated by the MZM driven by 10-Gbps 2^7–1 pseudorandom binary sequence data. The output of the first MZM is fed to the second modulator known as the pulse carver, driven by a 5-GHz clock pulse generating about 33% duty-cycle RZ pulses.

Thus, the four RZ-DPSK signals produced are then multiplexed by a 4×1 AWG MUX on 60 GHz channel grid and transmitted over 25 km single mode feeder fiber. The downlink multiplexed signals is first de-multiplexed using 1×4 AWG DEMUX and then transmitted to the corresponding ONU. At the access node, a 3 dB optical splitter divides downstream into two parts. An intensity modulation technique of 10-Gbps OOK is used to re-modulate the first half of the power splitter to generate upstream data signal. The second half of the power splitter is demodulated by 1-bit delayed interferometer (DI) and balanced photo diodes. The IM is biased at transmission null point

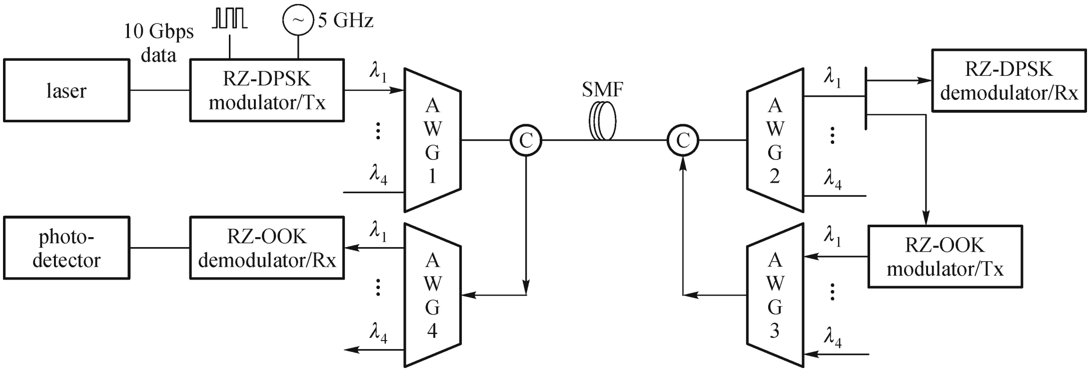

Fig. 3 Schematic diagram of single fiber AWG WDM-PON system

and the driving voltage is set to $2V_\pi$.

In case of dual feeder the re-modulated RZ OOK upstream signal is transmitted back to the OLT through another 25 km of SMF-28 before being received by a direct detection PIN receiver. In a single feeder fiber architecture as the uplink and downlink paths are merged by means of optical circulators, the generated upstream signal returns to the OLT through a complete path through the same fiber before its reception by a direct detection PIN receiver. The pseudorandom bit stream (PRBS) length of the upstream data is set to 2^7–1. A 4th order Bessel low-pass electrical filter (LPF) with 3 dB bandwidth of 12.5 GHz is used as RZ OOK encoder for 10 Gbps upstream data. The general settings of the fiber used in our simulation are given in Table 1.

Table 1 Simulation parameters

parameters	values
dispersion parameter of SMF	17 ps/nm/km
dispersion slope of SMF	0.075 ps/nm^2/km
attenuation coefficient of SMF	0.2 dB/km
effective core area of SMF	80 μm^2
non linear index-coefficient of SMF	2.6×10^{-20}
responsivity of photo detector	1 A/W
dark current of photo detector	10 nA

4 Performance analysis and results

The bit error rate (BER) as a function of received optical power for both the downstream and upstream transmission for four channels for dual feeder fiber WDM-PON is shown in Fig. 4 using back to back scenario and after traversing 25 km SMF. In case of the back to back scenario, the 10-Gbps DPSK data signal provides a BER of 10^{-9} at a received power of -39 dBm in the downstream direction, while in the upstream the 10-Gbps OOK data signal provides a BER of 10^{-9} at a received power of -28 dBm. After traversing 25 km SMF the 10-Gbps DPSK data signal provides a BER of 10^{-9} at received power of -38 dBm in the downstream direction , while in the upstream the 10-Gbps OOK data signal provides a BER of 10^{-9} at a received power of -24 dBm. In upstream, a power penalty of 4.0 dB relative to B2B scenario has been experienced at BER of 10^{-9} after traversing 25 km SMF. The constant performance of both downstream and upstream signals clearly shows the application of the scheme for the implementation in WDM-PONs.

The BER as a function of received optical power for both the downstream and upstream transmission for four channels for single feeder fiber WDM-PON is shown in Fig. 5 using back to back scenario and after traversing 25 km SMF. In case of the back to back scenario, the 10-Gbps DPSK data signal provides a BER of 10^{-9} at received power of -41 dBm in the downstream direction, while in the upstream the 10-Gbps OOK data signal provides a BER of 10^{-9} at a received power of -28 dBm. After traversing 25 km SMF.

The 10-Gbps DPSK data signal provides a BER of 10^{-9} at received power of -40 dBm in the downstream direction , while in the upstream the 10-Gbps OOK data signal provides a BER of 10^{-9} at a received power of -34 dBm. In upstream, a power penalty of 6.0 dB relative to B2B scenario has been experienced at BER of 10^{-9} after traversing of 25 km SMF. This power penalty could be largely caused by two basic components of RB, i.e., the carrier backscattering and the signal backscattering along with chromatic dispersion. However, the stable performance of both downstream and upstream signals clearly illustrates the deployment of such a low-cost scheme for implementation in future WDM-PONs.

The loop power penalty of upstream signal comparative to the downstream signal in dual fiber configuration is ($38-24=14$ dBm) as shown in Fig. 4, whereas for single fiber architecture it is ($40-34=6$ dBm) as shown in Fig. 5. Therefore, it is evident from the above results that the single fiber architecture shows better loop power penalty as compared to dual fiber architecture. Figures 6(a) and 6(b) show the corresponding optical eye diagram for downlink and uplink channels. The eyes are clear and wide open.

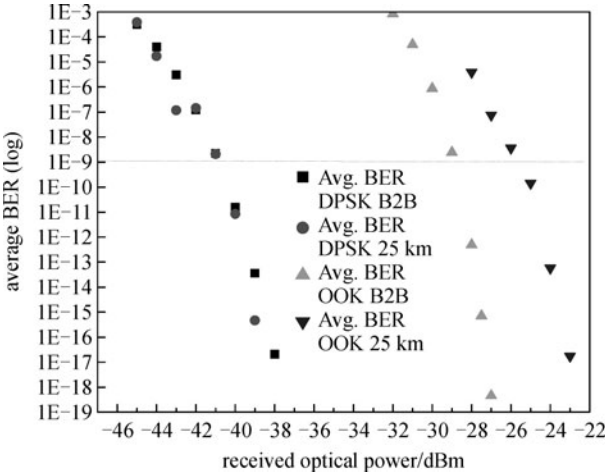

Fig. 4 BER graph for downlink and uplink of dual feeder WDM-PON

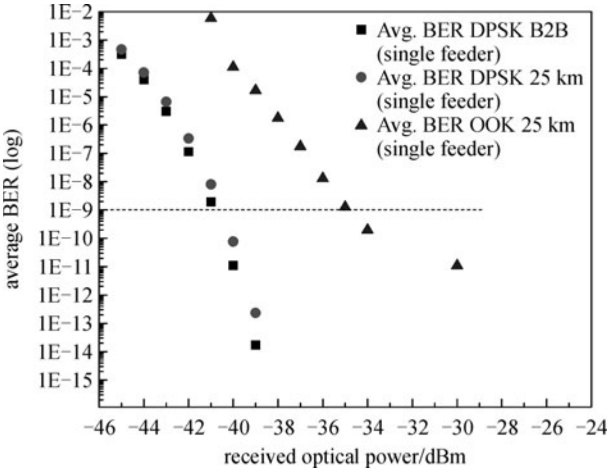

Fig. 5 BER graph for downlink and uplink of single feeder WDM-PON

5 Conclusions

We proposed and demonstrated a single-fiber, full-duplex, colorless WDM-PON architecture based on AWG with enhanced tolerance to impairments induced by RB and analytically compared it with the dual feeder fiber arrangement. It is demonstrated that the high extinctions ratio in both RZ-shaped DPSK downstream and intensity remodulated upstream data signals help to increase the tolerance to RB noise. It is concluded that the single feeder fiber arrangement is cost effective as RB can be mitigated. An error-free colorless transmission over a distance of 25 km with lower BER is achieved in both arrangements. The upstream power penalties of dual feeder fiber and single feeder fiber systems are 4.0 and 6.0 dBm, respectively.

Acknowledgements This work was supported in part by the National Basic Research Program (No. 2010CB328204), the National High Technology Research and Development Program (No. 2012AA011301), the National Natural Science Foundation of China (Grant No. 60932004), the Research Fund for the Doctoral Program of Higher Education (RFDP Project) (No. 20090005110013) and the Fundamental Research Funds for the Central Universities (No. 2011RC0406).

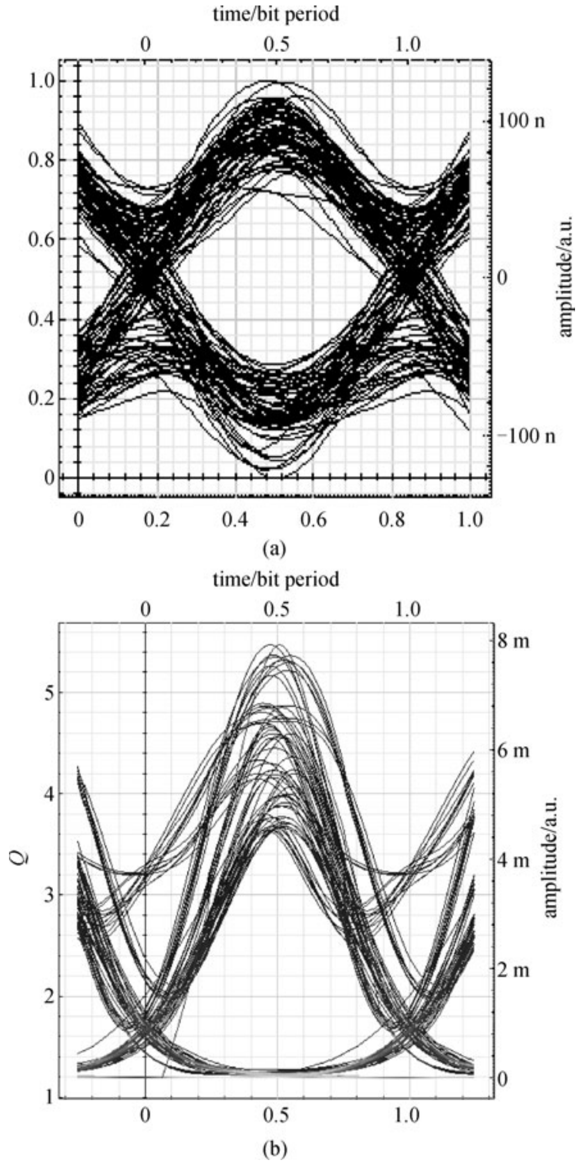

Fig. 6 Eye diagrams for (a) DPSK downlink and (b) OOK uplink for single fiber architecture

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