Performance enhancement of WDM-PONs: Interferometric noise reduction

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ABSTRACT

In this paper, we propose and evaluate a wavelength division multiplexing passive optical network (WDM-PON) architecture with a centralized light source (CLS). The use of only one 10 GHz band reject filter at the remote node (RN) allows WDM-PON to have a minimal value of the optical interferometric noise, which is induced by Rayleigh backscattering (RB), in the main lobe of each downstream (DS) optical signal. Utilizing this filter achieves an optical interferometric noise reduction in the upstream (US) direction and the simulation results indicate an enhancement in the performance of a bit error rate (BER) to be 10^{-11} and in the Q-factor to be above 6.0. Owning to the US signal modulation without extra light source, this architecture successes in power saving and efficient utilization of the wavelength.

Keywords: WDM-PON, CLS, RB interferometric noise, BER.

1. INTRODUCTION

The most widely common access network is the passive optical network (PON) which is characterized by its large bandwidth data transmission and reliability. Several PON architectures have been proposed [1]. Among them, the WDM-PON that provides an attractive solution for broadband services (video conferencing, internet access, and multimedia services) for next-generation networks [2]. WDM-PON is the most successful technique in increasing the system capacity [3, 4]. WDM-PONs is applied in a few countries, and it is looking forward to be a long-term solution for high performance access networks [5].

The WDM-PON with a CLS is the cost-effective solution for the next-generation of PONs [6]. However, the network with a wavelength reuse gives rise to interferometric noise caused by RB [7]. RB noise is a critical issue that can severely degrade the performance of the US signal in single fiber system because upstream and downstream signals are using the same wavelength [8]. Some researchers proposed several models to represent the mechanism of the RB noise [9, 10]. Q. Feng et al. investigated the intensity and spectrum characteristics of backscattered noises and their influence in a bidirectional PON system [11].

In this paper, a WDM-PON architecture is offered and investigated to reduce the RB interferometric noise. Differential-phase-shift-keying (DPSK) modulation format is used for 10 Gb/s DS at OLT. DPSK has the advantage of detecting the transmitted data by phase. Therefore, using band reject filter at RN to cut off 10 GHz band from the main lobe of DS signal will not affect the DS data. In the US direction, on-off keying (OOK) modulation format is used for 2.5 Gb/s. This architecture has the advantage of transmitting the signal over 45 km without any active elements.
The remainder of this paper is organized as follows. Section 2 reviews the existing RB mitigation and reduction techniques. The details of the proposed architecture are explained in Sec. 3. In Sec. 4, system evaluation and obtained results are discussed. The merits of this work are clarified in Sec. 5 which is devoted for the main conclusions.

2. RELATED WORK

Reduction and mitigation are the two main strategies used in the most literatures to compensate the RB. In Ref. [12], a complex WDM PON architecture uses a quadrature amplitude modulation (QAM) orthogonal frequency division multiplexing (OFDM) at DS modulation and two fibers 20 km length to mitigate the RB interferometric noise effect.

In [13], the architecture utilizes DPSK modulation at DS and optical carrier-suppressed subcarrier modulation (OCS-SCM) at US modulation with 20 km fiber length. This scheme increases complexity at ONU to mitigate the RB interferometric noise.

A full-duplex PON access architecture is demonstrated at [14], utilizing orthogonal codes and correlation receiving methods. This PON can mitigate the RB interferometric noise by using reflective semiconductor optical amplifier (RSOA), but this requires high receiving power in the ONU. The data rate for the DS signals is 5 Gb/s and for the US signal is 1.25 Gb/s with a BER of 10\(^{-7}\).

3. WDM-PON PROPOSED ARCHITECTURE

The proposed WDM-PON architecture, which is illustrated in Fig. 1, has 16-channels and centralized light source. This architecture is capable of transmitting 10 Gb/s for each DS channel and 2.5 Gb/s for US.

![Fig. 1 16-Channel WDM-PON proposed system with CLS.](image)

In order to evaluate the performance of the band reject filter in WDM-PON system, a simulation is carried out using the ‘Optisystm™’ simulation software from ‘Optiwave’.
Table 1 represents the operating parameters applied to the proposed system which are extracted from standards and literature [15].

Table 1 WDM-PON system parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream Bit Rate</td>
<td>10</td>
<td>Gb/s</td>
</tr>
<tr>
<td>Upstream Bit Rate</td>
<td>2.5</td>
<td>Gb/s</td>
</tr>
<tr>
<td>Distance</td>
<td>45</td>
<td>km</td>
</tr>
<tr>
<td>Channel Spacing</td>
<td>50</td>
<td>GHz</td>
</tr>
<tr>
<td>Channels Center Frequency</td>
<td>193.1</td>
<td>THz</td>
</tr>
<tr>
<td>Number of Channels</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Signal Power</td>
<td>5</td>
<td>dBm</td>
</tr>
</tbody>
</table>

In the following section, the simulation parameters of OLT, RN and ONU are explained in details.

3.1. Optical Line Terminal (OLT)

Each OLT consists of a DS transmitter and an US receiver as illustrated in Fig. 2.

![Diagram of OLT Internal Structure](image)

Fig. 2. OLT Internal structure.

A DPSK modulator is the DS transmitter. For generating the optical DPSK modulated signal, two Mach-Zehnder modulators (MZMs) are utilized (MZM1 and MZM2) as shown in Fig. 2. MZM1 is a phase modulator and has 500 dB extinction ratio. The electrical inputs of MZM1 are connected by a 10 Gb/s non-return-to-zero (NRZ) pattern with duobinary precoder. For the optical input of MZM1, a continuous wave (CW) laser source with 5 dBm launched power is applied.

MZM2 cuts out only the amplitude-modulation-free center portions of the optical DPSK modulated signal by applying 5 GHz clock pulse on its electrical inputs. MZM2 is called a pulse carver and it has 50 dB extinction ratio.

In the US receiver shown in Fig. 2, the OOK demodulator is used. It consists of PIN photodetector to convert the optical signal into an electrical signal and a low pass filter (LPF) is used to enhance the electrical signal and prepare it for data extraction. The PIN specifications are tabulated in Table 2 [16].
Table 2 PIN specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark current</td>
<td>10</td>
<td>nA</td>
</tr>
<tr>
<td>Responsivity</td>
<td>0.8</td>
<td>A/W</td>
</tr>
</tbody>
</table>

Now, the optical signals are prepared for multiplexing and transmitting over 45 km single-mode fiber (SMF). The SMF specifications are tabulated in Table 3 \(^{[17]}\).

Table 3 SMF specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (s)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation</td>
<td>0.2</td>
<td>dB/km</td>
</tr>
<tr>
<td>RB coefficient</td>
<td>5e-005</td>
<td>km(^{-1})</td>
</tr>
<tr>
<td>Length</td>
<td>45</td>
<td>Km</td>
</tr>
</tbody>
</table>

3.2. Remote Node (RN)

The RN internal structure is illustrated in Fig. 3. At the RN, only one band reject filter is used to cut off 10 GHz bandwidth (which is a very narrow band) from the main lobe of the 16 transmitted DS optical signals which contains the main power of RB \(^{[18]}\). Due to the periodic frequency response of the band reject filter, the RB interferometric noise could be simultaneously cut off from all the 16 DS signals.

![Fig. 3. RN internal structure](image)

Figure 4(a) shows the 16 DS channels spectrum before being applied to the band reject filter. The red residual is representing the RB interferometric noise effect and its power \(\sim 73 \text{ dBm}\). The band reject filter can effectively cut off the RB interferometric noise of the optical DS signals with a very narrow spectral width as shown in Fig. 4(b).
3.3. Optical Network Unit (ONU)

Figure 5 demonstrates the ONU internal structure. Each ONU contains DS receiver, an US transmitter and an optical coupler. A 20:80 optical coupler is used to divide the DS signal into two parts. The 20% of the DS signal is used in extracting the DS information and the remaining 80% is the power source for US transmission.

In the DS receiver, signal is demodulated by DPSK demodulator and a LPF is used to refine the electrical signal before observing the data. The DPSK demodulating method is achieved by comparing the phase of two sequential bits. An incoming DPSK optical signal is first split into two beams with equal intensities, in which one beam is delayed in space by an optical path difference that introduces a time delay corresponding to one bit as shown in Fig. 5. The two beams in the two paths are then coherently recombined to interfere each other destructively. The interference intensity is measured and becomes the intensity-keyed signal.

In the US transmitter, an OOK modulator is utilized. The OOK modulator is composed of a MZM which uses 80% of the DS signal as a power source. A 2.5 Gb/s data sequence is generated and applied also to the MZM data input as shown in Fig. 5. The output of MZM is OOK which is a simple format compared with other formats mentioned in Refs. [19, 20]. Furthermore, there is no need to add a laser power source on each ONU, leading to a more cost effective system than that studied in Ref. [21].
The US signals are free from RB interferometric noise. The modulated signals are applied to the MUX and are ready to be retransmitted over 45 km. At the other end, the US signals are demultiplexed and each OLT can pick its own wavelength.

4. SIMULATION RESULTS AND DISCUSSION

To verify the proposed WDM-PON architecture, it is evaluated and discussed using a simulation. The eye diagram of random channels is presented to verify the successful transmission. The eye diagrams and the Q-factor are key performance indicators for all optical and non-optical networks [22]. Figure 6 represents the eye diagrams for random channels without using the band reject filter at the RN. The red line shows the maximum amplitude of each eye diagram that represents the value of the Q-factor.

![Eye diagrams](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Fig. 6. Eye diagrams for random channels at their OLTs in the upstream receiver without band reject filter at RN.
From Fig. 6, the maximum Q-factor is 5.2 corresponding to $10^{-7}$ BER. These values are not suitable when compared with result of Ref. [23].

In this section, the effective enhancement for using the band reject filter at RN on the performance of the proposed WDM architecture is presented. Figure 7 displays the eye diagrams for channels 2, 8, 9 and 16 (random channels as samples) with using band reject filter at RN. From Fig. 7, it can be observed that the size of the eye openings, the magnitudes of the amplitude and timing errors enhanced. After a successful transmission of the proposed CLS scheme, the obtained results show a BER of $10^{-11}$ and Q-factor above 6.0 for almost all channels.

![Eye diagrams for random channels at their OLTs in the upstream receiver with band reject filter at RN.](image)

Fig. 7. Eye diagrams for random channels at their OLTs in the upstream receiver with band reject filter at RN.

5. CONCLUSION

In this work, a 16-channels WDM-PON system using CLS scheme is proposed, simulated and evaluated. A 73 dBm RB interferometric noise is successfully cut off using one band reject filter at the RN. Due to the great suppression of the RB interferometric noise, a 45km transmission distance is achieved without active elements. Our proposed WDM architecture
achieved a remarkable extended distance with BER of $10^{-11}$. The proposed system has the advantage of expanding the DS capacity to be 160 Gb/s (16 channels×10 Gb/s) and 40 Gb/s (16 channels×2.5 Gb/s) for the US transmission capacity. This scheme minimizes the ONU complexity since there is no need to add a laser power source at each one.

REFERENCES
