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ARTICLE

20-Gb/s Transmission Over 25-km in Wavelength Division Multiplexing Passive Optical Network with Centralized Light Source

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In this study, a full duplex of 16-channel wavelength division multiplexing passive optical network (WDM-PON) architecture is designed and investigated using a centralized light source (CLS). A 20-Gb/s downstream bit rate is achieved without using a digital signal processing (DSP) unit or active elements. A carefully designed Mach-Zehnder modulator (MZM) operates as a pulse carver to refine single channel spectrum is utilized at each optical line terminal (OLT). More channels, a maximum bit error rate (BER) of 10^{-13} and at least quality factor (*Q*-factor) of 7.0 are achieved. An on off keying (OOK) format of 5-Gbit/s is used for the upstream transmission. This is done with low complexity and a transmission distance of 25 km.

Keywords: WDM-PON, MZM, CLS, DPSK, OOK, BER.

1. INTRODUCTION

Telecommunication networks using optical fibers as the primary transmission medium are commonly referred to as optical fiber networks and are designed in such a way that the unique attributes of optical fibers are fully utilized.[1] Among the various multiplexing approaches (time, frequency, code division, etc.), wavelength-division-multiplexing (WDM) offers a good compromise among the number of subscribers that can be served with low system complexity. Furthermore, WDM offers scalability, and allows different service providers to share the same optical network. In addition, it facilitates time or frequency multiplexing on selected wavelengths.[2] Passive optical networks (PONs), which are short-reach optical networks free from optical amplification stages and powered elements, have been widely considered by operators to provide connectivity over different access media to a large number of subscribers.[3]

The wavelength-division-multiplexing passive optical network (WDM-PON) has become a promising solution for the next generation of fiber-to-the-home (FTTH) architecture owing to its virtually unlimited bandwidth, security, and protocol transparency.[4] WDM-PONs offer much higher transmission capacity and longer transmission distance than current PONs by using separate wavelengths for each end unit.[3,5]

Nonlinear and dispersion effects may affect the performance of a WDM-PON system, but certain modulation formats can be used to improve the quality of the signal.[6] RZ-DPSK formats provide significant advantages including power saving and minimization of nonlinear and dispersion effects when used in WDM-PON designs.[7,8] The CLS technique that has been introduced and recently analyzed[9] has additional power-saving benefits, especially when coupled with DPSK in WDM-PON architectures.[10,11]

Researchers designed and evaluated various WDM-PON architectures with the purpose of meeting the rapidly growing demand for bandwidth as well as excellent performance (i.e., low power consumption, readability, low complexity, and low BER).[12,13]

In this paper, the capacity of a CLS architecture is expanded to a record of 16-channel full-duplex operation. This work is primarily concerned with the advantages

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of central power source scheme as a power-saving architecture for WDM-PON.[11] A downstream capacity of 320-Gbit/s (20-Gbit/s × 16 channels) and an upstream capacity 80-Gbit/s (5-Gbit/s × 16 channels) are successfully achieved. This capacity enhancement is accomplished with using a pulse carver MZM that refines the modulated signal spectrum. The proposed system is achieved with a lower power consumption compared to Refs. [14, 13] with a remarkable BER, transmission distance and without using a DSP unit as in Refs. [15, 16]. Increasing the number of channels with low power penalty combined with an exceptional BER/Q-factor and an acceptable transmission distance is the primary goal of this work. An RZ-DPSK and an OOK are used in downstream and upstream, respectively.

The remainder of the paper is organized as follows. Section 2 explains the detailed architecture of the proposed WDM-PON CLS scheme for downstream and upstream processes. Simulation results are presented and discussed in Section 3. This is followed by the main conclusions in Section 4.

2. ARCHITECTURE OF THE PROPOSED CENTRAL SOURCE WDM-PON SYSTEM

A full-duplex 16-channel WDM-PON centralized light source system that is capable of transmitting 20 Gb/s per downstream channel is illustrated in Figure 1. The generated downstream RZ-DPSK signal is multiplexed with a multiplexer (MUX). The RZ-DPSK versus NRZ-DPSK, in comparison RZ-DPSK, was found to have a distinct advantage in the deep saturation regime, showing almost no distortion in the received eye diagram.[8] Furthermore, it considers the usage of DPSK in the receiver to gain the benefits of DPSK. The balance detection method for DPSK successfully used for large tolerance to signal power variations in the receiver decision. No carrier component is used in DPSK receiver; this makes the DPSK receiver a cost effective modulation format.[6] The DPSK system has the advantages of high receiver sensitivity using balanced detection, high spectral efficiency, and large tolerance to the chromatic dispersion and narrow optical filtering which are more elastic to nonlinear effects than other system formats.[7]

The multiplexed signal is transmitted over a 25-km single-mode fiber (SMF). At the other end, a demultiplexer (DeMUX) is used to demultiplex the downstream signals and send them to their respective optical network units (ONUs). Each ONU retransmits the uploaded payload to respective OLTs using an OOK modulation technique of 5 Gb/s for each channel. Table I represents the

Table I. Overall system parameters.

Parameter	Value (s)	Unit
Distance$^{\alpha}$	25	km
Channel spacing$^{\beta}$	50	GHz
First channel$^{\beta}$	193.1	THz
Signal power	0	dBm

Notes: $^{\alpha}$since distance is >20 km, the system can be categorized as a highly scalable new generation PON.[17] $^{\beta}$Channel spacing and first channel match fixed-grid nominal central frequencies for WDM systems in the international telecommunication union (ITU) standards.[18]

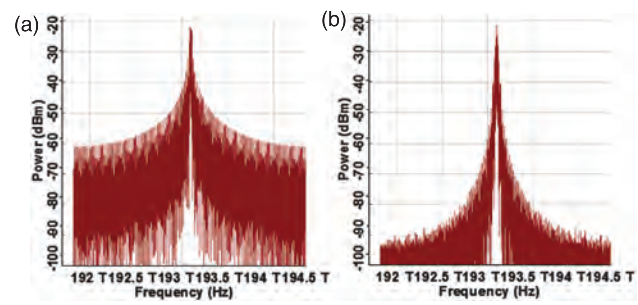

Fig. 2. Optical signals before and after the second MZM. (a) Optical signal before MZM2 (b) Optical signal after MZM2.

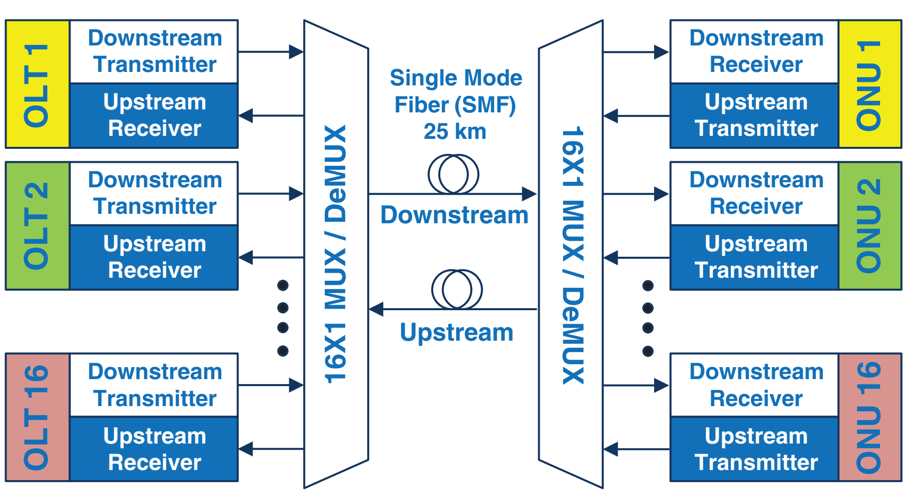

Fig. 1. 16-channel WDM-PON proposed system.

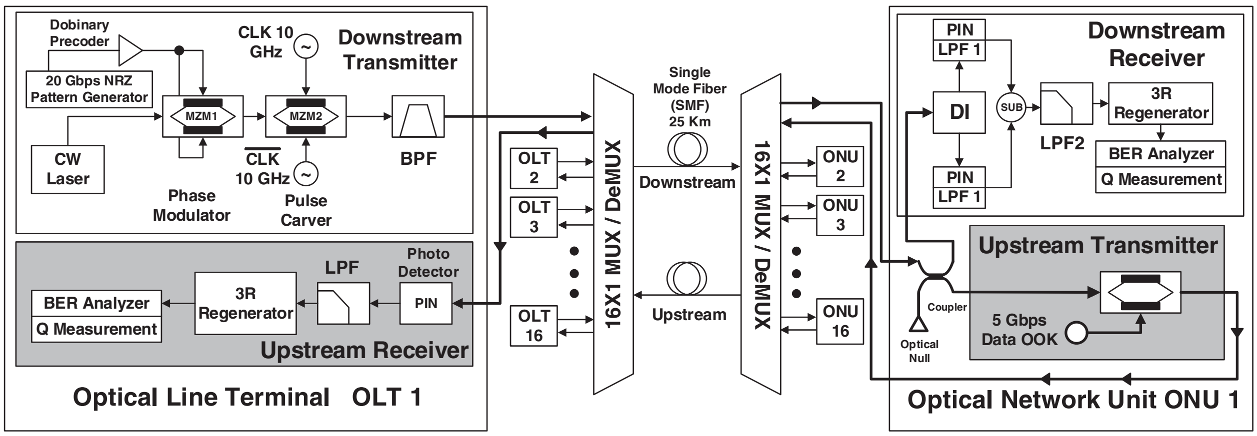

Fig. 3. WDM-PON proposed system with internal structure for each OLT and ONU.

Table II. Specification of SMF.

Parameter$^{\alpha}$	Value	Unit
Numerical aperture (NA)	0.14	N/A
Attenuation	$\leq$0.2	dB/km
Attenuation difference	$\leq$0.02	dB/km
Dispersion	$\leq$18.0	ps/nm · km

Note: $^{\alpha}$at (193.1 THz ≈ 1550 nm).

operating parameters applied to the proposed system which are extracted from other literature and standards.

2.1. Downstream Architecture

A 20-Gbit/s non-return-to-zero (NRZ) pattern is generated with a continuous wave (CW) laser source and is supplied to a Mach-Zehnder modulator 1 (MZM1). Subsequently, the duobinary precoder is used to form the electrical DPSK as shown in Figure 3. Then, the optical DPSK is applied to the second modulator, MZM2 (pulse carver), that cuts out only the amplitude-modulation-free center portions of the bits.[19] The optical signals after MZM1 and MZM2 are presented, respectively, in Figures 2(a and b).

These figures clearly show the importance of using the second modulator in eliminating the spectral broadening, and thereby, increasing the number of channels. Increasing the number of channels with low power penalty combined with an exceptional BER/Q-factor and an acceptable transmission distance is the primary goal of this work as will be demonstrated in the following sections. However, it is important to note that there is a residual chirp even with the zero-chirp biasing condition. This residual degrades the performance by decreasing the optical power from 6 to 4.143 dBm (before and after MZM2, or pulse carver).

Now, the optical signal is prepared for multiplexing and transmitting over 25 km. The ONU receives the downstream signal after demultiplexing to an optical coupler. The coupler is 20:80; hence the 20% of the downstream used in extracting the downstream information and the other 80% is the power source for the upstream transmission. The first part is applied to a typical balanced DPSK receiver as shown in the downstream receiver block of Figure 3.

2.2. Upstream Architecture

The other part of the DPSK signal extracted from the coupler is passed through a MZM. The other arm of MZM is driven by a 5-Gbit/s upstream data payload. The remodulated OOK upstream signal is multiplexed and transmitted back to the OLT through another 25 km of SMF (without laser source), as shown in Figure 3. Table II summaries the most important specifications of the used single mode fiber (SMF).

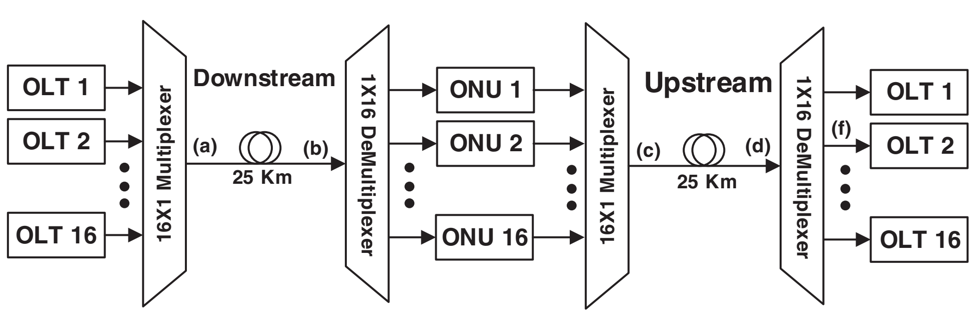

Fig. 4. System extended diagram.

3. SIMULATION RESULTS AND DISCUSSION

With the carefully choosing MZM, the minimum channel spacing of the CLS scheme is 50 GHz, not 60 GHz as demonstrated in Ref. [20]. As mentioned before, this will

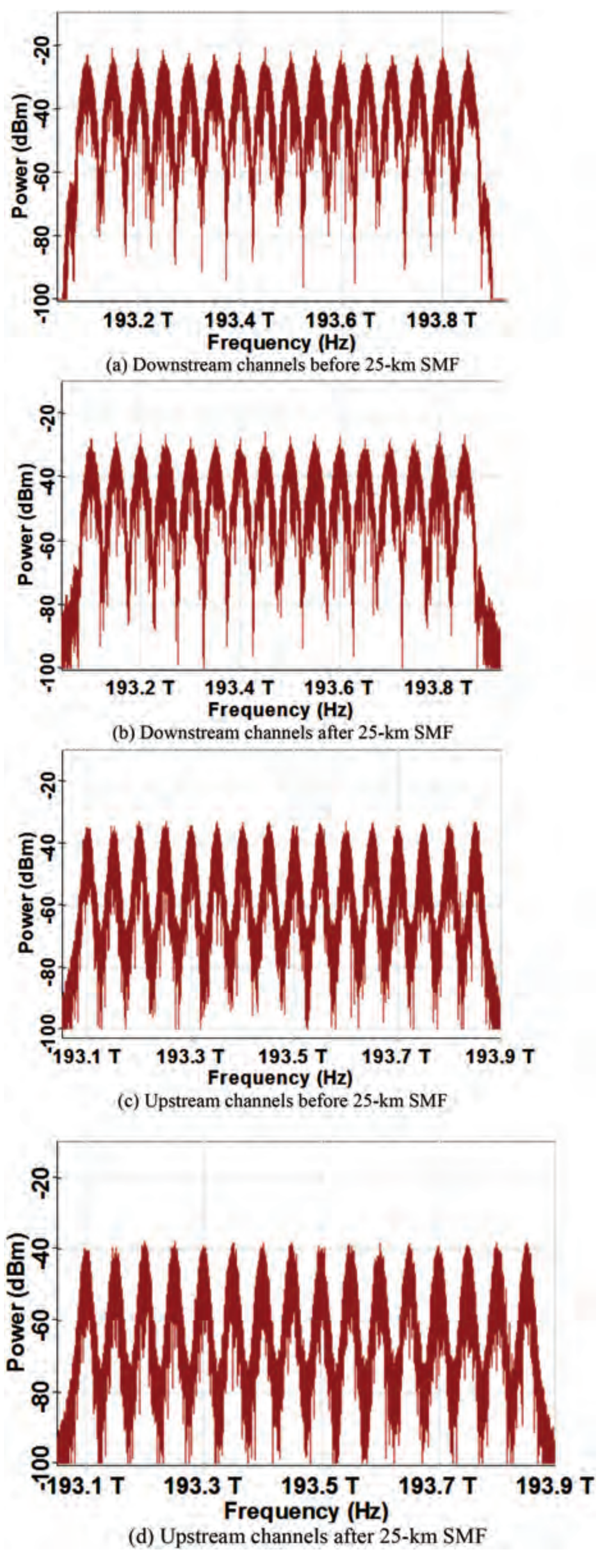

Fig. 5. Signal spectrum monitoring points of downstream and upstream.

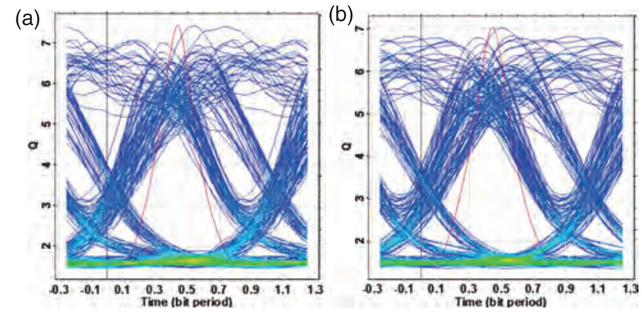

Fig. 6. Eye diagrams of (a) Channel 2, (b) Channel 16.

also enable adding more channels with maximum BER of 10^{-13}. In this section, a 16-channel WDM-PON with CLS scheme is simulated, analyzed, and evaluated. The system setup is shown in Figure 4, which is an extended version of Figure 1.

Figure 5 shows access points (a, b, c, and d) used for monitoring each stage of downstream and upstream transmission in the system. Figure 5(a) shows a multiplexed 16-channel 20 Gbit/s, each DPSK coded, generated from OLTs downstream transmitters and after applied to a multiplexer (point (a) Fig. 4). After being transmitted over 25 km, the 16 channels spectrum is presented in Figure 5(b) (point (b) Fig. 4).

Figure 5(c) (point (c) Fig. 4) shows the multiplexed 16-channel 5 Gbit/s, after processing in the ONU downstream receiver and upstream transmitter. A reduction in the power level, to −40 dBm, is observed due to the multiplexer insertion loss. The spectrum of upstream 16 channels is presented in Figure 5(d) (point (d) of Fig. 4).

The eye diagrams and the *Q*-factor are key performance indicators for all optical and non-optical networks. Specifications of exceptional eye diagram performance and great *Q*-factor limits for optical networking can be found in renowned works.[21,22] BER calculation is based on mathematical model and is extracted from researches and related works in WDM-PON performance analysis[23,24]

Figure 6 presents samples for the eye diagrams; channel 2 and channel 16 at their OLTs in the upstream receiver after a successful transmission through the proposed CLS scheme. The size of the eye openings and the magnitudes of the amplitude and timing errors are indicators that help determine the quality of transmission achieved.[21,22] Results show a BER of 10^{-13} and *Q*-factor above 7.0 for all channels.

4. CONCLUSION

In this work, a 16-channel full-duplex WDM-PON system using CLS architecture is simulated, analyzed, and evaluated. A centralized light source architecture targeting significant power-saving operation is achieved. A full system capacity of 320-Gbit/s and 80-Gbit/s is successfully achieved for downstream and upstream, respectively.

This capacity enhancement is accomplished with using a pulse carver MZM that refines the spectrum of the modulated signal spectrum. DPSK is used in downstream transmission, whereas OOK modulation format is used for upstream transmission. The number of channels is increased with a low power penalty with 10^{-13} BER, 7.0 Q-factor and an acceptable transmission distance of 25 km. The choice of theses specific transmission formats facilitates minimizing the ONU cost and complexity as much as possible.

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