Bidirectional intensity modulated/direct detection optical OFDM WDM-PON system*

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In this paper, we have evaluated a bidirectional wavelength division multiplexing passive optical network (WDM-PON) employing intensity modulated/direct detection optical orthogonal frequency division multiplexing (IM/DD-OFDM). The proposed system employs 100 Gbit/s 16 quadrature amplitude modulation (16-QAM) downstream and 5 Gbit/s on-off keying (OOK) upstream wavelengths, respectively. The proposed system is considered low-cost as non-coherent IM/DD OFDM technology and a simple reflective semiconductor optical amplifier (RSOA) colorless transmitter are employed and no dispersion compensating fiber (DCF) is needed. Based on the bit error rate (*BER*) results of WDM signals, the proposed WDM-PON system can achieve up to 1.6 Tbit/s (100 Gbit/s/λ × 16 wavelengths) downstream transmission over a 30 km single mode fiber (SMF).

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The wavelength division multiplexing passive optical network (WDM-PON) is considered a cost-effective solution in broadband optical access networks due to its capabilities of higher capacity, superior performance, and longer range[1,2]. WDM-PON can be enhanced by using optical orthogonal frequency division multiplexing (OFDM). OFDM is a high-efficiency modulation technique that can be utilized in WDM-PON to increase bandwidth usage and extend transmission distance. With OFDM, you can overcome the limitations of optical fiber, such as chromatic and polarization dispersion, as well as inter-symbol interference[3]. The OFDM is a multicarrier high data rate transmission technique used mainly in wireless communication systems. The OFDM scheme utilizes several lower-rate orthogonal subcarriers to transmit the overall high data rate. As a result of its multicarrier nature, OFDM signals usually exhibit amplitude variations in the time domain and have a relatively large dynamic range, referred to as the peak to average power ratio (*PAPR*). Several methods can be used for reducing *PAPR* in OFDM systems, including clipping, coding, non-linear compounding, ton reservation and ton injection, selective mapping (SLM), and partially transmit sequence (PTS)[4]. Generally, *PAPR* has no impact on short haul optical access networks since no high-power amplifiers are utilized.

The coherent OFDM systems offer higher receiver sensitivity. Direct detection (DD) OFDM is an attractive solution for PONs because it reduces phase noise and frequency offset while reducing system complexity[5,6]. The operation cost of PONs can be reduced by employing colorless optical sources at optical network units (ONUs). These colorless sources, such as the reflective semiconductor optical amplifier (RSOA) and injection-locked Fabry-Perot laser diode (FP-LD), are used to re-modulate the downstream signal with the upstream data[7,8]. Spectrally efficient modulation techniques such as *M*-ary quadrature amplitude modulation (*M*-QAM) can be employed for intensity modulated/direct detection (IM/DD) optical OFDM systems to increase both the capacity and efficiency of these systems. Recently, IM/DD optical OFDM systems have been investigated as a cost-effective solution for PONs[9-12]. A 40 Gbit/s time and wavelength division multiplexed passive optical network (TWDM-PON) utilizing *M*-QAM-OFDM modulation format with multi-color laser diodes (LDs) for visible light communication (VLC) was demonstrated in Ref.[13]. In Ref.[14], an RSOA-based radio-over-fibre (RoF) access network configuration has been proposed to feed future millimeter-wave radio systems. In Ref.[15], a cost-effective RSOA-based bidirectional WDM radio on free space optics (Ro-FSO) PON was demonstrated, where 10 Gbit/s data/voice and 1.49 Gbit/s high definition television (HDTV) signals were sent over 500 m FSO

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channel in downstream, and 1.25 Gbit/s data/voice signal was sent in upstream. Low cost WDM-PON architecture based on incoherent unpolarized light was demonstrated using an RSOA as a colorless optical source in Ref.[16]. In Ref.[17], multiple-input multiple-output (MIMO) RoF-PON architecture utilizing a 5G universal filtered multicarrier waveform and an OFDM wired signal was investigated for next-generation integrated wired and wireless access networks. In Ref.[18], a constellation-shaping chaotic encryption scheme was proposed to improve signal transmission performance and physical layer security in OFDM-PON. In Ref.[19], a bidirectional 11.25 Gbit/s 6 GHz OFDM wireless downstream and 2.5 Gbit/s OOK wired upstream access was demonstrated experimentally by using a single wavelength in WDM-PON architecture.

This paper investigates OFDM WDM-PON system providing up to 100 Gbit/s 16-QAM OFDM downstream and 5 Gbit/s OOK upstream signals using a single wavelength. The wavelength reuse system employs a colorless ONU based on wavelength-seeded RSOA to reduce WDM-PON costs. The block diagram of the proposed WDM-PON system is shown in Fig.1. At the central office (CO), there are N continuous-wave (CW) laser sources, where a data rate of 100 Gbit/s is generated for each one using a pseudo random binary sequence (PRBS) generator. The generated bits are converted into symbols using a 16-QAM sequence generator (4 bits per symbol). The QAM signals are then modulated into multiple orthogonal sub-carriers using an OFDM modulator. A fast Fourier transform (FFT) size of 1 024 is used in conjunction with a CP size of 100 to produce 512 OFDM subcarriers in 16-QAM format. After IFFT, CP is added to each OFDM symbol to prevent inter-symbol interference (ISI) between OFDM symbols. As the number of OFDM subcarriers (512) is half that of FFT points (1 024), the generated bit rate is 50 Gbit/s.

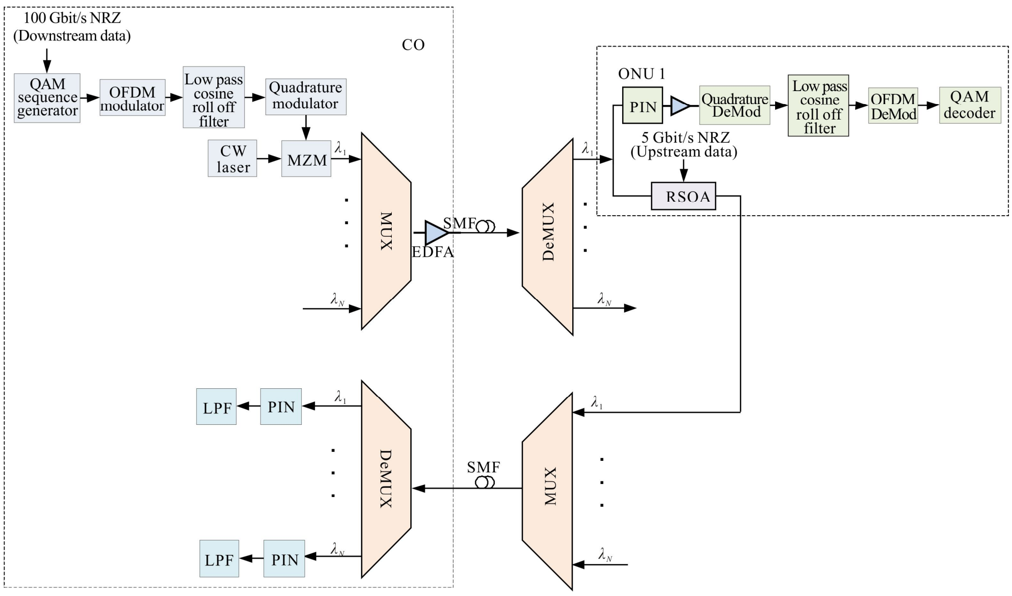

Fig.1 The proposed IM/DD OFDM WDM-PON architecture

Subcarrier tones with a lower rate will have a frequency range from 0 to 2.5 GHz. Using an analog mixer and a radio frequency (RF) source, a quadrature electrical modulator is utilized to increase the frequency of OFDM downstream signals up to 20 GHz. The Mach-Zehnder modulator (MZM) modulates the RF electrical signal into the optical domain by utilizing a CW laser source with a linewidth of 0.01 MHz and an output power of 10 dB to reduce the effect of fiber nonlinearity. Following the MZM, the optical signal passes to an N×1 WDM multiplexer (MUX) that multiplexes N downstream wavelength signals before being amplified by an erbium doped fiber amplifier (EDFA) that has 10 dB gain and 4 dB noise figure (NF), respectively. The resulting aggregate optical signal is then sent over a single mode fiber (SMF) with an attenuation of 0.2 dB/km and a dispersion of 16 $ps \cdot nm^{-1} \cdot km^{-1}$. A WDM demultiplexer (DeMUX) at the remote node (RN) is used to separate the WDM OFDM signals, which are then routed to different ONUs. A 3-dB optical splitter is used at each ONU to receive half of each WDM signal, which is then converted to an electrical signal by a PIN photo-detector (PD). The PIN has a thermal power density of 15×10^{-24} W/Hz and a dark current of 10 nA. The received electrical signal is then amplified using an electrical amplifier. The electrical amplifier has a gain of 10 dB and a noise power spectral density of −60 dBm/Hz. The amplified signal is down-converted and recovered to the baseband between 0 and 2.5 GHz using a quadrature demodulator (Q-DeMod). The transmitted QAM signals are then successfully recovered using an OFDM demodulator. The QAM sequence detector converts incoming symbols (QAM signals) to bits based on the number of bits per symbol. The remaining optical signal is injected into an RSOA for re-demodulation with the 5 Gbit/s OOK upstream data. Tab.1 lists the parameters of the RSOA. The parameters of the RSOA have been carefully optimized to increase the bandwidth and support higher data rates. The RSOA operates in the gain saturation region, so the downstream data is eliminated, and the upstream data is directly carried by the downstream signal. The re-modulated signals of these RSOAs are then combined again by a WDM MUX at the RN. Then the combined signal is sent back upstream to the CO over an SMF. At the CO, upstream signals are demultiplexed by a $1\times N$ DeMUX and then every wavelength signal is detected by a PIN PD.

Tab.1 Main RSOA parameters

Parameter	Value
Input facet reflectivity	50×10^{-6}
Output facet reflectivity	50×10^{-6}
Active length	0.000 6 m
Taper length	0.000 1 m
Width	0.4×10^{-6}
Height	0.4×10^{-6}
Optical confinement factor	0.45
Nonlinear gain parameter	112×10^{-6} m^3

The OFDM WDM-PON system was investigated using the OptiSystem simulation tool. The simulated system comprises N=16 wavelengths. Each optical line terminal (OLT)/ONU path, which is identified by an individual wavelength (λ), can handle data rates up to 100 Gbit/s downstream and 5 Gbit/s upstream, respectively. The 16 wavelengths were allocated from 193.1 THz (λ_1=1 552.52 nm) to λ_{16}=1 546.52 nm with 50 GHz channel spacing.

Fig.2 shows the spectra of the OFDM signal before the quadrature modulator (Q-Mod) and after the Q-DeMod at the CO and ONU, respectively. Fig.3 shows the spectra of the OFDM signal after the Q-Mod and the detected signal after the PIN PD at the CO and ONU, respectively. It is clear from Fig.3 that the spectrum of the baseband OFDM signal has been shifted by 20 GHz using the Q-Mod. Additionally, the results indicate the high gain is introduced by the Q-DeMod. These results were obtained at λ_1.

Bit error rate (*BER*) versus optical signal-to-noise ratio (*OSNR*) measurements are used to examine the performance of downstream OFDM and upstream OOK signals. Fig.4 and Fig.5 show the *BER* values after 20 km SMF for the OFDM downstream and OOK upstream traffic, respectively, using wavelengths 1 552.52 nm (λ_1), 1 549.72 nm (λ_8) and 1 546.52 nm (λ_{16}). λ_1, λ_8 and λ_{16} were chosen to be viewed in the figure to show the results of the first, middle, and last wavelengths of the spectrum. The results for the downlink show that as would be expected, the *BER* improves as the *OSNR* increases. However, the uplink results indicate that there is little variation in the *BER* with the increase of the *OSNR*. This can be explained by the fact that the RSOA is operating in the saturation region. Additionally, the results show that chromatic dispersion, channel noise, and ISI have no significant effect on downstream OFDM or upstream OOK modulated signals. The *BER* results are clearly above the forward error correction (FEC) limit [~3.8×10^{-3} (−2.4 dB)], which represents the maximum *BER* level at which FEC could be used to bring the FEC to an acceptable level. For example, the downstream WDM signals λ_1, λ_8 and λ_{16} can achieve a *BER* of 1.6×10^{-4}, 2×10^{-4} and 5.2×10^{-4} (at *OSNR*=30 dB), respectively.

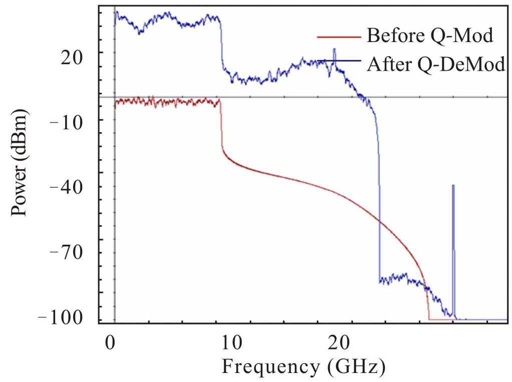

Fig.2 Spectra of the OFDM signal before the Q-Mod and after the Q-DeMod

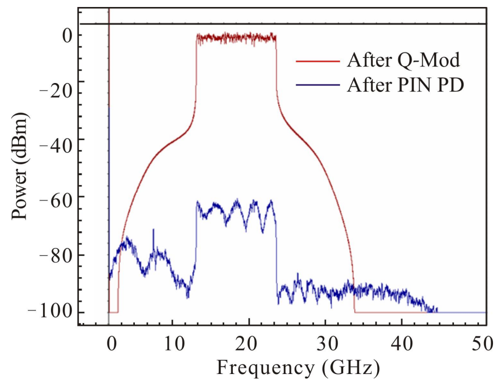

Fig.3 Spectra of the OFDM signal after the Q-Mod and the detected signal after the PIN PD

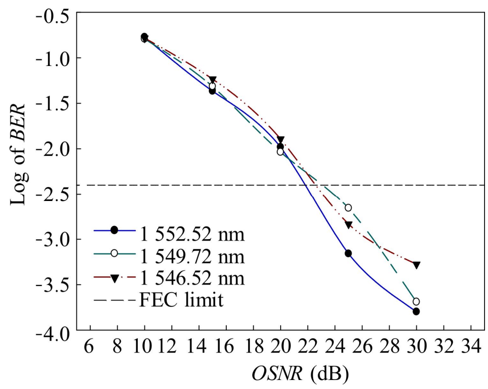

Fig.4 *BER* vs. *OSNR* for downlink

Fig.6 and Fig.7 show the variations in *BER* with link range for downstream OFDM and upstream OOK signals, respectively. The results demonstrate that the system can achieve a bidirectional transmission distance of 30 km SMF, as indicated by the intersection of the *BER* curves for downlink and uplink with the FEC limit.

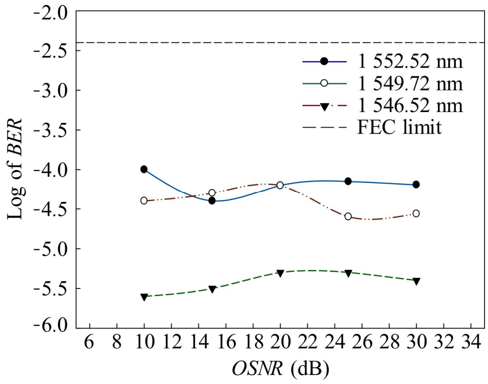

Fig.5 *BER* vs. *OSNR* for uplink

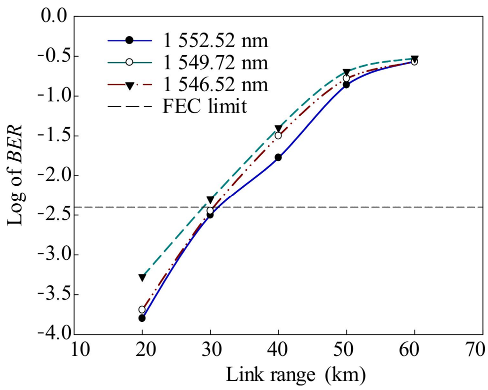

Fig.6 *BER* vs. link range for downlink

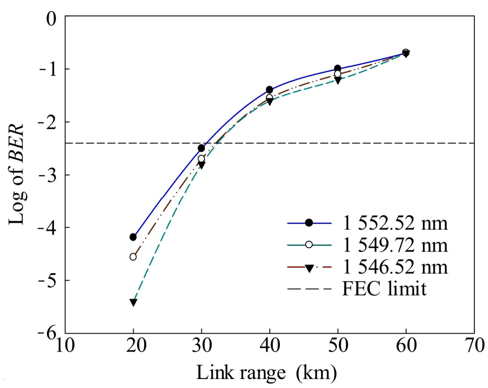

Fig.7 *BER* vs. link range for uplink

In conclusion, a cost-effective high speed OFDM WDM-PON system utilizing a centralized light-wave source and DD has been proposed and investigated. An RSOA is utilized as a colorless optical source to re-modulate OFDM downstream signals for upstream transmission. The RSOA's parameters were optimized to increase its bandwidth and support higher data rates. The results show that a data rate of up to 100 Gbit/s for downlink transmission and 5 Gbit/s for uplink transmission can be realized without dispersion compensation. The acquired *BER* results suggest that the proposed WDM-PON system can achieve up to 1.6 Tbit/s (100 Gbit/s/λ × 16 wavelengths) downstream transmission over 30 km SMF. As a result, this system offers a promising solution for next-generation wavelength reuse WDM-PONs, which might deliver a variety of broadband services, including high-speed Internet, cloud data centers, and mobile backhaul.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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