A novel duplex WDM-PON with DPSK modulated downstream and re-modulation of the downlink signal for OOK upstream*

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We experimentally demonstrate and analyze a 10 Gbit/s full duplex wavelength division multiplexing passive optical network (WDM-PON) system. A non-return-to-zero differential phase shift keying (NRZ-DPSK) modulation technique is first utilized for downlink direction, and then the downlink signal is re-modulated for the uplink direction using intensity modulation technique of on-off keying (OOK) with a data rate of 10 Gbit/s per channel. An effective colorless WDM-PON full duplex transmission system is achieved for the data rate of 10 Gbit/s per channel with a channel spacing of 60 GHz over the distance of 25 km with low power penalty.

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The integration of wired and wireless services over a single network makes WDM-PON as a single access platform to serve both fixed and mobile users in an efficient manner[1,2]. To avoid expensive optical transmitters for larger deployment, an access network architecture based on a centralized light source at central station, namely the optical line terminal (OLT), and using the re-modulation of the downstream wavelength received at the optical network unit (ONU) is an optimum solution[3,4]. On the other hand, differential phase shift keying (DPSK)[5-7] is a non-coherent kind of phase shift keying technique, which can be used to extend transmission distance, reduce optical power requirements and simplifiy circuitry configuration.

Recently different schemes with colorless full duplex operations have been proposed for WDM-PON. The uplink transmission rates in Refs.[8,9] are only limited to 2.5 Gbit/s and 5 Gbit/s, respectively. In Ref.[10], a colorless carrier-reuse scheme for WDM-PONs is reported. In Refs.[11] and [12], the proposed solution employed two-stage AWGs and many splitters for broadcast transmission. But the AWGs can introduce high signal losses, and the architectures proposed in Refs.[11] and [12] are very complicated and expensive. The solutions proposed in Refs.[13] and [14] are typically based on spectrum-sliced seeding for injection locked Fabry-Perot (IL-FP) lasers and SOA, respectively. But their transmission rate is limited to 1.25 Gbit/s due to the high intensity noise of spectrum-sliced signal. In Ref.[15], a cost-efficient 10.7 Gbit/s directly modulated DPSK transmitter in a bidirectional WDM-PON is utilized, which also re-modulates the downlink optical signal for 2.5 Gbit/s OOK upstream transmission.

In this paper, we propose a novel full duplex $n\times1$ WDM-PON system which is capable of transmitting 10 Gbit/s per channel in a full duplex mode. The schematic diagram is shown in Fig.1. A continuous light source is externally modulated by a $LiNbO_3$ Mach-Zehnder modulator (MZM) because of their higher response frequency for transmission with high data rate of 10 Gbit/s. The MZM is operated at the minimum transmission point with a DC bias of $-V\pi$ and a peak-to-peak modulation of $2V\pi$, and a phase skip of π occurs when crossing the minimum transmission point from the transfer function, which is given by:

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$$E_{out}(t) = E_{in}(t) \cdot \cos[\Delta\varphi_{MZM}(t)/2] = E_{in}(t) \cdot \cos[u(t)\pi/(2V\pi)] \quad , \qquad (1)$$

where $\Delta\varphi_{MZM}(t) = \varphi_1(t) - \varphi_2(t) = 2\varphi(t)$ is the induced phase difference between the fields of the upper and lower arms.

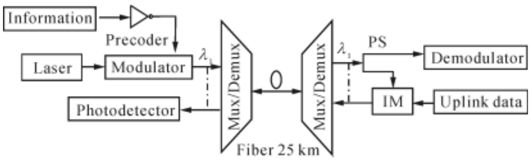

Fig.1 Schematic diagram of DPSK downlink and OOK uplink full duplex system of 10 Gbit/s

Normally, a differential precoder is necessary for transmission. The generated downstream DPSK signal is multiplexed by a multiplexer (Mux) with other downlink channels each of which has a data rate of 10 Gbit/s. The multiplexed signal is transmitted over a bidirectional feeder fiber. The feeder fiber is standard single-mode fiber (SMF) of 25 km. At the other end, a demultiplexer (Demux) is used to demultiplex the downstream signals and send them to respective ONU. At each ONU, after a power splitter (PS), the half of the downstream phase encoded signal is re-modulated with 10 Gbit/s data rate using an intensity modulation technique (i.e.,OOK) to be transmitted back to the OLT.

The transmission performance of the proposed WDM-PON with four 10 Gbit/s downlink channels, and four 10 Gbit/s uplink channels over 25 km bidirectional feeder fiber is evaluated by simulations using OptiSystem 7.0. Fig.2(a) shows the simulation setup for the proposed novel bidirectional WDM-PON system using a centralized light source for downlink (DL) and uplink (UL). As distributed feedback (DFB) lasers can be used for enabling much higher data rate up to 10 Gbit/s, four continuous waves (CWs) with a launch power of 0 dBm are generated by four DFB lasers at wavelengths of 1552.52 nm (λ_1), 1552.04 nm (λ_2), 1551.56 nm (λ_3), and 1551.08 nm (λ_4). They are multiplexed by a 4 × 1WDM multiplexer with 60 GHz channel spacing. The four multiplexed channels are then transmitted over a 25 km feeder fiber. The general settings of fiber used in our simulation are chromatic dispersion of 16.75 ps/(nm·km) and dispersion slope of 0.075. The downlink multiplexed signal is demultiplexed using a 1 × 4 WDM demultiplexer, and then transmitted to the corresponding ONU. At the receiving ONU, a 3 dB optical splitter is used to tap half of the optical power for the downstream receiver. A Mach-Zehnder delay interferometric (MZDI) demodulator is used to convert the phase-modulated DPSK signal to the intensity-modulated signal before it is received by a regular direct detection PIN receiver. The other half of the DPSK signal is injected into a Mach-Zehnder intensity modulator (IM) driven by a 10 Gbit/s upstream data with NRZ modulation format to suit for WDM transmission[16]. The re-modulated OOK upstream signal is transmitted back to the OLT through another 25 km of SMF-28, before it is received by a direct direction pin receiver. As identical wavelengths are used for downlink and uplink transmission, a dual fiber transmission structure between OLT and ONU is used for preventing transmission performance from being limited by reflections (Rayleigh backscattering and discrete reflections)[17]. Backscattering phenomena can also be eliminated by using different wavelengths for downstream and upstream transmission. However, the splitting and accumulation of signal at the remote nod (RN) then need expensive components. In the simulation, pin photodetector receivers are used. The general parameters of the photodetector in our simulations are set as responsivity of 1 A/W and dark current of 10 nA. Fig.2(b) and (c) show the four downlink multiplexed DPSK signals and four uplink multiplexed OOK signals, respectively.

The BER as a function of received optical power for all the downstream and upstream channels is illustrated in Fig.3.

The individual power penalties measured at 10^{-9} BER for DPSK downlink channels (1, 2, 3 and 4) are 0.2 dBm, 0.6 dBm, 0.5 dBm and 0.7 dBm, respectively, for a distance of 25 km. Similarly for the same distance, the measured power penalties at 10^{-9} BER for the OOK uplink channels (1, 2, 3 and 4) are 0.1 dBm, 0.1 dBm, 0.2 dBm and 0.1 dBm, respectively.

Fig.4 shows the BER for four downlink DPSK channels and four uplink OOK channels for a distance of 25 km. It is also evident from Fig.4 that the performances of the DPSK downlink channel 1(ch-1) and channel 4 (ch-4) are better than those of channel 2 (ch-2) and channel 3(ch-3) as the outer channels, and hence is not or less influenced by adjacent channel interferences. The performances of ch-2 and ch-3 are approximately the same but seem to be a little affected by adjacent channel interferences, as the inner channels in the system.

The BERs of four DPSK downlink channels and four OOK uplink channels for the back-to-back (B2B) case are shown in Fig.5. At a 10^{-9} BER, the average power penalty of all the four multiplexed DPSK downstream signals is about 0.5 dB after the transmission of 25 km in an SMF without any signal amplification or dispersion compensation.

On the other hand, at a 10^{-9} BER, the average power penalty for the four multiplexed OOK upstream signals is less than 0.2 dB after the corresponding upstream transmitted over a 25 km SMF without any signal amplification or dispersion compensation as shown in Fig.6.

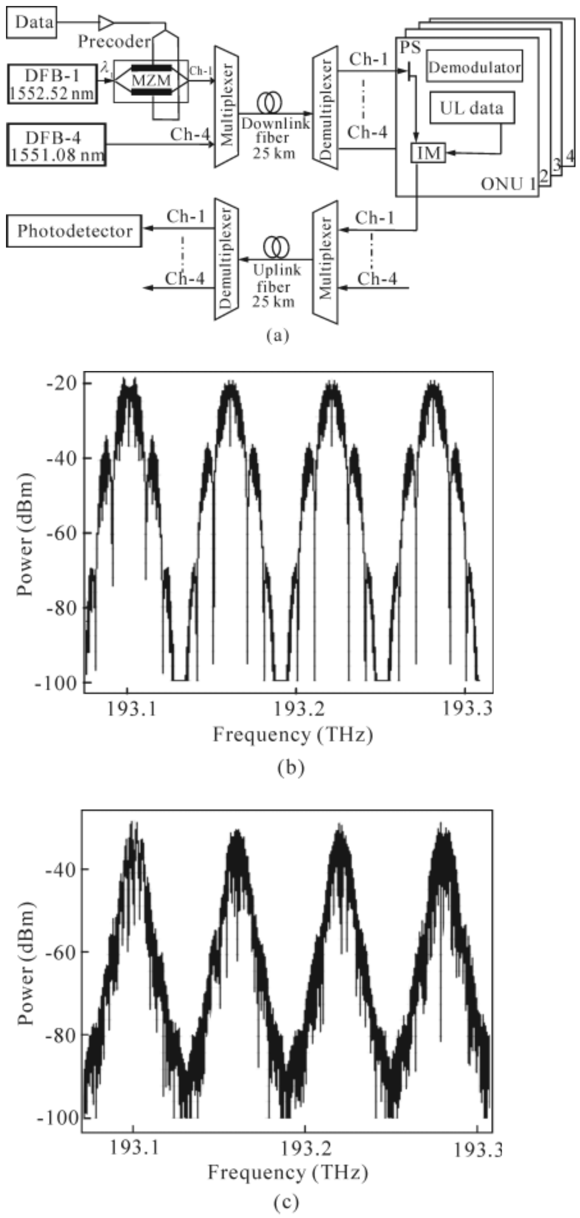

Fig.2(a) Proposed full duplex 10 Gbit/s DPSK DL, and OOK NRZ based UL system; (b) Four downlink multiplexed DPSK signal; (c) Four uplink multiplexed OOK signal

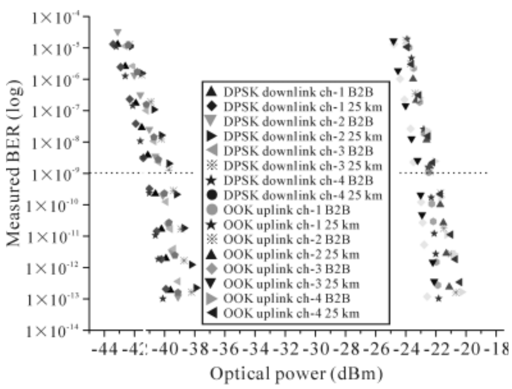

Fig.3 BER for four DPSK downlink and OOK uplink multiplexed channels (B2B and 25 km)

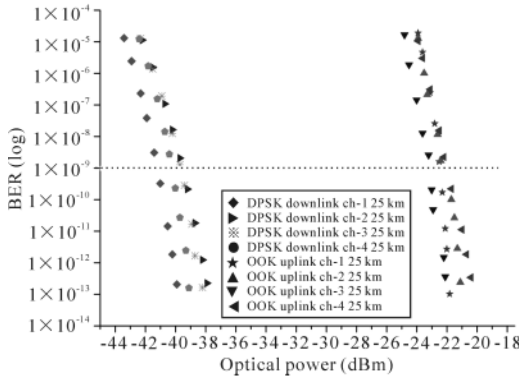

Fig.4 BER for four DPSK downlink and OOK uplink multiplexed channels for 25 km

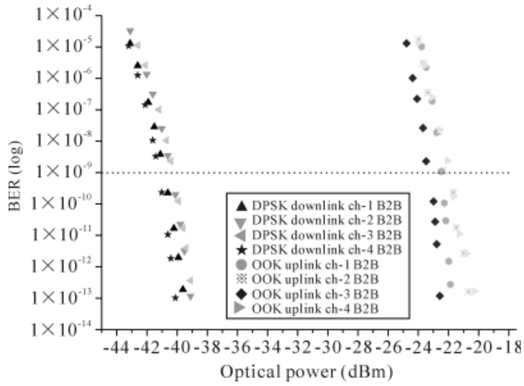

Fig.5 BER of four DPSK downlink and OOK uplink multiplexed channels for B2B

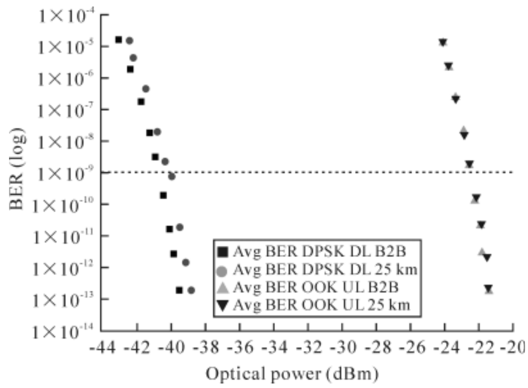

Fig.6 Average BER of four DPSK downlink and OOK uplink multiplexed channels (B2B and 25 km)

Fig.7 shows the eye diagrams for all the four multiplexed NRZ DPSK downlink channels. The eyes are wide and open. Hence it is evident from the figures that error free transmission is achieved for both downstream and upstream directions.

Hence a 10 Gbit/s full duplex WDM-PON system is analyzed by first utilizing the NRZ-DPSK modulation technique for downlink direction and then re-modulating the downlink signal for the uplink direction with a data rate of 10 Gbit/s per channel. A cost effective colorless WDM-PON full du-

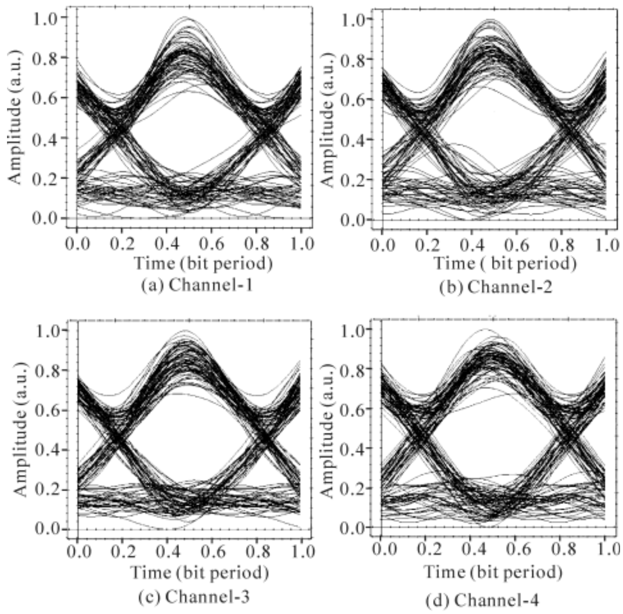

Fig.7 Eye diagrams for downlink DPSK channels

plex transmission operation for a data rate of 10 Gbit/s per channel over a distance of 25 km with low power penalty is achieved without any signal amplification or dispersion compensation management.

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