Single fiber colorless symmetric WDM-PON architecture using time interleaved remodulation technique for mitigating Rayleigh backscattering resilience*

Muhammad Idrees Afridi, ZHANG Jie(张杰), ZHAO Yong-li(赵永利), Abdul Latif and Shahab Ahmed Niazi**

State Key Laboratory of Information Photonics and Optical Communications, School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China

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A time interleaved differential phase shift keying (DPSK) remodulation technique is proposed to mitigate the effect of Rayleigh backscattering (RBS)-induced noise in a single fiber colorless wavelength-division-multiplexing passive optical network (WDM-PON). In order to achieve a cost effective optical network unit (ONU) solution without dedicated laser sources for upstream signals to provide optimum symmetric capacity in a colorless WDM-PON, remodulation becomes the core attraction. Also as the performance of colorless WDM-PON systems suffers from the transmission impairments due to RBS, it is mitigated by using this remodulation scheme. Simulation results show that downstream and upstream signals achieve the error-free performance at 10 Gbit/s with negligible penalty, and enhance the tolerance to RBS-induced noise over a 25 km single-mode fiber.

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Remodulation in wavelength-division-multiplexing passive optical network (WDM-PON) systems has attracted vital interest in order to achieve a cost effective optical network unit (ONU) solution without dedicated light sources for upstream signals for providing optimum capacity in WDM-PON. Various remodulation approaches have been proposed to achieve robust performance for both downstream and upstream transmissions[1,2]. Novel devices, such as reflective semiconductor optical amplifier (RSOA) with high data rate up to 10 Gbit/s[3], as well as new remodulation format[2] were introduced. Subcarrier remodulation was utilized in Ref.[2] to separate the spectra of reflected noise and upstream signal. The schemes based on noise predictive equalization, line coding and ring based WDM-PON were reported in Refs.[4-6] to reduce the effect of Rayleigh backscattering (RBS)-induced noise in WDM-PONs. All the mentioned schemes either use complex modulation formats with high deployment cost, or need extra circuits and devices at ONU. Therefore, in this paper, a phase remodulation method is proposed, which demonstrates time-interleaving between downstream and upstream signals to mitigate RBS noise. The tolerance of the upstream signal against the RBS-induced noise is enhanced by reducing the modulation depth of the downstream differential phase shift keying (DPSK) signal.

The operating principle of the proposed remodulation scheme is explained in Fig.1. After $T/2$ offset of upstream and downstream signals, where T is the bit period, an exclusive or XOR operation is applied on the two independent phase modulated patterns[7]. The phase difference between the lead-

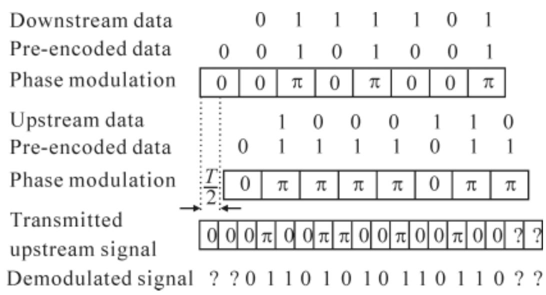

Fig.1 Operating principle of time interleaved phase remodulation

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** E-mail: midreesafridi@gmail.com

ing half of a bit in the upstream DPSK signal and the trailing half of the previous bit can not be affected by the original phase modulation of the upstream data[8]. By using a half-bit-delay differential interferometer (DI) at optical line terminal (OLT), the received upstream signal can be simply demodulated and the upstream data can be correctly detected on trailing half bits of the demodulated signal.

A full-duplex transmission is established here by splitting the original downstream continuous wave (CW) in the OLT into two orthogonal polarizations, one of which is modulated for downstream data transmission while the other is fed to the phase modulation (PM) for upstream transmission. Independent transmission of data and unmodulated carriers over the two polarizations for each ONU overcomes time-interleaving in the OLT of the available transmission time-slots, as illustrated in Fig.2, allowing for their simultaneous transmission to avoid multiplexing of idle time and required guard time. Assuming in symmetrical broadband services, such as video conferencing, online gaming and Web 2.0 applications, the proposed scheme can potentially double the bandwidth utilization for each subscriber, resulting in the increased network upstream and downstream throughput.

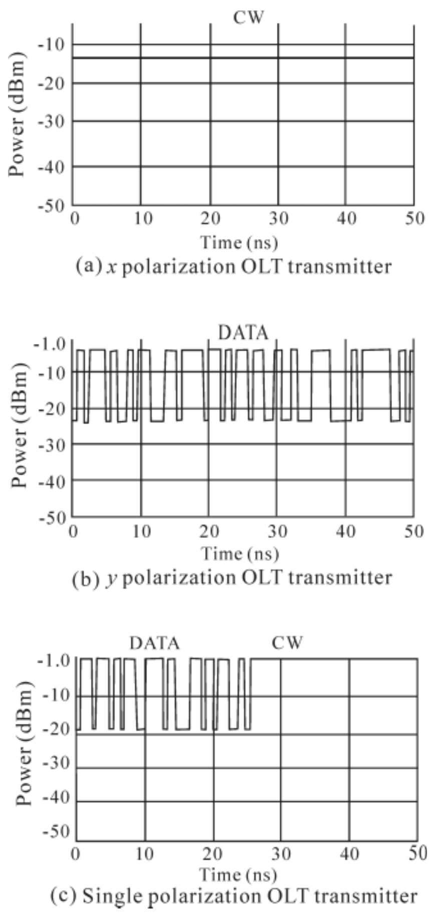

Fig.2 Time domain representation of data and CW by time-interleaved technique

The proposed arrayed waveguide grating (AWG) based single fiber WDM-PON architecture is shown in Fig.3. AWG, which was first devised by M. K. Smit[9], is the key device in WDM optical communication systems, and is also known as the waveguide grating router (WGR) or the phasar (phased array). It is a highly developed and commercially successful planar waveguide device which performs wavelength multiplexing, demultiplexing, wavelength filtering, signal routing and optical cross-connecting. In addition to WDM, it is also being used in areas such as signal processing, spectral analysis and sensing. The proposed WDM-PON network contains some mandatory elements, such as continuous light source, return to zero (RZ)-DPSK transmitter/ receiver, AWG, single-mode fiber (SMF), PM receiver/transmitter and photodetector (PD). The RZ-DPSK transmitter consists of a continuous laser source and two cascaded $LiNbO_3$ Mach-Zehnder modulators (MZMs). The first modulator called the data modulator is used to perform the PM and generate a conventional non return to zero (NRZ)-DPSK optical signal. The MZM is operated at its minimum transmission point (null) with a direct current (DC) bias of $-V_\pi$ and a peak-to-peak modulation of $2V_\pi$. A phase skip of π occurs when crossing the minimum transmission point from the field transfer function which is given by:

$$E_{out}(t) = E_{in}(t)\cdot\cos\left[\frac{\Delta_{\phi MZM}(t)}{2}\right] = E_{in}(t)\cdot\cos\left[\frac{u(t)}{2V_\pi}\right], \quad (1)$$

where $\Delta_{\phi MZM}(t) = \phi_1(t) - \phi_2(t) = 2\phi_1(t)$ is the induced phase difference between the fields of the upper and lower arms.

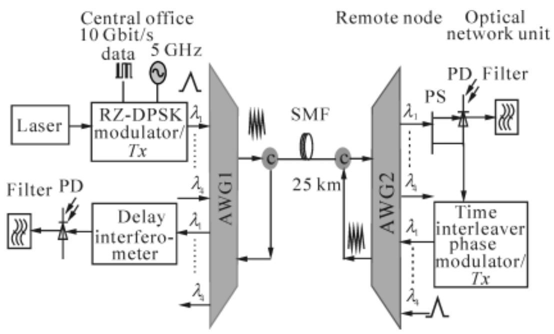

Fig.3 Schematic diagram of the proposed remodulation scheme in WDM-PON

Accordingly the input light field is given by:

$$E_{in}(t) = |E_0|e^{j\omega_c t} . \quad (2)$$

After passing through the second MZM called the pulse carver, the light field would become

$$E_{out}(t) = \frac{E_{in}(t)}{2}\cdot[e^{j\phi_1 t} + e^{j\phi_2 t}] , \quad (3)$$

$$\phi_1(t)=\frac{\pi}{2}\frac{1}{V_\pi}[V_{1m}\sin(\omega_1 t+\psi_1)+V_1]\ , \tag{4}$$

$$\phi_2(t)=\frac{\pi}{2}\frac{1}{V_\pi}[V_{2m}\sin(\omega_2 t+\psi_2)+V_2]\ , \tag{5}$$

where V_{im}, $\omega_i(=2f_i\pi)$ and $\psi_i(i=1, 2)$ are the amplitude, angular frequency and phase of the clock signal on two arms of MZM, respectively. Similarly, V_1 and V_2 can provide the voltage bias on two spur tracks of MZM, respectively. When the single arm works causing the appearance of phase separation, V_π is the switching voltage from the maximum to the minimum. In order to make the MZM work at the station without chirp, the voltages of two single arms can be added to a fixed voltage bias, that is $V_1(t)+V_2(t)=V_{\text{bias}}$, and thus the output of the light field becomes

$$E_{\text{out}}(t)=E_{\text{in}}(t)\cos\left[\frac{\pi}{2V_\pi}(V_{\text{in}}-V_{\text{bias}})\right]\mathrm{e}^{\mathrm{j}(\pi V_{\text{bias}}/2V)}\ . \tag{6}$$

The output of the light intensity is

$$P_{\text{out}}(t)=P_{\text{in}}(t)\cos^2\left[\frac{\pi(V_{\text{in}}-V_{\text{bias}})}{2V_\pi}\right]=$$
$$\frac{P_{\text{in}}(t)}{2}[1+\cos(\pi\sin\omega_0 t)]\ . \tag{7}$$

In the above equation, the optical impulse cycle is $2\pi/\omega_0$, the angular frequency is ω_0, and the full-width at half-maximum (FWHM) is π/ω_0. The generated output is a periodic RZ-DPSK pulse train with the phase of each pulse modulated between 0 and π according to the data.

The generated downstream RZ-DPSK signal is then fed to AWG along with other downlink channels at a data rate of 10 Gbit/s. The multiplexed signal is transmitted over an SMF with the length of 25 km. 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 (PS), half of the downstream phase encoded signal is re-modulated with 10 Gbit/s data using time interleaved PM technique 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 uplink and downlink paths are merged by means of an optical circulator (C) which helps the attenuation of a possible reflection.

We establish a model for simulation using Optisystem 7.0 according to network architecture as shown in Fig.3 in order to discuss the performance of the proposed WDM-PON system. Four continuous light waves with launch power of 0 dBm are generated by four distributed feedback (DFB) lasers at wavelengths of 1552.52 nm, 1552.04 nm, 1551.56 nm and 1551.08 nm for four different channels, respectively, keeping 60 Hz channel spacing. A transmitter consisting of two cascaded $LiNbO_3$ MZMs is used to modulate all channels independently. PM (biased at the null point) is performed by the first modulator of each transmitter. So each generated wavelength is firstly externally modulated by the MZM driven by 10 Gbit/s 2^7-1 pseudorandom binary sequence (PRBS) data. The output of the first MZM is fed to the second modulator driven by a 5 GHz clock pulse generating about 33% duty-cycle RZ pulses. The four produced RZ-DPSK signals are then multiplexed by a 4 × 1 AWG multiplexer (MUX) with 60 GHz channel grid, and transmitted over a 25 km SMF. The downlink signal is firstly de-multiplexed using 1×4 AWG DEMUX, and then transmitted to the corresponding ONU. At the remote node, a 3dB optical splitter divides downstream into two parts. A PM technique is used to remodulate the first half from the power splitter to generate upstream signal of 10 Gbit/s 2^7-1 PRBS data which is $T/2$ time-interleaved with respect to downstream data via a PM. The second half is demodulated by a 1 bit delayed interferometer and balanced photo diodes by using detuning principle of AWG[10]. The PM is biased at transmission null point, and the driving voltage is set to $2V_\pi$. A 4th order Bessel low-pass electrical filter (LPF) with 3 dB bandwidth of 12.5 GHz is used as encoder for 10 Gbit/s upstream data. The general settings of the fiber used in our simulation are given in Tab.1.

Tab.1 Simulation parameters

Parameter	Value
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
Nonlinear index-coefficient of SMF	2.6 × 10^{-20}
Responsitivity of PD	1 A/W
Dark current of PD	10 nA

The bit error rate (BER) as a function of received optical power for both the downstream and upstream transmissions for 4 channels in WDM-PON is shown in Fig.4 using back to back (B2B) scenario and after transmitting 25 km along SMF. In case of B2B scenario, the 10 Gbit/s DPSK data signal provides a BER of 10^{-9} at received power of -41 dBm in the downstream direction, whereas in the upstream, the 10 Gbit/s data signal provides a BER of 10^{-9} at received power of -28 dBm. After transmitting 25 km along SMF, the 10 Gbit/s 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 Gbit/s data signal provides a BER of 10^{-9} at received power of -34 dBm. In upstream, a power penalty of 6.0 dB relative to B2B scenario is presented at BER of 10^{-9} after transmitting 25 km along SMF. This power penalty can be largely caused by two components of RBS, 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 that the RBS-induced noise is appreciably minimized, and such a low-cost scheme can be implemented in future WDM-PONs. Fig.5 shows the corresponding optical eye diagrams for downlink and uplink channels. The eyes are clear and widely open.

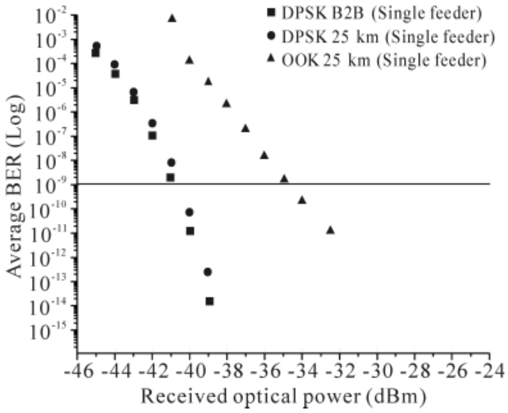

Fig.4 Average BER vs. received power for downlink and uplink channels

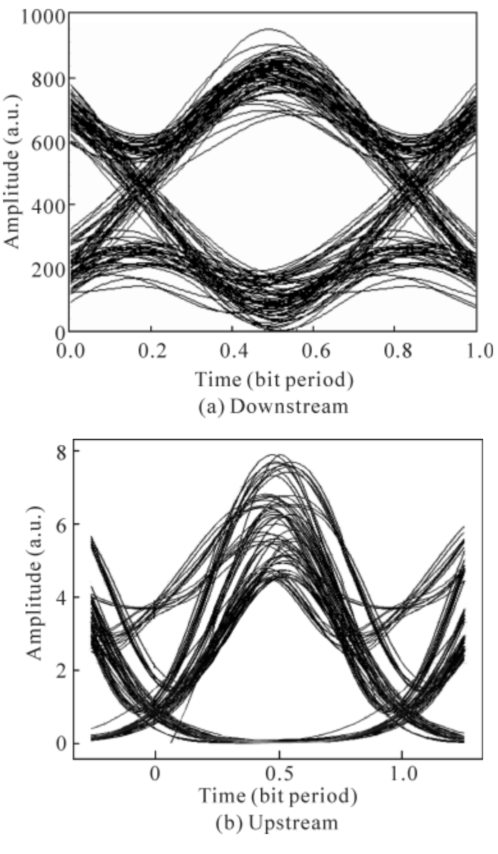

Fig.5 Eye diagrams for DPSK downstream and upstream for single fiber architecture

We propose and demonstrate a single-fiber, full-duplex, colorless WDM-PON architecture based on AWG with enhanced tolerance against impairments from RBS by using time interleaved remodulation technique. It is demonstrated that the high extinction ratios in both RZ-shaped DPSK downstream and time-interleaved remodulated upstream data signals help to increase the tolerance against RBS-induced noise. It is concluded that the single feeder fiber is cost effective as the simplicity of WDM-PON in addition to RBS mitigation. An error-free colorless transmission over a distance of 25 km with lower BER is achieved.

References

[1] Hoon Kim, 10 Gbps Upstream Transmission for WDM-PON Using RSOA and Delay Interferometer, Optical Fiber Communication Conference, Los Angeles, OMP8 (2011).

[2] ITU report, Trends in Telecommunication Reform 2010/11: Enabling Tomorrow's Digital World, 2011.

[3] Zhensheng Jia, Jianjun Yu, Arshad Chowdhury, Ellinas G. and Gee-Kung Chang, Photonic Technology Letter **20**, 1691 (2007).

[4] Q. Guo and A.V. Tran, Electronics Letters **47**, 1333 (2011).

[5] Chiuchiarelli A., Presi M., Proietti R., Contestabile G., Choudhury P., Giorgi L. and Ciaramella E., IEEE Photonics Technol. Lett. **22**, 85 (2010).

[6] C. H. Yeh and C. W. Chow, IEEE Communication Letters **15**, 1114 (2011).

[7] Jing Xu, Lian-Kuan Chen and Chun-Kit Chan, High Extinction Ratio Phase Re-modulation for 10 Gb/s WDM-PON with Enhanced Tolerance to Rayleigh Noise, 9th International Conference on Optical Internet (COIN), 1 (2010).

[8] Guo-wei Lu and Miyazaki T., An 80 GHz Chirp-Free Carrier-Suppressed Optical Pulse Generator Using Cascaded 20 GHz Clock-Driven Mach-Zehnder Modulators, Conference on Lasers and Electro-Optics-Pacific Rim, 1 (2007).

[9] M. K. Smit, Electronics Letters **24**, 385 (1988).

[10] Y. Yu and J. B Rosas-Farnandez, Novel and Flexible WDM NRZ System with Demultiplexing and Demodulation Using a Single Standard AWG, Optical Fiber Communication Conference, OThF7 (2009).