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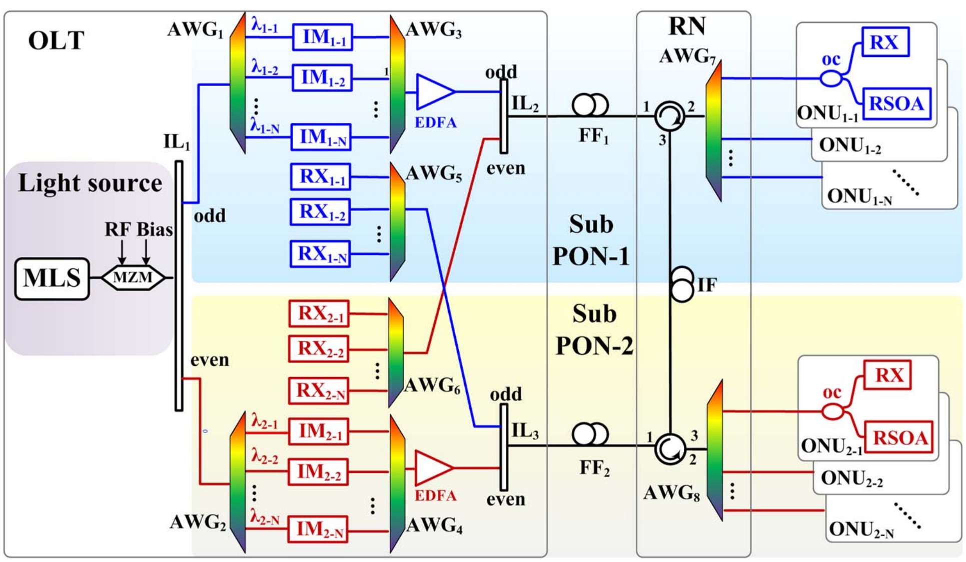

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25-GHz-Spaced DWDM-PON With Mitigated Rayleigh Backscattering and Back-Reflection Effects

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Abstract: A novel 25-GHz-spaced dense wavelength-division multiplexing passive optical network (DWDM-PON) is proposed to improve the utilization of wavelength resource and mitigate the Rayleigh backscattering (RB) and back-reflection effects. A colorless optical network unit (ONU) is realized by remodulating the downstream (DS) signal via a gain-saturated reflective semiconductor optical amplifier (RSOA). Due to the simple inter-connecting architecture at the remote node (RN), the DS and upstream (US) signals in each feed fiber (FF) are carried on different channels. Therefore, the RB and back-reflection effects are significantly reduced. The feasibility and merits of the proposed system are experimentally demonstrated with the error-free transmission of 10-Gb/s DS and 1.25-Gb/s US signals over a 25-km single-mode fiber.

Index Terms: Dense wavelength-division multiplexing passive optical network (DWDM-PON), reflective semiconductor optical amplifier (RSOA), Rayleigh backscattering (RB).

1. Introduction

Time division multiplexing passive optical network (TDM-PON) has been deployed all over the world as the last mile access system [1]. But the rapid development of bandwidth intensive applications such as IPTV, HDTV and video-on-demand has pushed the capacity of current TDM-PON to its limit. Hence, WDM-PON is now widely acknowledged as an attractive solution to provide high speed services and flexible bandwidth upgradability [2], [3]. To further improve the system capacity and support more subscribers in the future dense wavelength-division multiplexing passive optical network (DWDM-PON), the number of wavelengths should be increased. Thus reducing the channel spacing from currently available 100/50 GHz to 25 GHz is desirable [4]–[6]

On the other hand, the colorless operation of optical network unit (ONU) is important to make the system more cost-effective and manageable, as it moves the wavelength provision and management to the optical line terminal (OLT). Using reflective ONU transmitter is one promising solution to realize colorless ONU. The US signal could be modulated on the continuous-wave (CW) carrier distributed from the OLT. To further improve the utilization of wavelength resource, ONU should have the capability to remodulate downstream (DS) signal so that no extra seeding light is needed. These reflective transmitters include reflective semiconductor optical amplifier (RSOA)

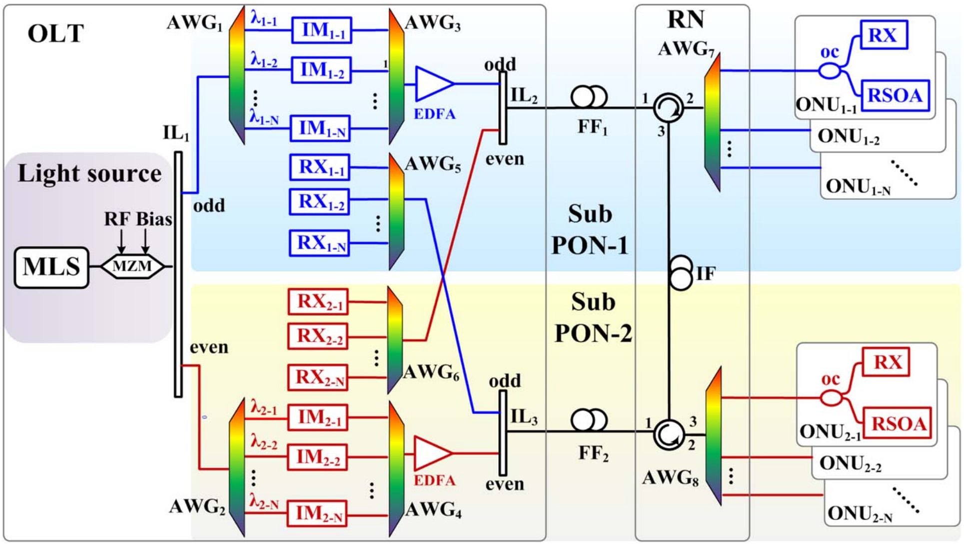

Fig. 1. Architecture of the proposed DWDM-PON system. MLS: multiwavelength laser source; IL: interleaver; AWG: array waveguide grating; IM: intensity modulator; RX: receiver; OC: optical coupler.

[7]–[9], Fabry-Pérot laser diodes (FPLD) [10], [11] and reflective electro-absorption modulator (R-EAM) [12]. Although the aforementioned schemes have attractive advantages, their system performances suffer from the impairment caused by Rayleigh backscattering (RB) and back-reflection effects, since the signals in the bidirectional transmission are carried on the same wavelength. To overcome the impairment, a direct approach is installing the CW feeding light source in the RN [13], but active device is used in the RN configuration. Wavelength offset techniques like subcarrier multiplexing (SCM) [14], [15] are utilized to mitigate the degradation by modulating the US signal on the wavelength shifted from DS carrier. However, the cost and operation complexity for ONU are increased and the wavelength should be carefully located to guarantee both the DS and US transmission performances when 25-GHz array waveguide grating (AWG) is used to realize 25-GHz-spaced DWDM-PON [16]. Using different signal modulation formats is another effective choice, such as Manchester-duobinary/none-return-to-zero [17] and adaptively modulated optical orthogonal frequency division multiplexing (AMOOFDM) [18]. Cross remodulation technique has also been reported as an effective approach for reducing the RB noise in [19]. The transmitter in ONU is simple but optical filters are required both in the remote node (RN) and ONUs.

In this paper, we propose and experimentally demonstrate a DWDM-PON system with mitigated RB and back-reflection effects. 25-GHz-spaced channels are generated in OLT via the optical carrier suppression (OCS) technique to provide both the DS and US channels for two parallel sub PONs. Colorless ONUs are realized by using gain-saturated RSOAs for the US remodulation. The system capacity is doubled since 2N ONUs are supported by N central lasers with 50-GHz wavelength spacing. A simple interconnecting architecture is installed at RN, so that the DS and US signals transmitted in each feed fiber (FF) are carried on different channels, which totally eliminate the back reflection and RB effects in FF. The feasibility of the proposed scheme is experimentally demonstrated with 10-Gb/s DS and 1.25-Gb/s US transmission over 25-km single-mode fiber (SMF) transmission.

2. System Architecture and Operation Principle

Fig. 1 depicts the architecture of the proposed DWDM-PON which can be viewed as a combination of two neighboring sub PONs with N colorless ONUs in each. In OLT, multi-wavelength laser source (MLS) has the wavelength spacing of 50 GHz, and the output are injected into a Mach–Zehnder modulator (MZM) which is driven by a 12.5-GHz radio frequency (RF) clock. In this way, 2N

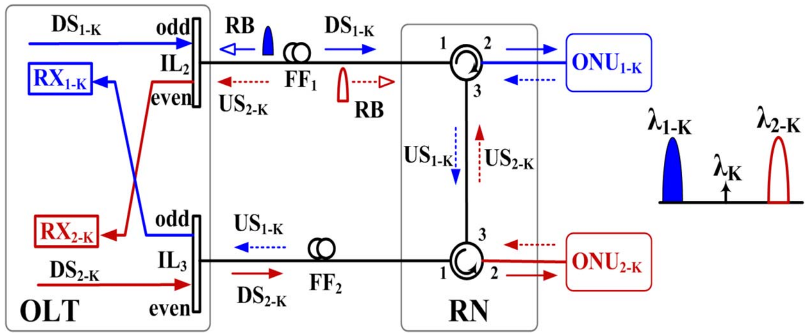

Fig. 2. Operation principle of the proposed system with eliminated RB and back-reflection noise in FF. DS: downstream; US: upstream; RB: Rayleigh backscattering.

25-GHz-spaced channels are generated via OCS process [20]. A 25/50-GHz interleaver (IL_1) is used to assign the N odd sideband channels ($\lambda_{1-1} \ldots \lambda_{1-N}$) and N even sideband channels ($\lambda_{2-1} \ldots \lambda_{2-N}$) to sub PON-1 and PON-2, respectively. Therefore, the spacing requirements of all AWGs used in this system are eased to 50 GHz. AWG_1 and AWG_2 are used to de-multiplex the N odd channels and N even channels. Each channel is injected into the corresponding intensity modulator (IM) for DS modulation. AWG_3 and AWG_4 multiplex the DS signals. Then two erbium doped fiber amplifiers (EDFAs) are installed to compensate the insertion loss in the OLT. IL_2 and IL_3 transmit the DS signals to the FFs and route the US signals to the proper US receiver (RX) arrays. At RN, a pair of AWGs is used to de-multiplex the DS signals and multiplex the US signals for each sub PON. These two PONs are interconnected by two circulators and an interconnection fiber (IF). In each ONU, the received DS signal is split by a 1×2 optical coupler (OC), where one part is injected into the RX for DS direct detection, while the other part is amplified and remodulated with US signal via a gain-saturated RSOA. Thanks to the two optical circulators and IF at RN, sub PON-1 and PON-2 both route the US signals back to the OLT by sharing each other's FF.

For clarity, the DS and US transmission processes for ONU_{1-K} and ONU_{2-K} are shown in Fig. 2 to illustrate the operation principle of the proposed system. It is obvious that the DS and US signals transmitted in both FFs are carried on different channels. Take the upper path for example, the DS signal is carried on λ_{1-K} and routed to ONU_{1-K}, while the US signal is remodulated on λ_{2-K} and sent by ONU_{2-K}. Since the even port of IL_2 only passes λ_{2-K}, the RB and back-reflection noise of the DS signal on λ_{1-K} will be blocked by the even port. Consequently, the US transmission performance on λ_{2-K} is not affected. Due to the interconnecting architecture at RN, the RB effects of the US signal on λ_{2-K} cannot go back to ONU_{2-K}. Therefore, the DS and US remodulated signals of ONU_{2-K} are not influenced. The case in FF_2 is similar: both the DS and US signals will not suffer from the impairment caused by the reflection noises. As a result, all the RB and back-reflection effects in both FFs are totally eliminated.

In this DWDM-PON system, N central wavelengths are used in OLT to generate the 25-GHz-spaced carriers for 2N ONUs by OCS process, which simplifies the complexity of DWDM transmitters and improves the utilization efficiency of wavelength resource. The spacing of all AWGs is eased to 50 GHz, reducing the requirement of aligning precision between the channels and the AWG grids. Compared with the schemes in [13]–[16], [19]. The interconnection architecture only needs two additional circulators and one IF that are wavelength insensitive. This keeps the RN configuration very simple. The cost of ONU structure is also very low without using any optical filter or complex modulation format. Also, the RSOA can be replaced by any other kind of remodulation transmitter.

Since future optical access network may support a great number of users, multiple fibers from one OLT to a RN can be expected. The two FFs can be deployed together so that the supported ONU number in one distribution area could be doubled [19]. On the other hand, these two sub PONs can be located separately with the RB and back-reflection effects mitigated by simply

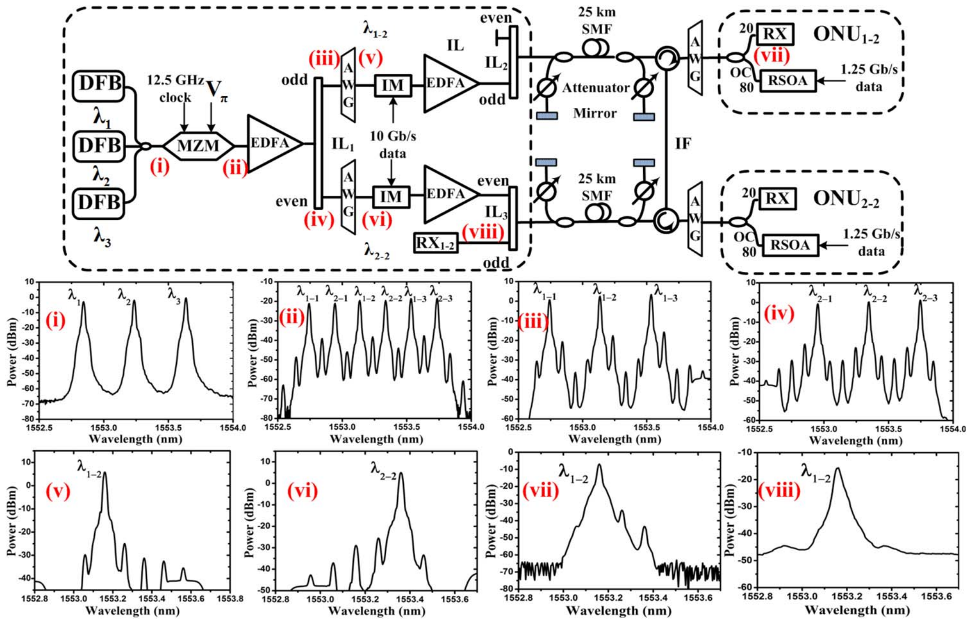

Fig. 3. Experimental setup of the proposed DWDM-PON system.

interconnecting the light path of their RNs. Moreover, the scheme of dual FFs can also be used to provide protection against the fiber failures in WDM-PON [7], [21].

3. Experimental Setup and Results

The experimental setup to verify the feasibility of the proposed system is shown in Fig. 3. In the OLT, three 50-GHz-spaced wavelengths at 1552.84 nm (λ_1), 1553.24 nm (λ_2), and 1553.64 nm (λ_3) are fed into one MZM to generate the OCS sidebands. The MZM is biased at transmission null point (7.0 V) and driven by a 12.5-GHz clock signal. Therefore, six channels with 25-GHz spacing are generated. Fig. 3(i) and Fig. 3(ii) illustrate the optical spectra before and after the OCS process. The carrier suppression ratio of about 25 dB can be achieved. After being amplified, all channels are separated by 25/50-GHz IL_1 and two AWGs. The AWGs are 50-GHz channel spaced and flat-top shaped with 3-dB bandwidth of 35 GHz (0.28 nm). We use λ_{1-2} and λ_{2-2} for example, as shown in Fig. 3(iii)-(vi). λ_{1-2} and λ_{2-2} are modulated by 10-Gb/s $2^{31}-1$ pseudorandom binary sequence (PRBS) for DS transmission. Note that the extinction ratio (ER) of DS signal is set as 5-dB in order to achieve the error-free US transmission [8]. IL_2 and IL_3 inject the DS signals to the 25-km standard SMFs and direct the US signals to the corresponding RXs. Two reflectors composed of an OC, an optical attenuator and an optical mirror are installed at both ends of each FF to investigate the reflection effects on the system performance. At RN, the interconnecting architecture consists of two circulators and an IF. The length of IF in this experiment is negligible compared with the FFs. Two AWGs multiplex the US signals and de-multiplex the DS signals for sub PON-1 and PON-2, respectively. In each ONU, the DS signals are separated by a 2×2 OC: one part enters the receiver for direct detection and the other is amplified and remodulated by a gain-saturated RSOA with 1.25-Gb/s data rate. The optical power of the injected light for RSOA is maintained at -12 dBm and the saturated output optical power is 7.5 dBm. The US data rate in this experiment is limited by the electrical bandwidth of the RSOA, which is 1.3 GHz. Higher modulation rate like 10 Gb/s could be realized by using equalization and forward error correction techniques [22], [23]. The optical spectrum of the DS and US signals on channel λ_{1-2} before entering the RXs are shown in Fig. 3(vii) and (viii), respectively.

Fig. 4(a) and (b) show the measured bit-error-rate (BER) and eye diagrams for DS and US signals. In the experiment, the receiver sensitivities in both directions are measured by employing

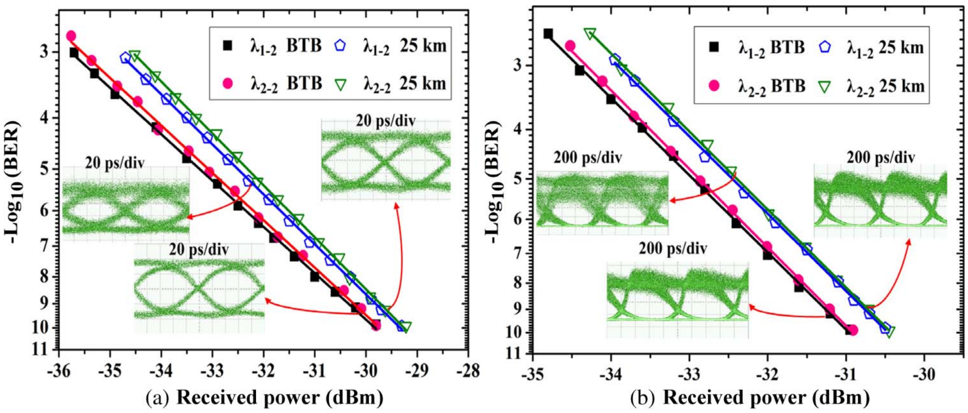

Fig. 4. BER measurement and eye diagrams for (a) DS 10-Gb/s signal and (b) US 1.25-Gb/s signal.

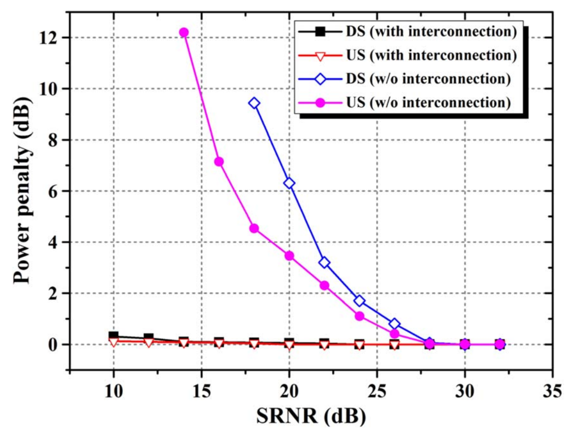

Fig. 5. Power penalty caused by the reflection noise with or without interconnection architecture.

an EDFA as a preamplifier since a PIN rather than an APD is used for signal detection. The EDFA is not necessary if an APD is used for higher sensitivity. Since channel λ_{1-2} and λ_{2-2} are generated from the same wavelength and assigned to different ONUs, their performances are shown to demonstrate the system feasibility. It is obvious that the BER curves for both channels are almost the same. At BER of 10^{-9}, the receiver sensitivity for DS signal is about -29.8 dBm. The power penalty induced by 25-km fiber transmission is about 0.4 dB, which is mainly due to the fiber dispersion. For US signal, the receiver sensitivity and power penalty are -30.7 dBm and 0.5 dB, respectively. The power penalty is mostly caused by the residual DS signal in the US transmission, as shown in the eye diagrams.

The reflectors in the experimental setup shown in Fig. 3 are used to investigate the performance degeneration caused by the RB and reflection effects in FFs. The comparisons of power penalties under different signal to reflected noise ratio (SRNR) are illustrated in Fig. 5. The performances of two systems are compared: one is the DWDM-PON we proposed with a interconnection architecture; in the other one the interconnection architecture is removed, thus the system turns to be a conventional WDM-PON with bidirectional transmission on the same wavelength. Just as expected, since the DS and US signals in each FF are carried on the different channels with 25-GHz spacing, the reflection effects have negligible influence on the transmission performance in the proposed system. While in a conventional WDM-PON without an interconnection architecture or other RB mitigated schemes, the power penalties increase rapidly as the SRNR decreases.

TABLE 1

Power budget calculation for DS and US signals

Element for power budget	DS	US
Launching power after EDFA (dBm)	8	-
Injected power into RSOA (dBm)	-	-12
RSOA saturated output (dBm)	-	7.5
Interlever insertion loss (dB)	1	1
25 km SMF loss (dB)	5	5
Optical circulator insertion loss (dB)	0.5	0.5×2
1×N AWG insertion loss (dB)	5	5×2
80:20 OC loss at ONU (dB)	7 (20% port)	1 (80% port)
Total insertion loss (dB)	18.5	18
Receiver sensitivity (dBm)	-29.8	-30.7
Power margin (dB)	19.3	20.2

The power budget analysis of the proposed system is also carried out, as shown in Table 1. In DS direction, the launching power output from the EDFA is set to be 8 dBm. The total loss is 18.5 dB, including the power losses induced by an IL (1 dB), 25-km SMF transmission (5 dB), an optical circulator (0.5 dB), an AWG (5 dB) and an 80:20 OC (7 dB for the 20% port). In US direction, since the output power of ROSA is decided by the power of input DS signal, we consider the case that the injected power is fixed at -12 dBm and the RSOA has a saturated output power of 7.5 dBm. The total loss for US signal is 18 dB since the 80% port of 80:20 OC (1 dB) is connected with the RSOA and two $1 \times N$ AWGs as well as two circulators are traversed. The power margins for DS and US transmission are 19.3 dB and 20.2 dB respectively. Therefore, the proposed system could support larger transmission scope. We can also find that a 1 : 64 splitting ratio for each channel can be supported for hybrid WDM/TDM access. Note that when power splitter for TDM fashion is introduced, the DS signal power injected into the RSOA may be lower than the gain-saturation regime. This problem can be solved by using an additional SOA before the input of RSOA [24], [25].

4. Conclusion

We have proposed and experimentally investigated a DWDM-PON with mitigated RB and back-reflection effects. In the demonstrated system, 2N 25-GHz-spaced channels are generated in the OLT to support both the DS and US transmission for 2N ONUs. In this way, high utilization of wavelength resource is achieved and large number of channels could be obtained to improve the system capacity. Due to the handy interconnecting architecture installed at RN, the RB and back-reflection effects in FFs are completely eliminated. The configurations of RN and ONUs are simple, since the spacing of AWGs is eased to 50 GHz, and very few extra components are required. Experimental demonstration of error-free transmission over 25-km fiber is carried out to verify the feasibility. The analysis of power margin shows that the proposed system could be extended for the hybrid WDM/TDM application so that more users are supported.

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