Symmetric 40-Gb/s TWDM-PON with 51-dB loss budget by using a single SOA as preamplifier, booster and format converter in ONU

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Abstract: In this paper, we propose to use a semiconductor optical amplifier (SOA) in the optical network unit (ONU) to improve the loss budget in time and wavelength division multiplexed-passive optical network (TWDM-PON) systems. The SOA boosts the upstream signal to increase the output power of the electro-absorption modulated laser (EML) and simultaneously pre-amplifies the downstream signal for sensitivity improvement. The penalty caused by cross gain modulation (XGM) effect is negligible due to the low extinction ratio (ER) of upstream signal and the large wavelength difference between upstream and downstream links. In order to achieve a higher output power, the SOA is driven into its saturation region, where the self-phase modulation (SPM) effect converts the intensity into phase information and realizes on-off-keying (OOK) to phase-shifted-keying (PSK) format conversion. In this way, the pattern effect is eliminated, which releases the requirement of gain-clamping on SOA. To further improve the loss budget of upstream link, an Erbium doped fiber amplifier (EDFA) is used in the optical line terminal (OLT) to pre-amplify the received signal. For the downstream direction, directly modulated laser (DML) is used as the laser source. Taking advantage of its carrier-less characteristic, directly modulated signal shows high tolerance to fiber nonlinearity, which could support a downstream launch power as high as + 16 dBm per channel. In addition, the signal is pre-amplified by the SOA in ONU before being detected, so the sensitivity limitation for downstream link is also removed. As a result, a truly passive symmetric 40-Gb/s TWDM-PON was demonstrated, achieving a link loss budget of 51 dB.

OCIS codes: (060.2330) Fiber optics communications; (250.5980) Semiconductor optical amplifiers; (060.2360) Fiber optics links and subsystems.

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1. Introduction

Time and wavelength division multiplexed PON (TWDM-PON) with 40-Gb/s aggregate capacity has been considered as the predominant solution for next-generation PON stage 2 (NG-PON2), which allows a smooth network upgrade attributed to its backward compatibility and low technical risk. Huawei has demonstrated a 40/10-Gb/s TWDM-PON with 38-dB loss budget [1], and assembled the optical line terminal (OLT) transceivers in CFP-module and optical network unit (ONU) transceivers in SFP + module with 36-dB loss budget [2]. As new applications like Internet Protocol Television (IPTV) and digital video (DV) uploading become more and more popular, upgrading the upstream capacity is necessary. It can be supposed symmetric 40-Gb/s TWDM-PON will be a new trend for NG-PON2. We have demonstrated the first symmetric 40-Gb/s TWDM-PON with 39-dB loss budget by using 10-Gb/s upstream transmitters [3].While higher loss budget is preferred for supporting larger number of users and decreasing the overall network construction cost [4, 5]. The link loss budget is mainly limited by the downstream receiver sensitivity and upstream transmitting power in ONU side. Semiconductor optical amplifier (SOA) is an attractive device as downstream preamplifier [6] and upstream booster [7, 8] to improve the link loss budget due to its wide gain bandwidth, small size, low power consumption and easy integration. Since the pattern effect of the booster SOA is a serious problem at strong input power, synchronized gain-clamping SOA has been proposed to suppress the pattern effect and improve the upstream power to + 10 dBm, realizing a 40-dB loss budget and 40-km reach symmetric 40-Gbit/s WDM/TDM-PON [8].

In this paper, we propose to use a single SOA in ONU as both downstream preamplifier and upstream booster to improve the loss budget. In the upstream direction, the SOA acts as a booster to improve the power of the C-band upstream signal to + 12 dBm, meanwhile, taking advantage of gain saturation and self-phase modulation (SPM) effects, the SOA also serves as a nonlinear element to convert on-off-keying (OOK) signal to phase-shifted-keying (PSK) format [9]. The format conversion scheme mitigates the pattern effect that severely distorts the signal in linear amplifications; therefore no gain-clamping SOA is required as in [7, 8]. In the downstream direction, the same SOA pre-amplifies the L-band downstream signal to increase the receiver sensitivity. The cross gain modulation (XGM) effect between

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downstream and upstream signals is minor due to large wavelength difference. Finally a symmetric 40-Gb/s TWDM-PON over 40-km SSMF with 51-dB loss budget has been experimentally demonstrated, which could support more than 2000 users with sufficient system margin.

2. Principle and performance evaluation of format conversion

We have previously proposed to use a saturated SOA to convert the remote OOK signal to BPSK signal in network node [9], but since the extinction ratio (ER) and power of the OOK signal needs to be well controlled, the network node is not a perfect application scenario. However, considering the OOK transmitter followed by SOA format converter as a high power PSK transmitter is a feasible idea since the ER and power of the OOK signal can be flexibly tuned inside the transmitter. The principle of the format conversion in booster SOA can be explained as following: due to the nonlinear property of gain saturated SOA, the '0' and '1' level of the signal will experience different gains and varied phase shifts thereby distorting the original signal. But if the ER and input power are properly set, the output signal can be with constant amplitude and phase difference of 180° thereby converts an OOK signal to PSK format. Figure 1 shows the structure of the proposed OOK-PSK converter. An electro-absorption modulated laser (EML) was driven by 10-Gb/s pseudo-random binary sequence (PRBS) data with a word length of 2^{31}-1. The SOA (model SOA-NL-OEC-1550 from CIP) is driven at 180 mA. ER and optical power of the OOK signal can be controlled by adjusting Vpp of the driving signal and the bias current of EML respectively.

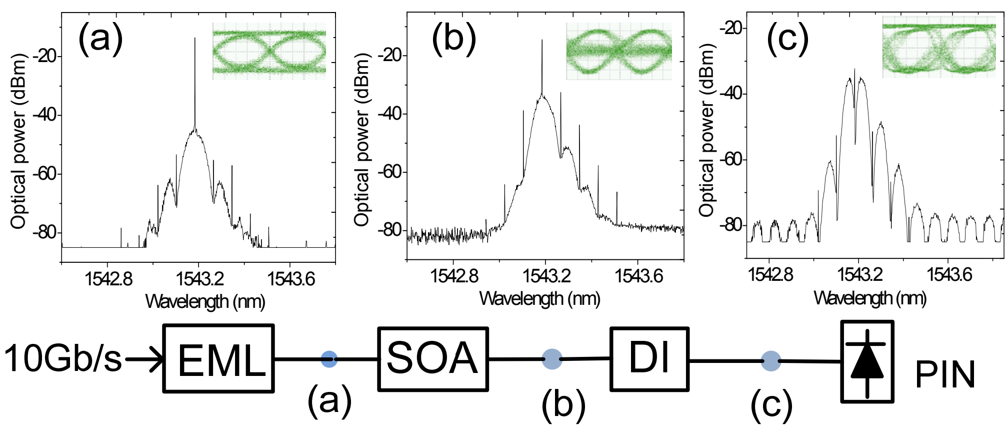

Fig. 1. Performance evaluation of OOK to PSK format conversion.

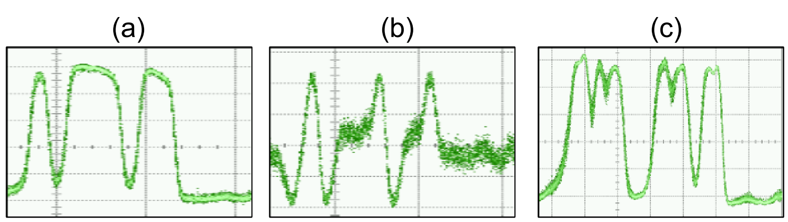

Fig. 2. Demonstration of format conversion and demodulation using data patterns.

The eye diagrams and optical spectra of the original OOK signal, the converted PSK signal and the demodulated signal from a delay interferometer (DI) measured at the corresponding marked points are provided in the insets. After the SOA, the intensity information on the signal is erased and only invisible phase differences are remained as shown in inset (b). The overshoot/undershoot on the signal origins from the limited recovery

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time of SOA. Finally, the DI converts the phase information into intensity and the pattern effect from saturated SOA is nearly mitigated. When the ER is 5.5 dB, with ~-2-dBm output power from the EML and + 12-dBm output power from the SOA, we obtained the highest amplitude from the output of DI, corresponding to an exact phase difference of 'π' between '1' and '0'. We also use a data pattern to serve as the input data to verify the validity of the proposed format conversion. Figure 2(a) shows the data pattern of '10111011 00000000', the output waveform from the SOA is provided in Fig. 2(b), and after demodulation, the data is recovered to '111001101 0000000' as Fig. 2(c) shows. Note that since the converted PSK signal is binary PSK (BPSK) rather than differential PSK (DPSK), the original data has to be encoded before modulation in practical applications, which is not demonstrated in our principle verification experiment. The encoding process can be expressed as:

$$b_n = \mathrm{mod}(a_n + b_{n-1}) \tag{1}$$

At the receiver side, the DI demodulates the data with differential decoding:

$$c_n = \mathrm{mod}(b_n + b_{n-1}) \tag{2}$$

Where mod in the Equations is the modulo-2 operation, a_n denotes the original data, b_n is the data pattern modulated on the EML and c_n is the decoded data received by users.

Besides, during DPSK demodulation, the receiver performance is related with the frequency offset between the optical signal and DI. It has been investigated that a frequency offset of 4% bit rate (i.e. 400 MHz in our 10-Gb/s system) leads to a receiver sensitivity penalty of 1.5 dB for NRZ-DPSK [10]. When the frequency offset increases to 10% bit rate (i.e. 1000 MHz), the DPSK system spread the sensitivity penalty to 5.5 dB. Therefore frequency stabilization method is required to ensure the receiving sensitivity in real applications [11, 12]. In the following part, using the proposed OOK-BPSK converter as high power upstream PSK transmitter in the ONU and meanwhile reusing the SOA as a downstream preamplifier, we demonstrate a symmetric 40-Gb/s TWDM-PON system and evaluate the system performance.

3. Experimental demonstration in TWDM-PON

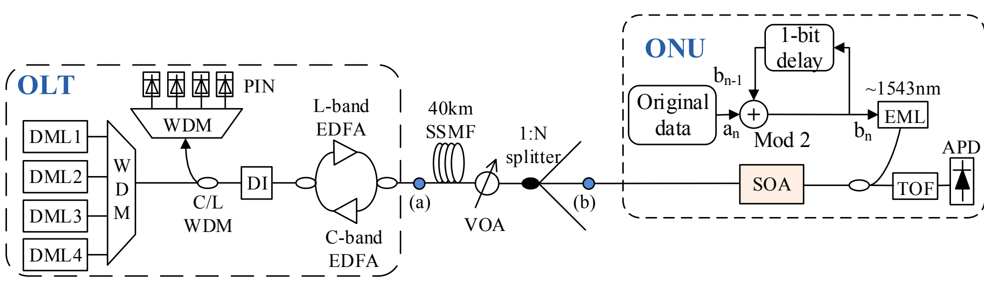

Fig. 3. Experimental setup.

We demonstrate a TWDM-PON system using the proposed high power PSK transmitter as upstream source. Figure 3 depicts the network configuration. Recently, ITU-T recommendation G.989.2 suggested C- band (1524-1544 nm) and L + band (1596-1603 nm) for upstream and downstream directions respectively in NG-PON2 [13], although the recommendation is still in draft and yet to be finally agreed, we used the wavelength plans in our experiment for demonstration. 4 directly modulated lasers (DMLs) operating at ~1605 nm with a channel space of 0.8 nm were used as downstream transmitters, and the upstream EML in ONU is operated at ~1543 nm. In the ONU side, the EML and SOA based PSK transmitter launch the 10-Gb/s BPSK signal into the transmission link with a power of + 12 dBm. Note that no fiber nonlinearity will be introduced even with such high upstream output power since the splitter in the remote node attenuates the power before the signal is launched into feeder fiber. After 40-km fiber transmission, the signals are pre-amplified by a C-band Erbium doped fiber amplifier (EDFA) before DI demodulation, wavelength division multiplexer (WDM) demultiplex and PIN detection. The DI with 10-GHz free-spectral-range serves as a phase demodulator in this experiment. In the downstream direction, the four channels are firstly multiplexed by a WDM. Then the same DI used for upstream demodulation is followed behind to serve as a periodical notch filter, which suppresses the frequency chirp of DML thereby enables long distance fiber transmission [3]. We have proved that due to the carrier-less characteristics, directly modulated signal has a higher threshold for Brillouin effect compared with external modulated on-off-keying (OOK) signals, which enables a higher launch power [14]. Therefore, before being launched into the SMF, an L-band EDFA boosted the signal power to 16 dBm per channel. At the receiver end, the downstream signals are pre-amplified by the same SOA before detected by the 10-GHz APD. A tunable optical filter (TOF) is used to select wavelength as well as filter out the amplified spontaneous emission (ASE) noise. The ASE spectrum of the SOA is shown in the inset of Fig. 3. The SOA had a 3-dB bandwidth of ~50 nm from 1535 nm to 1587 nm therefore can simultaneously amplify the downstream L-band signal and upstream C-band signals.

Figure 4 shows the measured BER curves of downstream and upstream signals. For the downstream direction, the eye diagram of 10-Gb/s directly-modulated downstream signal is severely distorted after 40-km fiber transmission without DI. The DML followed by DI acted as a chirp managed laser (CML) [15] and the power penalty is around 1 dB after 40-km fiber transmission. The SOA can improve the sensitivity of downstream signal by ~6 dB (considering the FEC limit BER of 3.8×10^{-3}) with the upstream signal off at the small signal gain of 18 dB. Experimental results show that the gain experienced by the downstream signal reduces when the two wavelengths move closer; therefore the large wavelength difference weakened their impacts on each other. In addition, the upstream PSK signal has a low ER that further reduces the XGM effect. So in our experiment, the XGM effect between upstream and downstream signal is minimal. However, even though the interaction between upstream and downstream links are quite weak because of the large wavelength difference, the gain experienced by the downstream signal is dragged down by 6 dB when the upstream signal is turned on due to gain saturation, resulting in a sensitivity degradation of ~2 dB. Finally, 4-dB sensitivity improvement and −35-dBm receiver sensitivity are achieved by using the SOA. Considering the transmission power of 16 dBm per channel, the downstream loss budget is 51 dB.

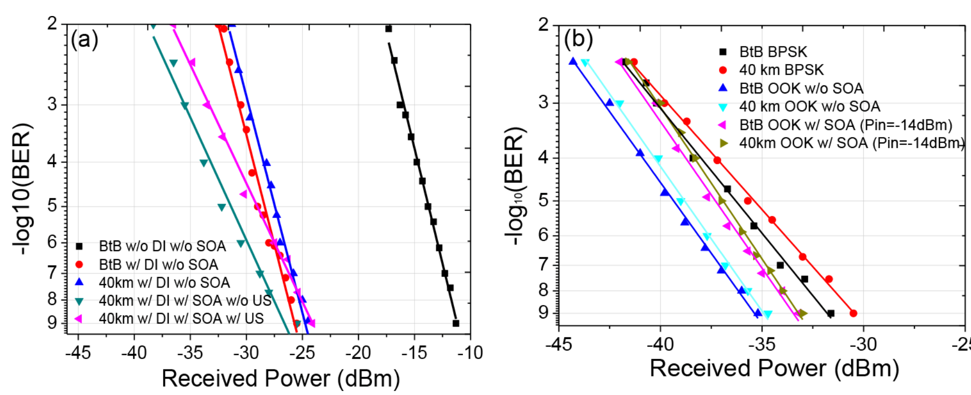

Fig. 4. BER curves of downstream (a) and upstream (b) signals.

For the upstream direction, the BPSK signal has similar back-to-back (BtB) sensitivity with the OOK signal at ER of 5 dB. After 40-km fiber transmission, the sensitivity of the demodulated BPSK signal is –41.5 dBm. Considering the BPSK transmitting power of + 12

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dBm, the upstream loss budget is 53.5 dB. By using balanced detection, the loss budget can be further improved by 3 dB to 56.3 dB. But the overall link loss budget is 51 dB limited by the downstream direction, which could be improved by using an L-band EDFA with higher output power in OLT and SOA with higher L-band gain in ONUs. Considering that the total downstream launch power of all channels will be beyond + 21 dBm, which has exceeded the eye-safety limits, some protection technique would be required. The pump of the L-band EDFA would be shut down quickly once the fiber broken issue is detected, so that the eye-safety can be ensured.

For comparison, we also evaluate the performance of upstream OOK transmitter. The standard EML has an ER of ~9 dB with ~0 dBm output power. The receiver sensitivity is −43.5 dBm after 40-km fiber transmission, corresponding to 43.5-dB loss budget. Directly boosting the signal using SOA induces strong pattern effect and the eye diagram is totally distorted and BER cannot be measured. In order to avoid gain saturation induced pattern effect, the output power of EML should be intentionally attenuated to less than −14 dBm for achieving the optimal receiver sensitivity of −41.5 dBm. The received power of upstream and downstream link refers to the power measured at the input of OLT and ONU, marked as (a) and (b) in Fig 3., respectively. The SOA output power is only + 8 dBm due to small input power, corresponding to 49.5-dB loss budget, which is at least 4 dB less than the BPSK transmitter case. Table 1 concludes the loss budget for all cases discussed above. The overall link loss budget is 51 dB by using the SOA as downstream preamplifier, upstream booster and format converter, which can support 40-km SMF transmission and more than 2000 users with at least 6-dB margin.

Table 1. Loss Budget Evaluation

	DS		US			
	w/o SOA	w/ SOA	w/o SOA	w/ SOA		
Extinction Ratio (dB)	N/A		9	9	9	5.5
Power into SOA (dBm)	N/A		N/A	0	−14	−2
Launch Power (dBm)	16		0	12	8	12
Sensitivity (dBm)	−31	−35	−43.5	N/A	−41.5	−41.5
Loss budget (dB)	47	**51**	43.5	N/A	49.5	**53.5**

We also try to use DML to replace the EML in ONU to achieve OOK-to-PSK conversion. However the intensity modulation of DML is always accompanied by frequency modulation and phase modulation. “0”, “1” and the rising/falling levels of the pulse correspond to different phases [16]. Therefore the directly modulated signal can be viewed as phase modulation with residual amplitude. When the signal is launched into the SOA, the phase variation originating from the SOA gain due to SPM effect will further change the phase relationship of different input power levels. So if the transmitter is a DML, specially designed pre-coding is required to achieve exact ‘π’ phase shift between “0” and “1” level at the output of SOA, which further adds the complexity of the transmitter. As for the linear amplification solution, similar with the linearly amplified EML case, the power injected to the SOA should be attenuated to less than −12 dBm to avoid pattern effect. After amplification, the power is boosted to 10 dBm. However, unlike the linearly amplified EML, the receiver sensitivity of directly modulated signal is reduced to −37 dBm and −36 dBm at the BER of 3.8×10^{-3} for BtB and 40-km SMF transmission case respectively, showing ~4-dB penalty compared with the unamplified case. In order to find the reason for the sensitivity degradation, we measured the eye diagrams and their ERs before and after amplification. The results are shown in Fig. 5. Note that the directly modulated signal launched into the SOA has an ER as low as 3.5 dB, resulting in its poor tolerance to amplification noise. After amplification, the ER is reduced to ~1.8 dB, which causes the signal degradation and results in the 4-dB sensitivity penalty. So

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we conclude that the EML rather than DML followed by a saturated SOA is a good choice for upstream transmitter.

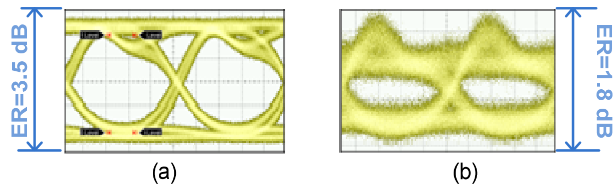

Fig. 5. Eye diagrams of upstream directly modulated signal (a) original 10 Gb/s upstream signal (b) SOA amplified 10 Gb/s upstream signal.

Finally, in terms of the cost of the proposed ONU structure, even though an additional SOA is used, the cost will not be too high attributed to the benefit of integration. For the standard 10-Gb/s EML with high output power, there is generally an SOA integrated right after the electrical absorption modulator (EAM) to improve the output power [17]. Compared with the standard EML, only a C/L band multiplexer is required to be integrated between EAM and SOA, which could be realized by hybrid integration [18]. The overall system loss budget is mainly limited by the ONU, where high downstream receiver sensitivity and high upstream power are required with low cost. Compared with coherent detection in ONU, using a SOA as a preamplifier to improve the downstream receiver sensitivity is a cost-effective solution. By re-using the SOA as an upstream booster and format converter, the cost can be shared by both downstream and upstream directions. In most of cases, better performance brings higher cost, but our goal is to maximize the performance to cost ratio for high loss budget TWDM-PON applications.

4. Conclusion

We propose to use a single SOA in ONU as downstream preamplifier and upstream booster to improve the loss budget of TWDM-PON system. To get a higher output power, the SOA works as an OOK-BPSK format converter for the upstream link, which can avoid the strong pattern effect induced sensitivity degradation in the conventional SOA booster, and no gain clamping methods are required to suppress the pattern effect. 51-dB loss budget is achieved with the ability to support 40-km fiber transmission and more than 2048 users. Experimental results demonstrate the feasibility of using a single SOA to increase the loss budget of both L-band downstream and the C-band upstream links.

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