Symmetric 40-Gb/s TWDM-PON With 39-dB Power Budget

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***Abstract*— Time- and wavelength-division multiplexed passive optical network (TWDM-PON) has been selected by full service access networks as a primary solution for next generation PON stage 2 in April 2012. In this letter, we propose and demonstrate a symmetric 40-Gb/s TWDM-PON with 39-dB power budget. A reflective semiconductor optical amplifier is used in optical network unit as a pre-amplifier to enhance the sensitivity of downstream signals. For the upstream direction, a thermally-tuned directly modulated laser with 10-Gb/s modulation rate is used as upstream colorless source, and a chirp management filter is employed in optical line terminal to mitigate chromatic dispersion therefore enabling fiber transmission. Symmetric 40-Gb/s TWDM-PON is experimentally demonstrated with a power budget of 39 dB, which could support 25-km fiber transmission and 1:1000 splitting ratio.**

***Index Terms*— Chirp management filter, directly modulated laser (DML), power budget, time- and wavelength-division multiplexed passive optical network (TWDM-PON).**

I. Introduction

NOWADAYS, passive optical network (PON) has been deployed worldwide by many telecommunication operators to provide broadband access. Time division multiplexing (TDM) based Gigabit Ethernet PONs (GEPONs) and Gigabit-capable PONs (GPONs) have been commercialized in several countries.Then XG-PON was suggested as an upgrade version, which could support a data rate up to 10Gb/s per feeder, namely next generation PON stage 1 (NG-PON1). However, the sustaining growth of bandwidth demand will eventually surpass the gigabit technologies and require the network upgrade to support higher data rate. Many different system configurations have been proposed to support beyond 40 Gb/s aggregate data rate, called as next generation PON stage 2 (NG-PON2), including wavelength division multiplexed PON (WDM-PON) [1], optical orthogonal frequency division multiplexed PON (OFDM-PON)[2], ultra-dense WDM-PON (UDWDM-PON) [3], time and wavelength division multiplexed PON (TWDM-PON) [4] etc. Among them, TWDM-PON has been selected by Full Service Access Network (FSAN) as the primary architecture for NG-PON2 [5]. By stacking several TDM-PONs with different wavelengths, the TDM-PON system can be upgraded to a TWDM-PON which could supply a higher bandwidth capacity while no change to the optical distribution network (ODN) is required. Due to its backward compatibility, technical maturity and component availability, this proposal is closest to the practical implementation. Huawei has reported a 4 wavelength stacked TWDM-PON system, achieving a downstream/upstream capability of 40/10 Gb/s and a power budget of 38 dB [6]. As new applications like IPTV and DV uploading become more and more popular, upgrading the upstream capacity is necessary in the future optical access network. It can be supposed that the symmetric 40 Gb/s TWDM-PON will be a new trend for NG-PON2.Chien-Hung Yeh et al. have presented a symmetric 40-Gb/s TWDM-PON by using 4 pairs of DFB lasers and external modulators as transmitters at both ends. An erbium-doped fiber amplifier (EDFA) was installed in the remote node (RN), which improved the power budget but changed the already deployed network structure [7].

We have demonstrated a symmetric 40-Gb/s TWDM-PON with completely compatible ODN for the first time [8]. A thermally-tuned 10-Gb/s directly modulated laser (DML) performs as colorless upstream laser source while a reflective semiconductor optical amplifier (RSOA) is installed in the optical network unit (ONU) to pre-amplify the downstream signal. A specially-designed tunable optical filter is employed in ONU for both downstream wavelength selection and upstream signal chirp management. Finally a 31-dB power budget was achieved, which could support a 25-km feeder fiber and 1:256 splitting ratio. In this letter, the system is further optimized to improve the power budget therefore supporting more users. By removing the chirp management filter from ONU to optical line terminal (OLT), right after the preamplifier for upstream signals, the impact of the filter insertion loss on the upstream power budget can be reduced therefore achieving a higher system power budget. A symmetric 40-Gb/s TWDM-PON is experimentally demonstrated with a power budget of 39 dB, which could support a 25-km feeder fiber and 1:1000 splitting ratio.

II. Upstream Transmitter Design

Colorless ONU is one of the key issues in standardizing the system, especially the choice of tunable transmitter.

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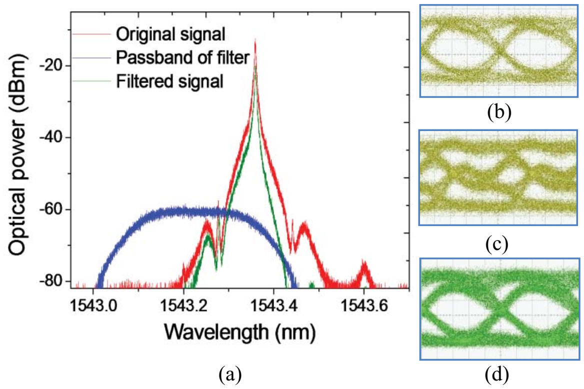


Fig. 1. Optical spectra and eye diagrams of the upstream signals. (a) Optical spectra of signals and optical filter. (b) Eye diagram of signal in BtB case. (c) Received signal without filter. (d) Received signal with filter.

The most common candidates are based on Fabret-Perot Laser diode (FP-LD), RSOA, and DML. However, for both FP-LD and RSOA, the modulation bandwidth is limited and electrical or optical equalization is necessary for 10-Gb/s direct modulation, which degrades the receiver sensitivity therefore limits the power budget. Thermally-tuned DML seems to be a promising candidate for a low cost and high performance colorless transmitter in 40-Gb/s TWDM-PON where only 4 wavelengths are required. By using a specially-designed optical filter to suppress the frequency chirp of the DML, the chromatic dispersion induced power penalty of a 10-Gb/s directly modulated signal can be reduced to 2 dB after 25-km single mode fiber (SMF) transmission. The eye diagrams and optical spectra of signals in back-to-back (BtB) case, after 25-km fiber transmission with and without the detuned spectral filtering cases are shown in Fig. 1. In the experiment, a 25-GHz super-Gaussian shaped bandpass filter was used.

The filter shape is essential for the perfect chirp management. Since we don't have filters of various shapes and bandwidth on hand, the design of the filter is analyzed by simulation using VPI. As the chromatic dispersion is caused by the frequency chirp of the DML, and the function of the filter is to filter out the low frequency parts which are the frequency chirp generated by "0"s, therefore enhance the extinction ratio of the signal. So as long as the "0"s are suppressed, the chirp induced dispersion could be avoided. The simulation was carried out using filters of two common shapes, Gaussian and super-Gaussian. We varied the bandwidth of the filter from 25 GHz to 100 GHz. By adjusting the offset between the central wavelength of the filter and the signal spectrum, we can always get an open eye diagram at the receiver end. With the increase of the filter bandwidth, the eye becomes degraded, and the super-Gaussion filter can achieve better results than Gaussion-shape filter. From the simulation results, we can conclude the sharp slope of the filter is essential for the perfect chirp management. The eye diagrams of signals in BtB case, after 25-km SMF transmission with and without filtering cases are shown in Fig. 2 taking three kinds of filters as examples.

III. Experimental Results

We set up an experiment to investigate our proposed system as shown in Fig. 3. The OLT has four pairs of transmitters and

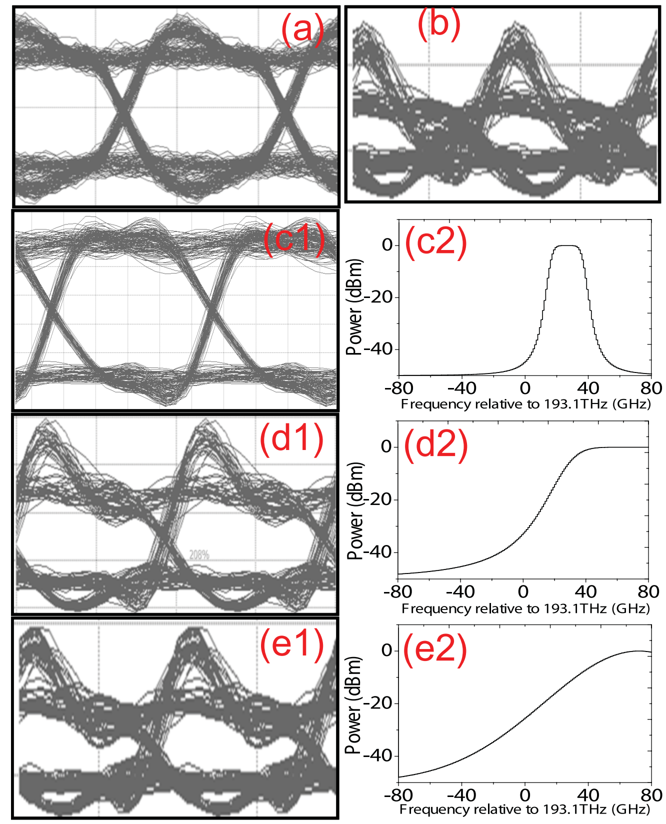


Fig. 2. Eye diagrams and filter shapes in filter designing simulations. (a) BtB signal, (b) after 25-km SMF transmission, (c1−e1) received signal filtered by 25-GHz Super-Gaussian shaped filter, 100-GHz Super-Gaussian filter, and 100-GHz Gaussian-shaped filter, and (c2−e2) passband of the 25-GHz Super-Gaussian shaped filter, 100-GHz Super-Gaussian shaped filter, and 100-GHz Gaussian-shaped filter, where frequency "0" corresponds to the central frequency of the signal spectrum.

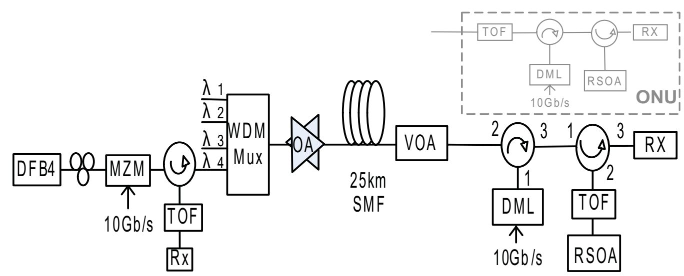


Fig. 3. Experimental setup.

receivers working on wavelengths separated by 0.8 nm. Since the wavelength plan in 40-Gb/s TWDM-PON has not been defined yet, we use four available DFB lasers in our lab whose wavelengths are from 1546 nm to 1550 nm. But the wavelength assignment will not affect the final experimental results. Each transmitter contains a DFB laser source and a Mach-Zehnder modulator (MZM) driven by 10-Gb/s pseudo-random bit sequence (PRBS) data. After wavelengths multiplexing, an Erbium-doped fiber amplifier (EDFA) boosts the downstream signal power to 10 dBm per wavelength. A variable optical attenuator (VOA) is placed after the transmission fiber to imitate the loss of the splitter and launches the downstream signal into the ONU. Before being detected by a PIN-TIA, a RSOA is used to amplify the downstream signal therefore improving

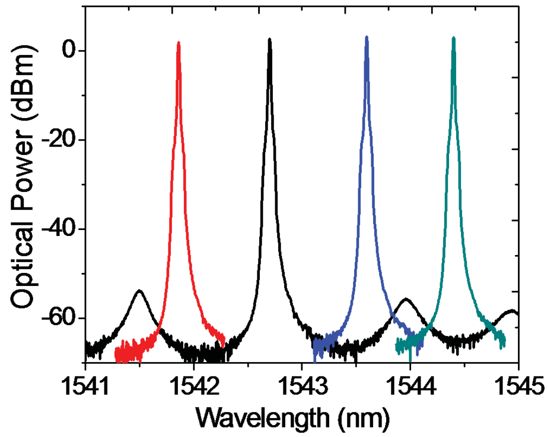
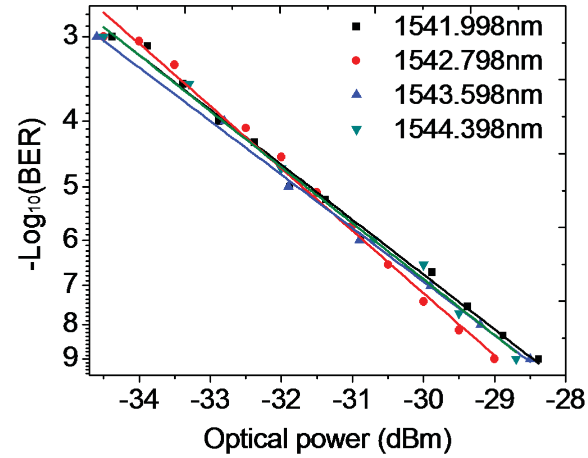


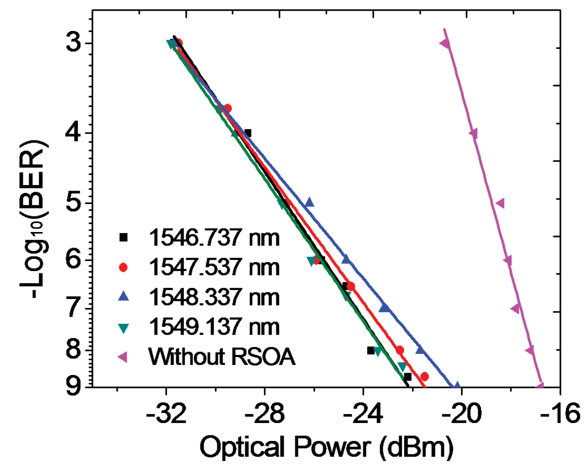
Fig. 4. Tuning ability of the DML.

the receiver sensitivity.The pre-amplification performance of the RSOA has been verified to be similar with that of SOA, and worse than that of EDFA, but the cost is lowest among them, therefore RSOA-based one is a compromise between the cost and performance, which is more suitable for the low-cost ONU. A standard tunable optical filter (TOF) between the RSOA and port2 of the optical circulator (OC2) is used to select the assigned downstream wavelength as well as filter out the amplification spontaneous emission (ASE) noise. In this way, the receiver sensitivity is improved by ~12 dB compared with the direct detection case. As for the upstream link, a DML driven by 10-Gb/s data serves as upstream transmitter. By tuning the temperature of the DML, the output wavelength changes accordingly. During 60 °C temperature tuning range, the output wavelength varies from 1541.8 nm to 1544.5 nm and the output power stably keeps at 5 dBm within the whole tuning range, which could support 4 wavelengths separated by 0.8 nm as shown in Fig. 4, perfectly meeting the requirement on upstream laser source of 40-Gb/s TWDM-PON.

In the experiment, we just use one DML and tune it to different wavelengths to imitate different ONUs. In practical applications, four wavelengths for different ONUs are combined by the optical splitter in ODN and then launch into the distribution fiber. After 25-km fiber transmission, the upstream signal is pre-amplified by an EDFA and then demultiplexed by a WDM demux. Before being detected by a PIN-TIA, a 25-GHz super-Gaussian shaped TOF is used to manage the frequency chirp of the DML therefore suppressing the dispersion induced penalty. In our previous work [8], the chirp management filter is placed at the ONU side, which can be used for both chirp management of the upstream signal and the downstream wavelength selection as shown in the inset of Fig. 3. However, since part of the upstream signal spectral is filtered, an extra loss of ~3 dB is inevitable. Combined with the insertion loss of the TOF, the upstream signal experiences a total loss of no less than 6 dB before multiplexed by the splitter therefore bringing down the power budget of the whole system. In order to eliminate the unwanted loss, we changed the system structure by repositioning the chirp management filter to the OLT side. As an EDFA is used in the OLT as a pre-amplifier, the loss of the filter can be compensated. Although the signal sensitivity is ~4 dB worse than the previous case,



(a)



(b)

Fig. 5. BERs of upstream and downstream signals.

TABLE I

UPSTREAM POWER BUDGET COMPARISON FOR DIFFERENT CHIRP MANAGEMENT FILTER LOCATION

	Output Power	Link Loss Induced By Filter	Sensitivity@1e-3	Power Budget
Case1	5 dBm	6 dB	−37.7 dBm	36.7 dB
Case2	5 dBm	0	−34 dBm	39 dB

the power budget has a 2 dB improvement as a whole. Note that the sensitivity of the upstream signal is better than we measured in Ref [8], since we use a different PIN-TIA with better sensitivity. Fig. 5(a) shows the measured BER curves of the upstream signals after 25-km SMF transmission and chirp management in continuous mode, where the extinction ratio (ER) of the DML is 7 dB and the PRBS length is $2^{31}-1$. Table 1 summarizes the upstream power budget for different filter location cases.

Except for the sensitivity improvement, the benefit of repositioning the chirp management filter can also reduce the ONU cost. Since a super-Gaussian shaped filter with narrow bandwidth is better for chirp management from the simulations, removing the special filter to OLT can relax the design complexity of the TOF in ONU, where only

TABLE II
POWER BUDGET EVALUATION OF THE PROPOSED SYMMETRIC 40-Gb/s TWDM-PON

	Output Power	Sensitivity@1e-3	Power Budget
Downstream	10 dBm	-31.5 dBm	41.5 dB
Upstream	5 dBm	-34 dBm	39 dB

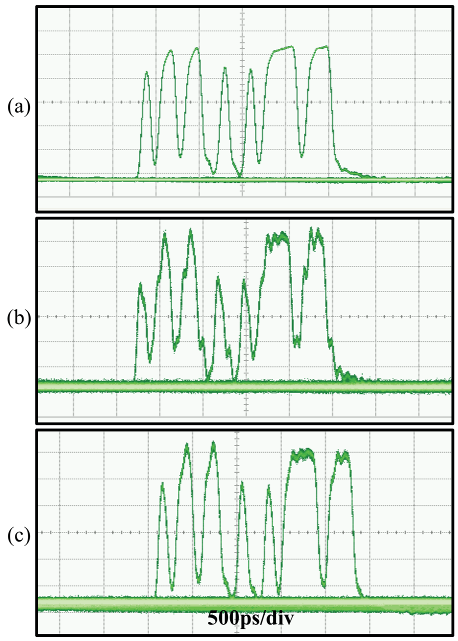


Fig. 6. Burst mode operation of the upstream signal. (a) Upstream signal in BtB case, (b) after 25-km SMF transmission without filtering, and (c) after 25-km SMF transmission after filtering.

selecting the downstream wavelength function is required, therefore reducing the ONU cost. Besides, the TOF can be placed between OC and RSOA to simultaneously select the downstream wavelength and remove the ASE noise therefore further improving the downstream signal sensitivity.

The downstream property was then measured. Using a RSOA ahead of the PIN-TIA as a pre-amplifier, the sensitivity at 1e-3 of the downstream signal can be improved to -31.5 dBm, which is better than the result of -29.5 dBm in our previous work because the TOF also removes the ASE noise. The BER curves for four downstream wavelengths with RSOA and one downstream wavelength without RSOA are shown in Fig. 5(b), where the ER of the downstream signal is 13 dB and the PRBS length is $2^{31}-1$.

We evaluated the power budget of the system as shown in Table 2. As the power of downstream signal is boosted to 10 dBm by the EDFA before launching into the fiber; the sensitivity at the receiver end is -31.5 dBm, so the power budget in downstream direction is 41.5 dB. In upstream direction, the output power of the DML is 5 dBm and the sensitivity of the received signal is -34 dBm, so the power budget of the upstream direction is 39 dB. The power budget of the whole system is limited at 39 dB by the upstream direction, which could support 25-km SMF transmission and 1:1000 splitting ratio. By replacing the PIN-TIA using an APD in the ONU, the downstream power budget could be further improved; therefore upstream power budget improvement will be the next research focus to support longer transmission distance and more users.

In the TWDM-PON system, the upstream transmitter is required to work in burst mode. We modulated the DML using burst mode signals and got the eye diagrams in BtB, after 25-km SMF transmission with and without filtering cases as shown in Fig. 6. Note that without filtering, the signal is severely distorted due to the chromatic dispersion. After using a 25-GHz super-Gaussian shaped filter to suppress the chirp, the extinction ratio is enhanced obviously, verifying that the proposed chirp managementmethod is suitable for burst mode operation. Since we don't have burst-more receiver (BMRx) so the sensitivity is only measured in continuous mode. But the reported BMRx can achieve the similar sensitivity with the continuous-mode receiver [9], so we believe the measured power budget in continuous mode is comparable in burst-mode operation, which need to be further verified.

IV. CONCLUSION

We have experimental demonstrated a symmetric 40-Gb/s TWDM-PON. By using RSOA in the ONU as pre-amplifier, the downstream sensitivity is enhanced by 12 dB. Thermally-tuned DML serves as colorless upstream laser source and the filter for chirp management is assigned in the OLT following the EDFA so that the insertion loss can be compensated. A 39-dB power budget is achieved, which could support a 25-km feeder and 1:1000 splitting ratio. The proposed system supplies a promising candidate for the NG-PON2 development.

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