Upstream capacity upgrade in TDM-PON using RSOA based tunable fiber ring laser

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Abstract: An upstream multi-wavelength shared (UMWS) time division multiplexing passive optical network (TDM-PON) is presented by using a reflective semiconductor amplifier (RSOA) and tunable optical filter (TOF) based directly modulated fiber ring laser as upstream laser source. The stable laser operation is easily achieved no matter what the bandwidth and shape of the TOF is and it can be directly modulated when the RSOA is driven at its saturation region. In this UMWS TDM-PON system, an individual wavelength can be assigned to the user who has a high bandwidth demand by tuning the central wavelength of the TOF in its upgraded optical network unit (ONU), while others maintain their traditional ONU structure and share the bandwidth via time slots, which greatly and dynamically upgrades the upstream capacity. We experimentally demonstrated the bidirectional transmission of downstream data at 10-Gb/s and upstream data at 1.25-Gb/s per wavelength over 25-km single mode fiber (SMF) with almost no power penalty at both ends. A stable performance is observed for the upstream wavelength tuned from 1530 nm to 1595 nm. Moreover, due to the high extinction ratio (ER) of the upstream signal, the burst-mode transmitting is successfully presented and a better time-division multiplexing performance can be obtained by turning off the unused lasers thanks to the rapid formation of the laser in the fiber ring.

OCIS codes: (060.2330) Fiber optics communications; (140.3600) Lasers, tunable; (250.5980) semiconductor optical amplifiers.

References and links

1. R. Heron, "Next generation optical access networks," in *Proc. of Access Networks and In-house Communications*, Toronto, Canada, paper AMA2 (2011).
2. Y. Banerjee, Y. Park, F. Clarke, H. Song, S. Tang, G. Kramer, K. Kim, and B. Mukherjee, "Wavelength division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited]," J. Opt. Netw. **4**(11), 737–758 (2005).
3. K. Grobe and J.-P. Elbers, "PON in adolescence: from TDMA to WDM-PON," IEEE Commun. Mag. **46**(1), 26–34 (2008).
4. C.-J. Chae and T. Jayasinghe, "Bandwidth-efficient capacity upgrade of Ethernet passive optical network systems," Electron. Lett. **42**(16), 938–939 (2006).
5. Y.-L. Hsueh, W.-T. Shaw, L. G. Kazovsky, A. Agata, and S. Yamamoto, "Success PON demonstrator: experimental exploration of next generation optical access networks," IEEE Commun. Mag. **43**(8), S26–S33 (2005).
6. T. Jayasinghe, C. J. Chae, and R. S. Tucker, "Scalability of RSOA-based multi-wavelength Ethernet PON architecture with dual feeder fiber," J. Opt. Netw. **6**(8), 1025–1040 (2007).

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7. M. Attygalle, Y. J. Wen, J. Shankar, A. Nirmalathas, X. Cheng, and Y. Wang, “Increasing upstream capacity in TDM-PON with multiple-wavelength transmission using Fabry-Perot laser diodes,” Opt. Express **15**(16), 10247–10252 (2007).
8. C. H. Yeh, C. W. Chow, C. H. Wang, F. Y. Shih, Y. F. Wu, and S. Chi, “Using four wavelength-multiplexed self-seeding Fabry-Perot lasers for 10 Gbps upstream traffic in TDM-PON,” Opt. Express **16**(23), 18857–18862 (2008).
9. M. Zhu, S. Xiao, Z. Zhou, W. Guo, L. Yi, M. Bi, W. Hu, and B. Geller, “An upstream multi-wavelength shared PON based on tunable self-seeding Fabry-Pérot laser diode for upstream capacity upgrade and wavelength multiplexing,” Opt. Express **19**(9), 8000–8010 (2011).
10. P. J. Urban, A. M. J. Koonen, G. D. Khoe, and H. Waardt, “Interferometric Crosstalk Reduction in an RSOA-Based WDM Passive Optical Network,” J. Lightwave Technol. **27**(22), 4943–4953 (2009).
11. M. Fujiwara, J. Kani, H. Suzuki, and K. Iwatsuki, “Impact of backreflection on upstream transmission in WDM single-fiber loopback access networks,” J. Lightwave Technol. **24**(2), 740–746 (2006).
12. J.-M. Kang, T.-Y. Kim, I.-H. Choi, S.-H. Lee, and S.-K. Han, “Self-seeded reflective semiconductor optical amplifier based optical transmitter four-stream WDM-PON link,” IET Optoelectron. **1**(2), 77–81 (2007).
13. Z. R. Lin, C. K. Liu, Y. J. Jhang, and G. Keiser, “Tunable directly modulated fiber ring laser using a reflective semiconductor optical amplifier for WDM access networks,” Opt. Express **18**(17), 17610–17619 (2010).
14. Z. Li, L. Yi, Y. Zhang, S. Xiao, and W. Hu, “Upstream multi-wavelength shared TDM-PON using RSOA based directly modulated tunable fiber ring laser,” in *Proc. SPIE* 8310, 83100T (2011).
15. A. Dhaini, C. Assi, M. Maier, and A. Shami, “Dynamic wavelength and bandwidth allocation in hybrid TDM/WDM EPON networks,” J. Lightwave Technol. **25**(1), 277–286 (2007).
16. G. P. Agrawal and N. A. Olsson, “Self-phase modulation and spectral broadening of optical pulses in semiconductor laser amplifiers,” IEEE J. Quantum Electron. **25**(11), 2297–2306 (1989).
17. H. Takashashi, “Temperature stability of thin-film narrow-bandpass filters produced by ion-assisted deposition,” Appl. Opt. **34**(4), 667–675 (1995).
18. M. Omella, V. Polo, J. Lazaro, B. Schrenk, and J. Prat, “10 Gbps RSOA transmission by direct duobinary modulation,” in *Proc. of European Conference on Optical Communication*, Brussels, paper Tu.3.E.4 (2008).
19. K. Y. Cho, Y. Takushima, and Y. C. Chung, “10-Gbps operation of RSOA for WDM PON,” IEEE Photon. Technol. Lett. **20**(18), 1533–1535 (2008).
20. H. Kim, “10-Gbps upstream transmission for WDM-PON using RSOA and delay interferometer,” in *Proc. of Optical Fiber Communication Conference*, Los Angeles, CA, paper OMP8 (2011).
21. L. G. Kazovsky, W. T. Shaw, D. Gutierrez, N. Cheng, and S. W. Wong, “Next-generation optical access networks,” J. Lightwave Technol. **25**(11), 3428–3442 (2007).
22. M. Hajduczenia and H. J. A. da Silva, “Next generation PON systems - Current status,” in *Proc. of International Conference on Transparent Optical Network*, Lisbon, Portugal, paper Tu.B5.2.1-Tu.B5.2.8 (2009).

1. Introduction

Time division multiplexing passive optical network (TDM-PON) has been deployed around the world as a suitable technology for the last mile broadband access. However, as new applications like IPTV and DV uploading become more and more popular, the upstream bandwidth demand grows rapidly, which is pushing the traditional TDM-PON to its capacity limitation since the capacity of a single wavelength channel is shared by all users. So upgrading the upstream capacity is necessary in the future optical access network. Some technical challenges including dispersion effects and the simultaneous demand of additional bit rate and optical budget are the main barriers to using high speed burst mode transceivers in pure TDM-PON [1–3]. Therefore introducing more wavelengths for upstream transmission was proposed as a promising solution, which is called as upstream multi-wavelength shared time division multiplexing-passive optical network (UMWS TDM-PON) [4–7]. In the upgraded network, downstream signals still broadcast via the optical splitter, while in the upstream link an individual wavelength can be assigned to the user who has a high bandwidth demand by using an upgraded optical network unit (ONU). The laser source in the upgraded ONU is a key technology requiring the properties of wide wavelength tuning range, high output power, low power ripple, high side mode suppression ratio (SMSR) and low cost.

Injection-locking [7] and self-seeding [8–9] Fabret-Perot laser diode (FP-LD) have been proposed as the upstream tunable laser source in the UMWS TDM-PON. Limited by the

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narrow spectral bandwidth and the fixed mode spacing in the FP-LD, the laser source has a wavelength tuning range of less than 20 nm and a tuning step of ~1nm, which requires the mode-selecting tunable filter to be continuously tunable to cover all modes of FP-LD or the filter passband exactly matches with the modes. Therefore the requirement on the tunable filter is quite high which will increase the cost of the upgraded ONU. Besides, the power ripple among different channels is higher than 5 dB, which will limit the loss budget of the upstream link.

Reflective semiconductor optical amplifier (RSOA) based upgraded ONU is also widely studied, which has shown a better performance than FP-LD in some aspects such as wider wavelength tuning range, flexible tuning step and higher output power. However, as the RSOA is seeded by the laser sources in the optical line terminal (OLT) [6], the wavelength number and tuning flexibility are determined by the centralized laser bank, which increases the cost of OLT. Besides, Rayleigh backscattering and back reflection induced crosstalk degrades the upstream signal quality severely in the centralized laser source case [10,11]. Self-seeding RSOA has also been proposed as the colorless source in ONU, in which a fiber Bragg grating (FBG) [12] or a tunable optical filter (TOF) [13] is used to seed the RSOA. As researches mostly focus on its applications in wavelength division multiplexing PON (WDM-PON), the burst mode transmission of the upstream laser which is quite necessary in UMWS TDM-PON applications has seldom been addressed. Besides, the requirement on the property of the optical filter, which is the key component in the self-seeding RSOA based fiber laser, has never been investigated.

We have proposed to use a RSOA and TOF based directly-modulated fiber ring laser as upstream laser source in UMWS TDM-PON [14]. In this paper, we fully investigated the performance of the upstream laser source by evaluating the burst mode transmitting performance, the requirement on the TOF, the longitudinal mode characteristics and the modulation bandwidth to prove its feasibility in the UMWS TDM-PON. The fiber laser can be directly modulated when the RSOA is driven at its saturation region. Thanks to the high extinction ratio (ER) of the upstream signal, the burst mode transmitting of the proposed laser source is successfully presented which enables several ONUs be time-multiplexed and share a same wavelength. Furthermore, the formation time of the fiber laser is measured to be ~80 ns, which is quick enough to meet the standard on/off time of the ONU in EPON, therefore the burst mode transmitting performance can be enhanced by turning off other ONUs when one ONU is transmitting signals within its time slot as the standard EPON. The requirement on the optical filter is also verified, which turns out the shape and bandwidth of the TOF do not affect the output power and the upstream transmission performance of the tunable fiber laser; therefore the laser source can be easily implemented with low cost solution. Experimental results show that the laser source features a wide wavelength tuning range from 1530 nm to 1595 nm, a SMSR larger than 60 dB, an output power higher than −3 dBm and power ripple less than 2 dB, which perfectly meet the requirement of an upgraded laser source in the UMWS TDM-PON. Bidirectional transmission of downstream data at 10 Gb/s and upstream data at 1.25 Gb/s per wavelength over 25-km single-mode fiber (SMF) has been demonstrated with almost no power penalty at both ends and the loss budget is evaluated to be ~16 dB, which could support 1:32 splitting ratio.

2. UMWS TDM-PON architecture

The configuration of the UMWS TDM-PON using our proposed upstream laser source is shown in Fig. 1. Only the users who require high upstream capacity need to upgrade the ONU structure. When the upstream capacity is overloaded, the upgraded ONU can be tuned to

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another wavelength and then a higher upstream capacity is available. Several upgraded ONUs can share the same new wavelength if the upstream capacity requirement of each user is not

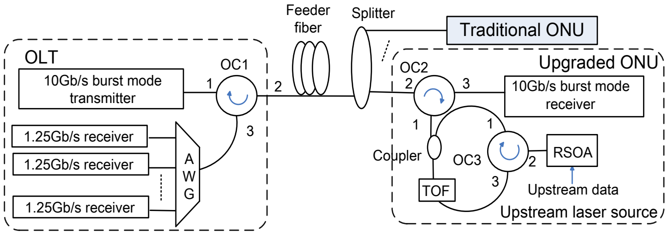

Fig. 1. Proposed UMWS TDM-PON configuration.

extremely high. A lot of dynamic bandwidth allocation algorithms have been proposed for TDM-PON and hybrid WDM/TDM-PON for higher bandwidth efficiency both in time and wavelength domains [15], which are also suitable for our proposal. The upstream laser source is composed of a coupler, a TOF, an optical circulator (OC) and a RSOA. The output wavelength of the laser source is flexibly controlled by tuning the central wavelength of the TOF. Upstream data can be directly modulated on the RSOA when the RSOA is driven at its saturated region [13]. At the OLT side, at least two sets of receivers are required for detecting the burst mode signals from traditional ONUs and upgraded ONUs after they are demultiplexed by an arrayed waveguide grating (AWG). Downstream signal is generated by a 10-Gb/s burst mode transmitter and broadcasted through the power splitter. The usage of OC2 enables the upstream and downstream signals transmitting in opposite directions, which can prevent the downstream signal and the back-reflected upstream signal from launching into the RSOA for reamplification therefore the crosstalk was suppressed. As shown in Fig. 1, the UMWS TDM-PON is completely compatible with the traditional TDM-PON configuration.

3. Experimental setup and results

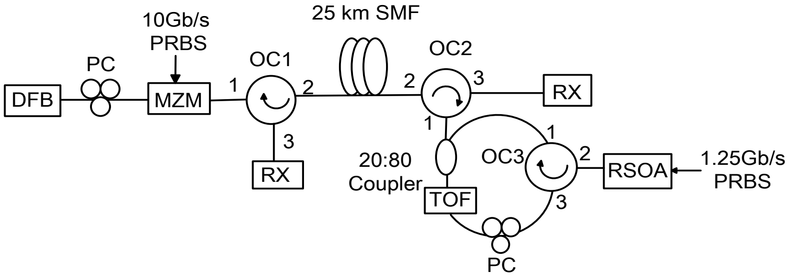

Fig. 2. Experimental setup.

We set up an experiment to investigate the performance of the proposed laser source in the single-fiber bidirectional UMWS TDM-PON, as shown in Fig. 2. A distributed feedback laser diode (DFB-LD) operating at 1550 nm and a Mach-Zehnder modulator (MZM) are used to generate a 10-Gb/s downstream signal. The downstream signal passes through an optical circulator (OC1) and then is launched into a 25-km long SMF feeder fiber for distribution. Finally the signal passes through OC2 and detected by the receiver. As for the upstream link, a 1.25-Gb/s pseudo-random bit sequence (PRBS) is modulated on the fiber laser as the upstream data, and part of the tunable laser output is coupled into the feeder fiber. A polarization controller (PC) inside the laser cavity is used to optimize the output power of the fiber laser. In

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practical application, a Faraday rotator mirror (FRM) can be used before the RSOA to mitigate the polarization dependent gain therefore stabilizing the output power of the fiber laser. After the 25-km SMF transmission, the upstream signal was launched into OC1 and finally detected by the receiver in OLT.

In order to verify the simplicity of the laser generation in the proposed fiber laser configuration, we vary the passband shape and the bandwidth of the TOF and measure the corresponding laser spectra as shown in Fig. 3. Note that the laser is always located at the long-wavelength edge of the filter passband and the output power is quite stable, no matter a narrowband Gaussian filter, a super-Gaussian filter, or a wideband flat-top filter are used. This frequency shift between the central wavelength of the TOF and the output laser wavelength is due to the self-phase modulation (SPM) induced spectral red-shift effect in the saturated RSOA, which has been experimentally verified in a saturated travelling-wave SOA [16]. The results prove that there is no strict requirement on the property of the optical filter therefore the laser source can be easily implemented by using low cost optical filters. For the upgraded ONUs sharing the same wavelength channel, the wavelength difference among ONUs should be less than the passband of the AWG in OLT to ensure they fall into the same detector, therefore it is better to use the same type of optical filter.

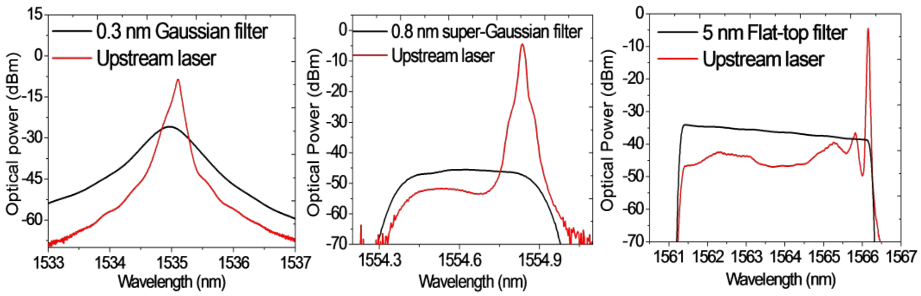

Fig. 3. Spectra of the upstream laser source and the passband of TOF.

As discussed above, the wavelength of the laser generated in the cavity is determined by the central wavelength of the TOF. The wavelength variation of the standard optical filter is from + 0.018nm to –0.005nm/°C [17], corresponding to the maximal wavelength deviation of ~1nm when the temperature varies from 0°C to 60°C. Only if the passband of the AWG is higher than 1 nm, the wavelength from the same ONU group will fall into the same 1.25G receiver through the AWG passband, enabling the TDM burst mode detection. Therefore the temperature variation will not affect the upstream TDM detection. The RSOA based self-seeded fiber laser is superior than the FP-LD based one in terms of temperature stability, where the central wavelength of the filter has to match with the modes of the FP-LD.

The fiber laser is working on multi-longitudinal mode when there is no data modulated on the RSOA as shown in Fig. 4(a) from both frequency-domain and time-domain measurement. Note that due to the limited resolution of the optical spectrum analyzer, the longitudinal mode components of the fiber laser cannot be recognized from the optical spectrum. We used an electrical spectrum analyzer to detect the beating frequency between the longitudinal modes, and the 95-MHz frequency component in Fig. 4(a) means the mode spacing is 95 MHz, corresponding to the cavity length of around 2.2 m. The competition among longitudinal modes results in the power fluctuation as shown in the inset of Fig. 4(a). When PRBS data is modulated on the RSOA at 1.25-Gb/s data rate, the measured eye diagram and the frequency distribution are shown in Fig. 4(b). The clearly open eye-diagram and penalty-free transmission of the modulated signal prove the single longitudinal mode operation. The word length of the PRBS data is set at $2^7 -1$ for easy measurement since longer PRBS word length resulting in much narrower frequency spacing, therefore the frequency spectrum is like a continued curve in 180 MHz range, which will cover the mode beating frequency at 95 MHz. We did not observe frequency spike at 95 MHz in Fig. 4(b), which also proves the single longitudinal operation after modulation. Note that the RSOA has to be biased at its saturation region (~70mA in our experiment) and the data driven voltage has to be optimized to ensure the laser still exist at data “0” therefore the laser does not need to reform from data“0” to “1” and the data “1” and “0” just corresponds to different laser power levels. The measured switching time between the power level of “0” and “1” is around 600 ps, corresponding to the rise/fall time of the modulated signal. However as we extend the cavity length to 2 km, corresponding to around 0.9-MHz longitudinal mode spacing as shown in Fig. 4(c), the laser generated in the fiber ring becomes unstable resulting in very strong power fluctuation as shown in the inset of Fig. 4(c). We can still observe the mode beating frequency after modulation and the eye diagram is quite noisy as shown in Fig. 4(d). This is because too many multi-longitudinal modes existed in the long-cavity fiber laser are difficult to be suppressed. The word length of the PRBS data is set at $2^{11} -1$ in this case. Therefore a short cavity length is preferred for a stable modulation performance.

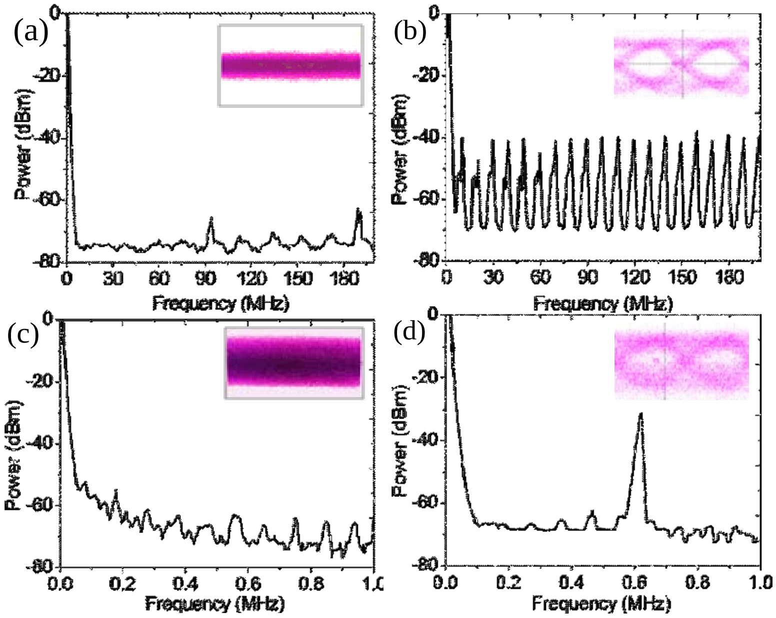

Fig. 4. The frequency-domain and time-domain measurement of the fiber laser and the 1.25-Gb/s upstream signal with different laser cavity length (a) Unmodulated laser in 2.2-m long cavity (b) 1.25-Gb/s upstream signal in 2.2-m long cavity (c) Unmodulated laser in 2-km long cavity (d) 1.25-Gb/s upstream signal in 2-km long cavity.

To evaluate the performance of the upstream laser source, we varied the central wavelength and the passband shape of the TOF and measured the bit-error rates (BERs) of the upstream signal both in back-to-back (BtB) case and after 25-km SMF transmission. The results measured under various filter cases are shown in Fig. 5. As the bandwidth of the TOF tuned from 0.3 nm to 5 nm, the passband shape varied from Gaussian, super-Gaussian to flat-top, and the central wavelength tuned from 1530 nm to 1595 nm, the signal sensitivities are similar and almost no power penalty was observed after transmission as shown in Fig. 5(a). Since the filter bandwidth and passband shape do not affect the laser performance, we use a super-Gaussian TOF with 0.8-nm bandwidth as an example to measure the output spectra of the fiber laser at different central wavelengths. Figure 5(b) shows the output spectrum of the laser source measured with a tuning step of 5 nm, and we can see that the laser source features an output power higher than –3 dBm, a power ripple less than 2dB, SMSR higher than 60 dB, which perfectly meet the requirement of the laser source in the upgraded ONU.

For achieving an optimal power budget, the split ratio of the coupler in the fiber laser was investigated taking the properties of upstream signal sensitivity and output power for consideration, and a 20/80 split ratio has been proved to be the best choice as shown in Table 1. The total link loss is evaluated to be ~10 dB, including the loss of the 25km feeder fiber of ~5 dB, the insertion loss of an AWG of ~4 dB, the loss of two OCs and optical connectors of ~1 dB. As the lowest output power of the laser source among wavelengths is ~-3 dBm, the worst sensitivity of the received signal is ~-29 dBm, the worst power budget of the upstream signal can be evaluated to be ~16 dB, indicating the feasibility of a 32-user network with 25-km long feeder fiber. In our experiment, a 10-Gb/s digital receiver is used for the 1.25-Gb/s upstream data detection therefore additional high frequency noise is introduced which degrades the sensitivity. In practical applications, a 1.25-Gb/s burst mode receiver should be used therefore the power budget will be higher. The power budget could be further improved if a RSOA with higher linear gain is used, with which both the output power and the signal quality can be optimized, therefore the supported user number could be increased.

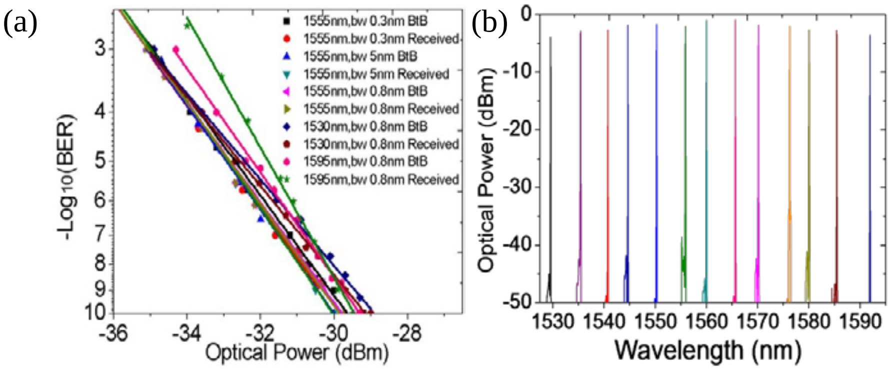

Fig. 5. Performance of the proposed upstream laser source.

Table 1. Power Budget Evaluation for Upstream

Coupler	Output power(dBm)	Sensitivity(dBm)	Total loss (dB)	Power budget(dB)
10/90	–1.66	–29	10	17.3
20/80	**-2.1**	**-30.8**	**10**	**18.7**
40/60	–3	–30.8	10	17.8
50/50	–4.2	–30.8	10	16.6

Then we fixed the operating wavelength of both upstream and downstream signals at 1550 nm to investigate the transmission property of the system. BER performances of the signals at both ends are measured in single-fiber bidirectional transmission case. The results are shown in Fig. 6. After transmission, there is almost no power penalty at both ends. The sensitivity of the downstream 10-Gb/s data is ~1 dB worse than the upstream 1.25-Gb/s data due to higher data rate. But the output power of the downstream DFB laser is much higher than the upstream fiber laser therefore the power budget will not be limited by the downstream signal.

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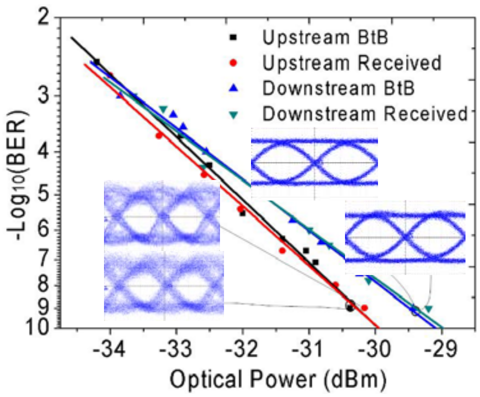

Fig. 6. BERs and eye diagrams measurement of the 10-Gb/s downstream and 1.25-Gb/s upstream signals.

The modulation bandwidth of the RSOA is ~1.5 GHz, which is evaluated by measuring the sensitivities of upstream signals under different data rates. Figure 7 shows the eye diagrams and sensitivity curves of the upstream signals. The higher the data rate is, the worse the signal quality is. When the data rate is up to 1.5 Gb/s, the sensitivity is ~3 dB worse compared with the 1.25 Gb/s case. And the error-free detection cannot be achieved for the 1.9 Gb/s data rate. The modulation bandwidth of RSOA is typically limited to 3 GHz, which is determined by the carrier lifetime in the active layer. For upgrading the operating data rate, methods such as a narrow-bandwidth modulation format [18], electronic equalization [19], or delay interferometer [20] have been carried out and enhanced the data rate to 10 Gb/s. Therefore the upstream data rate has a potential for further upgrading, which makes it more suitable for application.

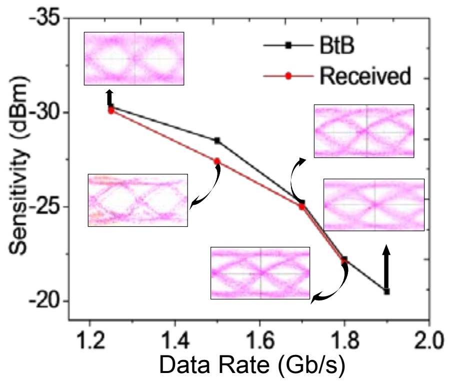

Fig. 7. Modulation bandwidth measurement of the RSOA.

In order to ensure that the proposed fiber laser can be used in TDM system, burst mode operations of the laser source are analyzed. Two upgraded ONUs can share the 1.25-Gbs upstream capacity by tuning the TOFs at the same wavelength. In the experiment two upgraded ONUs operated at 1550 nm and modulated with 1.25-Gb/s data packets were coupled together for the proof-of-concept. Figure 8 shows the data pattern received within burst mode operation. The measured ER of the upstream burst is ~8 dB as shown in Fig. 8(a). After coupling, the combined burst packets are achieved as shown in Figs. 8(b) and 8(c) in different time scales. The power difference between the two burst packets is originated from the uneven coupling ratio of the used coupler. Note that the emission power from the other ONU is not zero when one ONU is transmitting signal in its time slots, proving that a successful burst mode operation can be achieved even when other ONUs are not turned off in their idle periods.

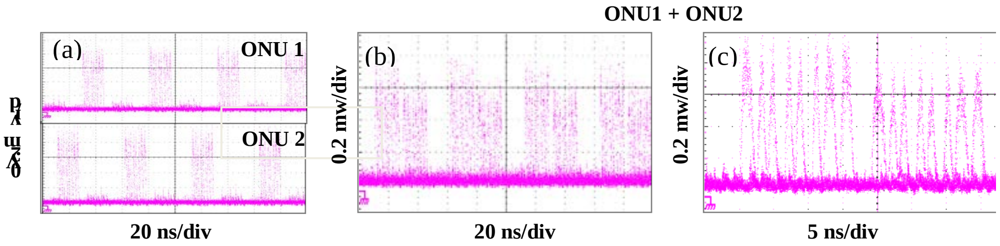

Fig. 8. Data traces in burst mode operation.

The burst transmission demonstrated above is suitable for the situation when a few ONUs are sharing one wavelength, however, optical power suppression of a burst-mode transmitter during idle periods is much more critical for TDM-PONs when more users are sharing the same wavelength, and the average power emitted by an idle ONU should not exceed –45 dBm [21]. Therefore it’s required to turn off other ONUs when one ONU is transmitting signal. Burst-mode operation requires the ONUs to be quickly turned on/off before/after burst is transmitted because the on/off speed directly determines the required guard time and thus, the transmission efficiency. In order to confirm the practicability of our proposal, we measured the on/off-time of the RSOA based fiber ring laser. We drove the RSOA with a 600 kHz/s clock signal and set the bias current at ~10 mA to ensure no laser is generated at off time. Therefore the “0” level of the clock signal can be treated as turning off the fiber laser. The measured results are shown in Fig. 9. We can obtain from Fig. 9(b) that the ONU-on-time is ~80 ns, and the ONU-off-time ~10 ns, which is quick enough to meet the requirement of EPON standard [22], demonstrating that the laser source can be a good candidate for burst mode transmitter. In this way, the feasibility of the proposed UMWS TDM-PON configuration using RSOA and TOF based tunable fiber ring laser as an upstream source was successfully demonstrated.

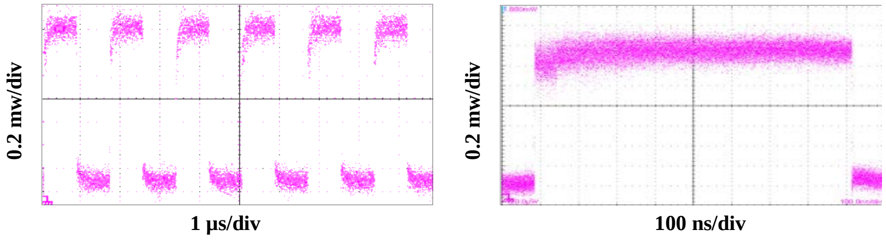

Fig. 9. ONU on/off time measurement.

Finally, the cost enhancement of the proposed architecture compared with the traditional TDM-PON is analyzed. In ONU side, the TOF is the key component determining whether the upgraded ONU is cost-effective and suitable for commercial application. As explained in Section 2, the TOF is only required in the upgraded ONU for the users with high upstream bandwidth requirement. Since in the UMWS TDM-PON, the number of the upgraded ONUs is limited and known, the tuning requirement on the optical filter is quite low, which is unnecessary to be continuously tuned and also a slow tuning speed is acceptable. Besides, there is no strict requirement on the passband shape and bandwidth of the filter as demonstrated in the experiment, so no matter the filter is Gaussian shape, super-Gaussian shape or flat-top

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shape and the bandwidth is as narrow as 0.3 nm or as wide as 5 nm, it can always be used in the laser source configuration and shows almost the same performance. For these reasons, the structure of the TOF can be as simple as a slow optical switch followed by several parallel thin-film filters with any bandwidth and shape. In OLT side, an AWG and multiple 1.25G receivers are required. As discussed above, the wavelength numbers in the UMWS TDM-PON are very limited; therefore the AWG could be a low cost coarse WDM demultiplexer. Besides, the AWG in the OLT lays a basis for further upgrading the UMWS TDM-PON to a bidirectional multi-wavelength TDM-PON. The 1.25G receiver is a common-used low speed burst mode receiver, which is shared by the users who operating on the same wavelength. Therefore the cost enhancement in OLT is not obvious. From both performance and cost viewpoints, the proposal is a good solution for the UMWS TDM-PON.

4. Conclusion

We have proposed an UMWS TDM-PON using a RSOA and TOF based directly modulated fiber ring laser as upstream laser source. Upstream capacity is greatly enhanced by introducing more wavelengths for upstream use. The properties of the laser source and the transmission performance of the PON system have been investigated. The output wavelength of the laser source can be flexibly controlled by tuning the central wavelength of the TOF and the laser source shows a stable performance when the wavelength tuned from 1530 nm to 1595 nm, and its features perfectly meet the requirement of an upgraded ONU. Experiment verified the filter passband shape and bandwidth do not affect the output power and transmission performance of the fiber laser, which relax the requirement on the TOF. Almost no power penalty was observed at both ends in the bidirectional transmission of downstream data at 10-Gb/s and upstream data at 1.25-Gb/s per wavelength over 25-km SMF. Thanks to the high ER of the upstream signal, the burst-mode transmitting was successfully presented. Furthermore, the turn on/off-time of the laser source was also measured, which is quick enough to meet the EPON standard, therefore a better burst mode transmission can be performed. The proposed laser source has been demonstrated to be cost-effective and easily implemented, which confirms the feasibility of using the proposal in the next generation TDM-PON construction.

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