Upstream Multi-Wavelength Shared PON with Wavelength-Tunable Self-seeding Fabry-Perot Laser Diode

Min Zhu, Shilin Xiao, Zhao Zhou, Wei Guo, Lilin Yi, He Chen, Jie Shi and Weisheng Hu
State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering
Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai 200240, China, Correspondent author: zhuminxuan@sjtu.edu.cn

Abstract: We proposed a Upstream Multi-Wavelength Shared PON using a tunable self-seeding FP-LD at ONU. The fiber laser performances are experimentally investigated. The paper also for the first time studies the effect of channel switch latency on the DBA with the IPACT scheme.
OCIS codes: (140.3510) Lasers, fiber; (140.3520) Lasers, injection-locked; (060.4510) Optical communications

1. Introduction

Time division multiplexed passive optical network (TDM-PON) such as Ethernet PON (EPON) and Gigabit PON (GPON) is a promising solution in the last mile access systems and being deployed around the world [1-2]. However, the introduction of bandwidth-intensive applications such as IPTV, HDTV and video-on-demand (VOD) will push the per-user capacity in such PONs to its limits as a single wavelength channel is shared among all users. Hence, 10 Gbps TDM-PONs are investigated in order to satisfy higher capacity requirements [2]. The 10 Gbps downstream broadcasting can be deployed easily using distributed feedback laser diode (DFB-LD) with external modulation. But 10 Gbps upstream burst mode transceivers can be expensive and not practical in the near future, since the cost of the optical network unit (ONU) is paid solely by the user.

In this paper, we proposed a novel Upstream Multi-Wavelength Shared (UMWS) PON architecture, based on a wavelength-tunable self-seeding Fabry-Perot Laser Diode (FP-LD) without fiber amplifiers inside the gain cavity at ONUs. The PON not only upgrades easily upstream capacity by introducing multiple wavelengths (to avoid higher burst mode data speed at ONUs), but also improves significantly bandwidth utilization with inter-channel statistical multiplexing. The proposed self-seeding laser module at ONU does not require external light injection sending from the optical line terminal (OLT) and dynamically locks onto only one of many longitudinal modes of the FP-LD. The performances of the wavelength and power stability, side-mode suppression ratio (SMSR), tuning range, and bit-error-rate (BER) have been experimentally studied with direct modulation of 1.25 Gbps upstream data. The paper also for the first time investigates the effect of channel switch latency (SL) on the dynamic bandwidth allocation (DBA) with the prevailing multi-wavelength Interleaved Polling with Adaptive Cycle Time (IPACT) scheme [3].

2. Proposed Scheme and Principle

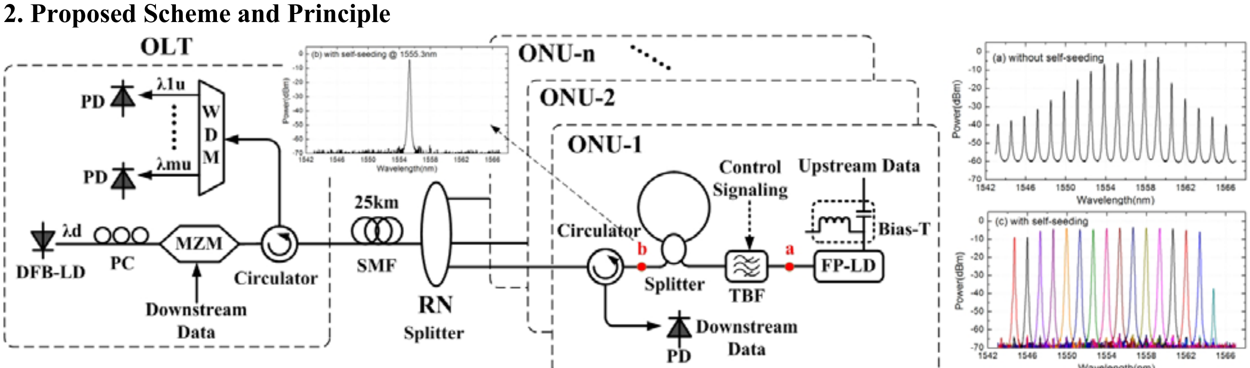

Fig. 1 Proposed UMWS PON architecture. (a) Original output spectrum of MLM FP-LD used operates at 30 mA in the temperature of 25^{0}C. (b) SLM output is obtained while the TBF is set at 1555.3nm. (c) Complex output spectra in the wavelengths of 1544.69nm to 1563.39 nm.

The UMWS PON architecture using a tunable self-seeding FP-LD at ONU is shown in Fig. 1. In the OLT, a DFB-LD and a Mach-Zehnder modulator (MZM) are used to generate downstream broadcasting signal (λd) to each ONU. A 1×m wavelength de-multiplexer/multiplexer (WDM) and a bank of Photo-Detectors (PDs) are used to receive upstream signals. In Remote Node (RN), a 1×n optical splitter is applied to split downstream carrier (λd) power to each ONU and to combine upstream multiple wavelengths (λ1u to λmu) sent back to OLT, respectively. In each ONU, we use a FP-LD, a tunable band-pass filter (TBF) and a 90:10 optical splitter to generate a 1.25Gpbs upstream signal in a self-seeding way. The transmission in the PON infrastructure is totally 25km single mode fiber (SMF) without dispersion compensation.

In the proof-of-principle experiment, we use 1.5μm FP-LD to simulate the unavailable 1.3μm FP-LD. The FP-LD has multi-longitudinal-mode (MLM) output with ~45% front-facet reflectivity. Fig. 1(a) shows the free run output spectrum of the MLM FP-LD without self-seeding when the bias current and temperature are 30mA and 25^{0}C respectively. The TBF is required to be capable of precisely changing their center wavelength according to a voltage signal. Once the ONU receives the downstream control signalling on the assigned wavelength channel for upstream transmission from the OLT, the control circuits are triggered for the TBF calibration. Thus, the MLM FP-LD is aligned to the certain filter mode of the TBF. The filtered single longitudinal mode (SLM) will be reflected by the fiber loop composed of a 90:10 optical splitter and injected back into the FP-LD. Therefore, the feedback light is selected by the TBF and transmits through the following fiber path: FP-LD → TBF → fiber loop → TBF →FP-LD → TBF → fiber loop → Output. Hence, the FP-LD will laser at single longitudinal mode and the optical output is amplified by self-seeded operation. When the 3-dB bandwidth and insertion loss of the TBF was 0.4 nm and 3.5 dB, the stable SLM output is shown in Fig. 1(b), while the TBF is set at 1553.86nm. Fig. 1(c) presents the complex output power spectra of the proposed laser module in the tuning range of 1544.69nm to 1563.39nm with the tuning step of ~1.34nm.

The proposed UMWS PON is a promising candidate for the next generation access network thanks to the following reasons. First, all ONUs share the all upstream wavelengths to transfer upstream data with a wavelength or finer sub-wavelength granularity, which greatly improves the resource utilization. Moreover, the PON provides an advantage of simply upgrading the present TDM-PON in a cost-effective way by only modifying the equipments at the OLT and ONU and keeping the fibre transmission link intact. Last but not least, the UMWS PON also presents a cautious upgrade path in that wavelength channels can be added on the user demand. More precisely, only ONUs with higher traffic demands may be upgraded by deploying proposed self-seeding laser module, while ONUs with lower traffic demands remain unaffected. Thus, a single-channel TDM-PON can be upgraded alternatively into a heterogeneous WDM/TDM PON in which the ONUs differ in upstream access capabilities.

3. Experimental Results

We experimentally investigate the proposed tuable self-seeding laser at ONUs. Fig. 2 shows the output power and SMSR versus the different lasing wavelength. The maximum and minimum output power are −3.4 and −9.0 dBm (ΔPmax = 5.6 dB) at the wavelength of 1546.0 and 1556.69 nm. The maximum and minimum SMSR are 65.5 and 71.4dB (ΔSMSRmax = 5.9 dB). The output power of the laser is determined by the gain profile of the FP-LD, hence it is lower at both ends of the spectrum.

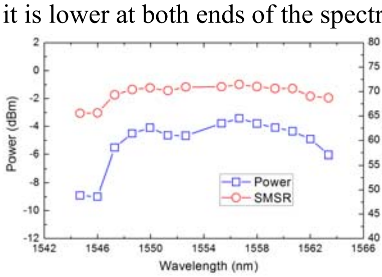

Fig. 2. Output power and SMSR spectra

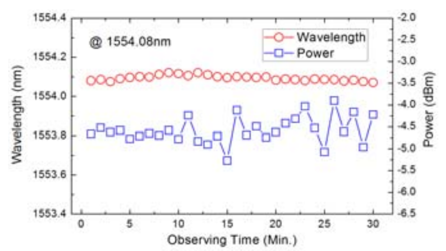

Fig. 3. Output variations of central wavelength and power at 1554.08 nm within 30 min observing time.

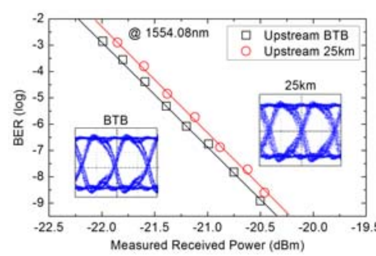

Fig. 4 BER and eye diagrams for the 1.25Gbps upstream data

To investigate the output performances of power and wavelength stabilities, a short-term stability is measured. The lasing wavelength is 1554.08 nm initially and the observing time is over 30 minutes. In Fig. 3, the wavelength variation and the power fluctuation are 0.05 nm and 1.37 dB, respectively. After two hours of observing, the stabilized output of the proposed fiber laser is still maintained. As a result, the proposed wavelength-tunable fiber laser has the advantage of simple scheme, low cost, better output efficiency and wide wavelength tuning range.

Fig. 4 presents the BER measurements and eye diagram of the 1.25Gbps upstream signals at the lasing wavelength 1554.08nm in the case of back-to-back and after 25-km SMF transmission without dispersion compensation. The power penalties are measured less than 0.2 dB.

4. WDM IPACT Scheme with Switch Latency (SL) Consideration

In the proposed UMWS PON, not only decisions on when and for how long (*Timeslot*) but also on which *Wavelength* channel to grant an ONU upstream transmission are required to make efficient use of the upstream bandwidth. Hence, we extend the conventional Interleaved Polling with Adaptive Cycle Time (IPACT) scheme with additional channel switch latency (SL) consideration and for the first time investigate the effect of channel SL on the network performance such as average delay, packet loss ratio and bandwidth utilization.

Since the OLT knows the Round Trip Time (RTT) of each ONU and keeps track of the next idle time of every upstream wavelength channel shown in the Eq. (1) in the Fig. 5. The $t_{Idle}\left(C_i\right)$ presents the next idle time epoch of the channel C_i. $t_G^j\left(C_i\right)$ is the time epoch when the last GATE was sent to ONU-*j* on channel C_i. $t_{P(G)}^j$ is the process time for the GATE message at ONU-*j*, which is assumed to be very small. The $t_T^j\left(C_i\right)$ is the transmission window size assigned by the OLT to ONU-*j*. *B* is the inter-packet guard time. With Eq. (1), we can calculate the start time of all upstream channels shown in Eq. (2). If the assigned upstream channel for ONU-*k* is different from the one in the last round, the start time *ST* will be delayed by the SL. By Eq. (3), the OLT schedules ONU-*k* to transmit on the earliest available channel at time t_{EST}^k among all channels. Then the OLT will send a GATE message to ONU-*k* at the time t_G^k after the corresponding REPORT from the same ONU is processed as stated in the Eq. (4).

$$t_{Idle}\left(C_i\right) = t_G^j\left(C_i\right) + t_{P(G)}^j + t_T^j\left(C_i\right) + RTT^j + B \qquad (1)$$

$$t_{ST}^k\left(C_i\right) = \begin{cases} t_{Idle}\left(C_i\right), & \text{if } C_i = C_{Last-round}^k \\ t_{Idle}\left(C_i\right) + SL, & \text{if } C_i \neq C_{Last-round}^k \end{cases} \qquad (2)$$

$$t_{EST}^k = \min\left\{t_{ST}^k\left(C_i\right),\ i = 1,2,......,m\right\} \qquad (3)$$

$$t_G^k\left(C_{t_{EST}^k}\right) = \max\left\{t_R^k + t_{P(R)}, t_{EST}^k - \frac{1}{2}RTT^k\right\} \qquad (4)$$

Fig. 5 Formula deduction for the WDM IPACT-SL scheme

5. Simulation Results and Analysis

In this section, we study the effect of channel switch latency (SL) on the network performance based on the multi-wavelength IPACT. In the simulations, we consider a PON consisting of *n*=32 ONUs and the number of upstream wavelength channels *m*=3. All ONUs have identical traffic load and varies from 0.1 to 0.9 using self-similar traffic source [4]. The traffic is generated by alternating Pareto-distributed ON/OFF source model. The shape parameter is 1.4 and the Hurst parameter can be calculated by H = (3-α)/2 = 0.8. The link data rate from users to an ONU is 100Mbps. The upstream rate of each wavelength channel is 1Gbps. The ONU buffer size is 10Mbytes.The distance between the OLT and ONUs are chosen randomly from 5 to 20 km. We adopt the Limited assignment scheme and the upper bound limitation of transmission window length is 15000 Bytes. The SL is measured by microsecond.

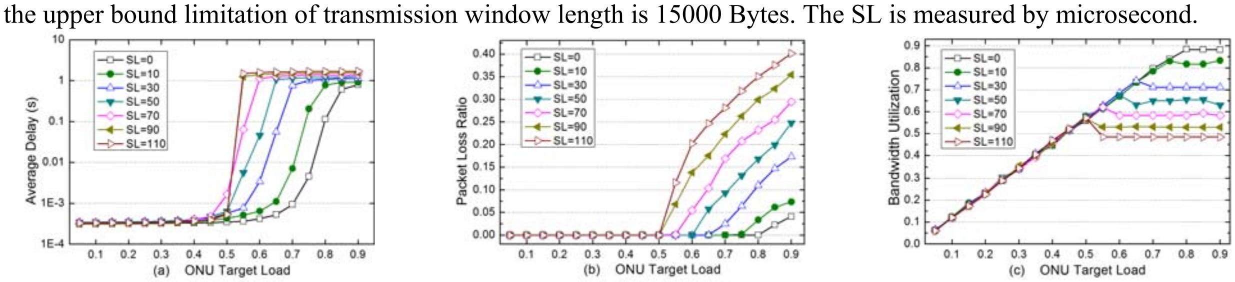

Fig. 7 (a) Average delay, (b) Packet Loss Ratio and (c) Bandwidth Utilization with different SL under varied ONU target load from 0.1 to 0.9

Fig.7 summaries the simulation results for the proposed WDM IPACT-SL scheme with different SL under varied ONU load. We find that when the traffic load is larger than 0.5, the higher the SL is, the lager average delay and packet loss ratio become, the lower bandwidth utilization turns. It is because hat larger channel SL causes the larger packet delay and buffer length, consequentially resulting in higher packet loss ratio. We note that the channel tends to be unused during the channel switch, so the larger channel SL corresponds to the lower bandwidth utilization.

6. Conclusion

We propose and experimentally demonstrate an UMWS PON based on the tunable self-seeding laser module at ONU in order to upgrade efficiently upstream capacity. The proposed fiber laser has a good performance of output power, optical SMSR and stabilities in the wavelength tuning range of 1547.18nm to 1561.92nm with tuning step of 1.34 nm. The BER measurement is performed for 1.25Gbps upstream data. At last, the simulation results show that the performance of WDM IPACT-SL will be degenerated as the SL increases.

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7. References

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