800 Gb/s (80 × 10 Gb/s) capacity WDM-PON based on ASE injection seeding

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Abstract: We demonstrate and characterize 800 Gb/s capacity WDM-PON with an ASE injection seeding. Required total seed power at central office to feeder fiber is 16 dBm for 20 km upstream transmission of 80 channels. We investigate the maximum transmission length according to channels. The transmission length is limited to 39.7 km by intra-channel crosstalk induced by Rayleigh back-scattering, provided that the dispersion is compensated. Also, we investigate the allowable differential path length to evaluate the flexibility of the system.

OCIS codes: (060.4510) Optical communications; (060.4259) Networks, packet-switched.

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1. Introduction

Advanced real-time applications are accelerating the evolution of optical access network with needs for high security, easy maintenance, great flexibility, as well as broad bandwidth [1–3]. To accomplish those aims, a wavelength division multiplexing passive optical network (WDM-PON) has been studied intensively [3–9]. Especially, a sustained high-speed connection over 10 Gb/s-per-channel with simple and cost-effective manner is an attainment target so as to accommodate a variety of services with a single platform. Also, an automatic wavelength allocation to each subscriber that is called color-free (colorless) has to be guaranteed without using complicate and expensive monitoring devices for a deployable system. Even though there are a lot of novel technologies, a deployment of commercial system is still beyond attainment since they are complex and rather costly. Moreover, the technologies based on coherent receptions and off-line processing increase the transmission latency. Among diverse methods, the seeded WDM-PON (or WDM system) based on amplified spontaneous emission (ASE) light was approved as an international standard for the optical access as well as metro network with 1.25 Gb/s-per-channel speed on 100 GHz grid thanks to excellent feasibility [10,11]. Based on this technology, the increase in bit-rate per channel to 10 Gb/s or over was considered difficult due to the beat noise of the spectrum-sliced ASE light and limited modulation bandwidth of the reflective modulators such as an anti-reflection coated Fabry-Perot laser diode (F-P LD) or a reflective semiconductor optical amplifier (RSOA). Lately, however, an interest in an integrated high-speed reflective modulator is being raised [12,13]. Also, it has been known that the 10 Gb/s signal transmission in the ASE-seeded WDM-PON is feasible at 100 GHz channel spacing based on the use of a high-speed reflective modulator and a forward error correction (FEC) [7]. The dispersion penalty restricts the dynamic range of distance from the RN (remote node, or the optical branching node) to subscribers in spite of using dispersion compensation fiber (DCF) at the optical line terminal (OLT). In addition to this, the high-speed reflective modulator could not suppress the noise at high frequencies effectively, having no room for increasing capacity. However, it is naturally desired that the next generation access network can accommodate a large number of users with high flexibility [14].

In this paper, we demonstrate the 20 km upstream transmission of 800 Gb/s (80 × 10 Gb/s) signal in the ASE injection seeded WDM-PON that has 50 GHz channel spacing. Each subscriber is equipped with a TO-can type RSOA and electro-absorption modulator (EAM) with two circulators for signal path designation (as emulation of an integrated high speed modulator). The effect of Rayleigh back-scattering (RBS) is investigated to show the available maximum reach according to channels. We also provide the determinant factors that lead to

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the channel dependence of RBS penalty. Moreover, the dynamic range of distance between the RN and subscribers is studied via the experimental analysis of dispersion penalty.

2. Experimental setup and results

Figure 1 shows an experimental setup for demonstration (upstream transmission only) of the 800 Gb/s capacity seeded WDM-PON based on ASE light. The setup is the same as the reference diagram of the standard WDM system except that the reflective optical network terminal (R-ONT) is equipped with a high-speed reflective modulator for 10 Gb/s operation with FEC [11]. We also assumed the use of FEC rather than implementing the FEC in practice. A wavelength band of 31.44 nm (1529.16 nm to 1560.60 nm) was used for 80 channels upstream transmission. For this, two 1 × 80 cyclic Flat-top arrayed waveguide gratings (AWGs) with 50 GHz (0.4 nm) channel spacing, were utilized at the OLT and the RN. Their 3 dB bandwidth and insertion loss were 41.3 GHz (0.33 nm) and 5 dB, respectively. Output power of the C band broadband light source (BLS) was 23 dBm, but a variable optical attenuator (VOA) was used between the BLS and the circulator to adjust the total seed power (P_{seed}) to the feeder fiber, and corresponding injection power (P_{inj}) that is defined as the optical input power to the R-ONT. The output spectrum of un-polarized ASE from the BLS was filtered by the AWG at the RN, having the input relative intensity noise (RIN) to the R-ONT of −107 dB/Hz [15]. The spectrum-sliced ASE light was injected to the RSOA through two optical circulators at the R-ONT. Polarization dependent gain (PDG) of the RSOA was measured to be less than 1 dB [9]. The output light of the RSOA was modulated with the EAM. Note that the RSOA, EAM, and two circulators can be replaced by an integrated reflective modulator such as an SOA-REAM for simple and cost-effective implementation [7,12]. We used these devices, since we do not have an SOA-REAM for 10 Gb/s operation. The optical signal from the R-ONT was delivered to the OLT, and detected by the APD-based optical receiver. A length and an attenuation coefficient of used single mode fiber (SMF) were 20 km and 0.23 dB/km, respectively. To compensate the chromatic dispersion of the SMF, a DCF module was utilized at the OLT. A large amount of attenuation by the DCF (6.3 dB) and EAM (6 dB) was compensated with the erbium doped fiber amplifier (EDFA) at the OLT.

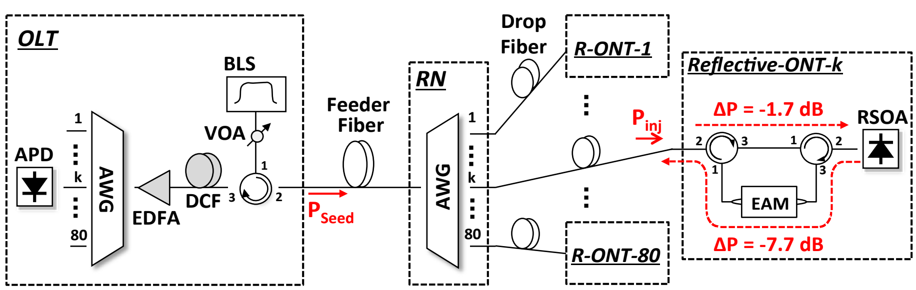

Fig. 1. Experimental setup for 800 Gb/s capacity seeded WDM-PON based on ASE light.

As shown in Fig. 2(a), the gain of R-ONT (defined as output power of R-ONT / input power to R-ONT) was decreased as the injection power (P_{inj}) increases. The increase in the injection power also brings about shift of the gain peak of the RSOA toward long wavelength channels due to depletion of the carrier density. Thus, among 80 channels, channel-80 has the highest gain when the injection power is larger than −20 dBm, while channel-40 has the highest gain when the injection power is less than −25 dBm. Also, we measured the average RIN detected by the receiver located at the OLT after passing by two AWGs in back-to-back (B-t-B) condition without the DCF (Fig. 2(b)). Generally, the RIN was reduced with the increase of the injection power (P_{inj}) due to the gain saturation. Moreover, since the noise suppression is proportional to the gain of the RSOA, short-wavelength channels are supposed

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to have worse RIN comparing to long-wavelength channels [16]. However, it is not true as seen in Fig. 2(b). The degradation of RIN at long-wavelength channels can be explained from asymmetric band-filling effect [17]. As a result, the channels around 20 have the best RIN performance. Two dashed lines in Fig. 2(b) indicate the RIN values that induce 2 and 3 dB BER penalties when utilizing an advanced FEC that uses RS (1901, 1855) with Extended Hamming Product Code (512,502) × (510,500). To keep the RIN-induced penalty less than 3 dB, the injection power has to be higher than −15 dBm.

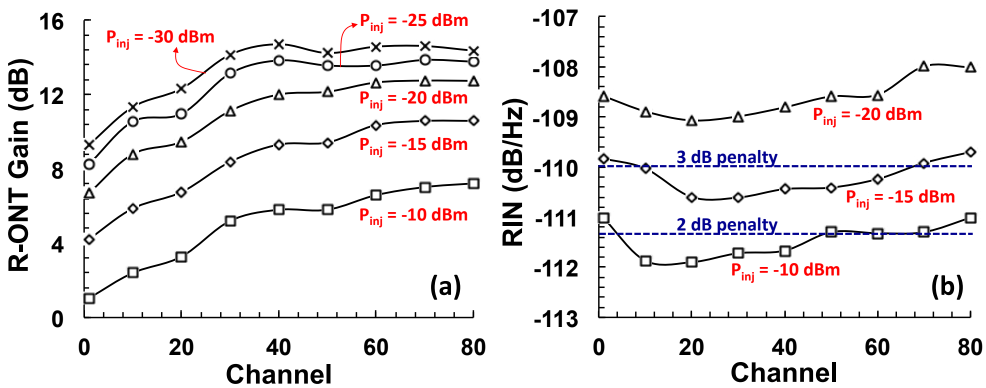

Fig. 2. Measured (a) R-ONT gain and (b) average RIN at receiver in B-t-B.

To investigate the transmission performance, we measured the bit error rate (BER) in B-t-B configuration and after 20 km upstream transmission at channel-40 as shown in Fig. 3. Considering the overhead for FEC coding of 6.69%, data rate of the non-return-to-zero (NRZ) signal was set to 10.7 Gb/s. A pattern length of pseudorandom binary sequence (PRBS) was 2^{31}-1. The BER threshold of the FEC (4.6×10^{-3}) was achieved at the injection power of −15 dBm and the performance was more enhanced with higher injection power (−10 dBm) as expected from the RIN measurement. The dispersion of this channel was fully compensated by DCF at OLT, and thus, the slight transmission penalty (< 0.5 dB) originates from the RBS of the seed light. To clarify this, simulation of the BER penalty by the RBS was performed via conventional BER analysis method using the measured levels of crosstalk (−18 and −21.2 dB for the injection power of −10 and −15 dBm, respectively) in 20 km transmission [18,19]. The simulation results showed 0.25 dB and 0.2 dB penalties by the RBS for the injection power of −10 dBm and −15 dBm, respectively.

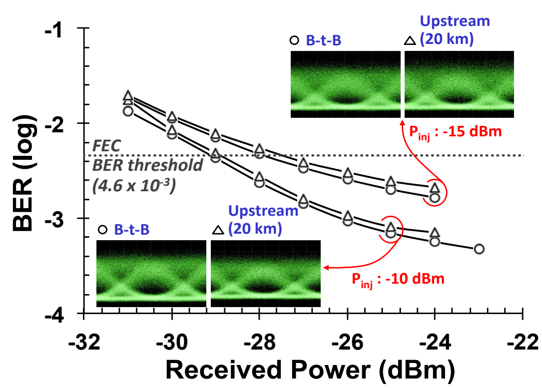

Fig. 3. Measured BER of channel-40 in back-to-back (B-t-B) condition and after 20 km upstream transmission.

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We also investigate feasibility of 20 km upstream transmission for all 80 channels as shown in Fig. 4. The red diamonds show the injection power to each R-ONT when the total seed power (P_{seed}) to the feeder fiber was 21 dBm. The variation of the injection power according to the channel comes from the non-flat output spectrum of the used BLS. The black triangles and circles show the BER of the received optical signal of 80 channels when the total seed power was 16 and 21 dBm, respectively. It is worth noting that the BER performance follows the channel-dependence of RIN performance. All channels are below the FEC threshold as seen in Fig. 4.

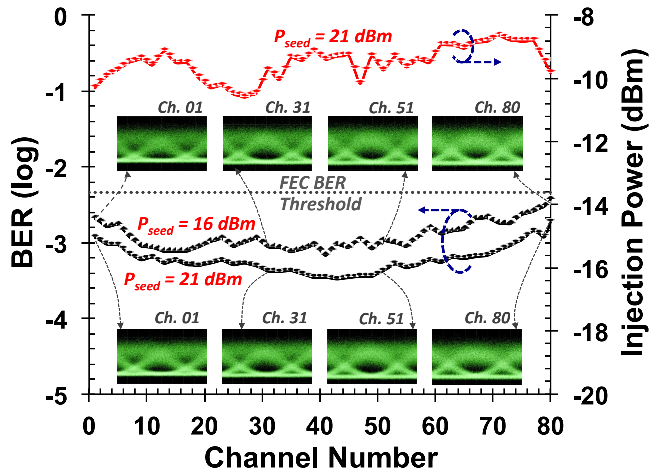

Fig. 4. Measured injection power and BER for various channel and seed power.

The dispersion penalty can be mitigated by a DCF module and/or by an electrical dispersion compensation and power budget issue can be solved by an EDFA at the OLT. However, the RBS-induced penalty increases as the transmission length increases. Thus it is a determinant factor of maximum transmission distance. The RBS-induced crosstalk makes two negative effects on the optical signal: increase of the RIN and degradation of the extinction ratio (ER). Thus, the channel which has the worst RIN and ER is most susceptible to the RBS. The crosstalk by the RBS is defined as the power difference between the RBS light and the optical signal at the receiver, and thus, can be estimated $R - G + 2\alpha_{Link}$ in dB, where R, G, and α_{Link} are the RBS coefficient, the R-ONT gain, and the link loss, respectively [20]. The RBS-induced crosstalk can be reduced simply increasing the R-ONT gain.

We investigate the maximum allowable link losses between the OLT and R-ONTs as a function of channels for the injection power of −10 and −15 dBm. The simulation was performed by calculating the BER with various levels of crosstalk induced by RBS. The available maximum link loss was obtained for the level of crosstalk that induces 1 dB penalty at the BER of the FEC threshold. It is clear that the experimental results are close to the simulation. The distances written in the Fig. 5 were obtained from the experimental results under the assumption that the AWG loss and fiber loss were 5 dB and 0.23 dB/km, respectively. The lower injection power (−15 dBm) gives the better allowable link loss than that of the higher injection power (−10 dBm). This feature can be understood from the reduced gain of the R-ONT due to gain saturation. However, the BER performance is better at higher injection power as shown in Fig. 3. The channel dependence of the maximum allowable link loss can be understood from the gain and the RIN of R-ONTs in Fig. 2. It may be noted that in case the transmission distance is longer than 30 km, the total launched BLS power at the OLT likely exceeds the range of the eye-safety (21.34 dBm).

In real PON, each R-ONT may have different fiber length from the RN. Also, as seen in Fig. 5, the available length of fiber is different according to the channel. In addition, the residual dispersion has channel dependence, since we have a DCF at the OLT. To understand the dynamic range of the difference in the length of fiber between channels, we show the allowable differential path length (DPL) in Fig. 6. To obtain the DPL at different channels, we assume a reference R-ONT which has a given injection power of P_{ref} and exact compensation of the dispersion (that is, no residual dispersion). For simplicity, we assumed that the BLS has a flat optical spectrum so that all channels have the same injection power for the same link loss. Thus, negative DPL indicates that the fiber length of the channel is shorter than that of the reference R-ONT, and therefore the injection power is higher than P_{Ref}. Positive DPL means the inverse case. In the experiment, the reference injection power was set to be −15 or −10 dBm. The negative (or positive) DPL were made by decreasing (or increasing) the length of the feeder fiber (the SMF between the DCF and circulator). The allowable DPL was determined by allowing for 1 dB penalty. The channel dependence of the DPL is in line with the channel dependence of the RIN. More specifically, the dispersion makes not only the pulse broadening, but also the increase in the RIN by the phase de-correlation. And thus, the channel that has worse RIN than others will be less tolerant to the dispersion [20]. For example, as seen in Fig. 2(b) and Fig. 6, channel 80 has the shortest DPL since the RIN of channel 80 is worse than other channels [20]. Seen in Fig. 6, channel-20 had the best flexibility in the DPL which was measured to be 18 km for −10 dBm injection power.

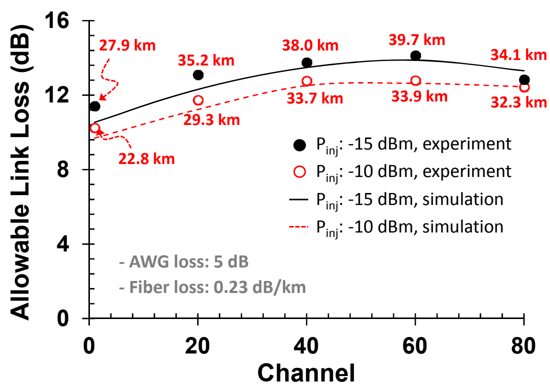

Fig. 5. Allowable link losses according to channels and injection power.

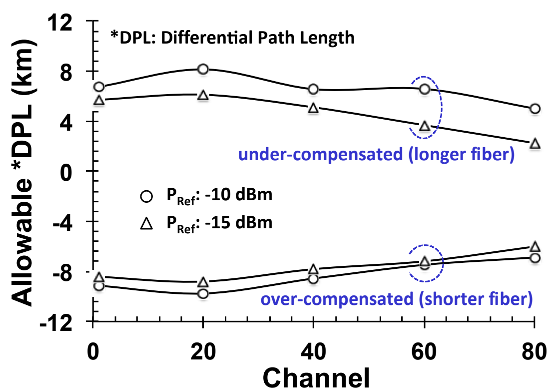

Fig. 6. Measured allowable differential path length (DPL) with channels.

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3. Discussion

In discussion, we compare a system performance with other WDM-PON technologies such as the coherent injection and self-seeding. For the WDM-PON based on coherent light seeding, the long-reach and high-speed over 10-Gb/s is possible with the cost of the low-noise coherent laser, coherent receiver, and advanced modulation format. However, it is vulnerable to the back reflection effect and rather complex. In the case of self-seeding, the colorless operation is guaranteed without the use of an external seed light. The performance of self-seeding strongly depends on the length of drop fiber though. The low extinction ratio also degrades the transmission performance. The proposed ASE seeded WDM-PON can accommodate the 80 subscribers with a colorless operation. Furthermore, it is highly tolerant of the back reflection effect due to the wide ASE bandwidth. However, the proposed system is severely affected by the chromatic dispersion, having the DCF mandatory. More details are given as follows in Table 1.

Table 1. Performance comparison of the various WDM-PONs

	Coherent injection		**Self-seeding**	**Proposed**
Data rate (Gb/s)	40	10	10	**10**
Reported number of channels	Not reported	4	16	**80**
Transmission length (km)	60	80	60	**22.8 ~39.7**
Injection power (dBm / channel)	−15	−10	-	**-15**
RIN	> −140 dB/Hz	Not reported	> −115 dB/Hz	**> −112 dB/Hz**
Back reflection	Vulnerable	Vulnerable	Vulnerable	**Tolerant**
Remarks	Coherent receiver required Rather complex		Low ER Sensitive to drop fiber length	
Reference	[21]	[12] [22]	[6] [23]	

4. Conclusion

In conclusion, we demonstrated the 20 km upstream transmission of 800 Gb/s signal in the ASE-seeded WDM-PON, where the R-ONT was comprised of an RSOA and an EAM, providing high-speed modulation, noise suppression, and amplification at the same time. The BER threshold of the FEC was achieved at 80 channels with total seed power of 16 dBm to the feed fiber at the OLT. The maximum transmission length was 39.7 km for channel-60 that is limited by intra-channel crosstalk induced by the RBS. Also, the demonstrated WDM-PON had an excellent flexibility in the DPL up to 18 km, for the channel-20.

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