DWDM-PON at 25 GHz channel spacing based on ASE injection seeding

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Abstract: We demonstrate a 25 GHz-channel-spaced DWDM-PON based on ASE injection seeding. A 60 km transmission at 1.25 Gb/s per channel is available with a 2nd generation FEC. The major limiting factor is the optical back reflection induced penalty. Thus a high gain reflective modulator and/or relocation of the seed light increase the transmission length. We demonstrated 90 km transmission with relocated seed light to remote node.

OCIS codes: (060.4510) Optical communications; (060.4250) Networks.

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1. Introduction

It is desired that the next generation access network accommodates a large number of users with an extended reach [1]. In addition, a high speed sustained connection should be guaranteed in order to embrace the radical changes of provided information and services. Thus, a lot of promising solutions were proposed and demonstrated [2–4]. Among them, a wavelength division multiplexing-passive optical network (WDM-PON) based on amplified spontaneous emission (ASE) injection seeding method has been regarded as a solution for the next generation access network [4]. Currently, this technology has been selected as an

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international standard for a low cost DWDM for metro and access applications [5]. However, the expansion of the capacity (> 40 channels) and extension of the reach (> 40 km) are still beyond attainment. We previously demonstrated DWDM-PON at 25 GHz channel spacing with help of the pre-filtering, but the distance was limited to 15 km [6]. The key limiting factors were the intensity noise of the spectrum sliced ASE light and optical back reflection [7]. Another concern is the required injection power of the seed light at the optical line terminal (OLT). To counterbalance the intensity noise and the impairments, a high injection power into the F-P LD or RSOA is required [8,9]. However, the back reflection induced penalty and the cost increase. The impairments and cost problems can be solved by using forward error correction (FEC) that is universally utilized to improve the bit error rate (BER) performance in a wide range of fields [10].

In this paper, we investigate the uppermost limit of the ASE injection seeded DWDM-PON with help of the FEC. The use of FEC enables the reduction of channel spacing and/or the increase in the transmission distance with affordable output power of the seed light at the fixed transmission speed. We analyze the required relative intensity noise (RIN) level when utilizing the FEC. Then, we investigate transmission performance at 25 GHz channel spacing targeting more than 128 channels. We use four different reflective modulators to compare the performances. Transmission distance of 60 km can be achieved with injection seeding at the OLT. The distance can be increased up to 90 km by shifting the seed light position to remote site.

2. RIN requirement

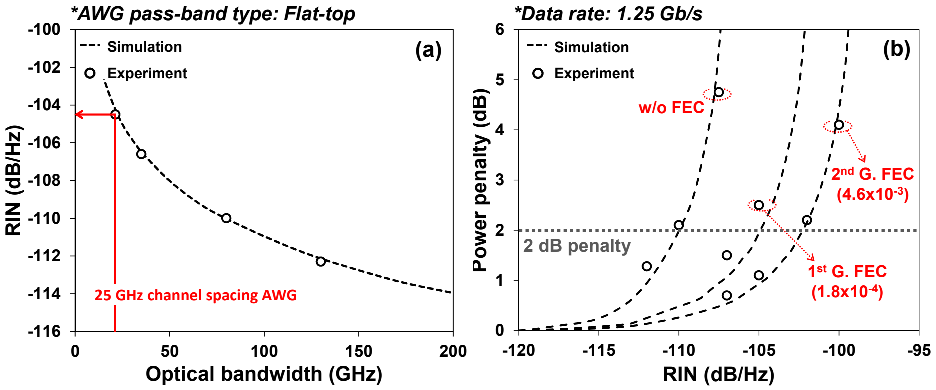

Fig. 1. Simulation and experiment results of (a) RIN as a function of the optical bandwidth and (b) BER penalty by RIN with and without FEC.

The RIN of the received signal that arises from beating between the uncorrelated frequency components of the spectrum-sliced ASE is a key factor of determining the system performance [7]. To investigate the effect of an optical bandwidth on the RIN, we generated an electric field of the ASE based on constant amplitude and uniformly distributed phase over [$0\sim2\pi$] in frequency domain. The spectrum sliced field was obtained by multiplying square root of transfer function of the super-Gaussian filter. The filter order was adjusted to 1.5 for matching a pass band characteristic of the used flat-top type wavelength filter. The RIN spectrum was obtained from the power spectral density of the generated spectrum-sliced ASE. The average RIN of the spectrum sliced ASE within the receiver bandwidth (~750 MHz) is increased as the optical bandwidth narrows as described in Fig. 1(a). At the 25 GHz channel spacing, the input RIN becomes about -104.4 dB/Hz when the utilized wavelength filter has 3 dB bandwidth of 21.3 GHz. We examined a performance degradation by the increase in the input RIN of the injection seeded DWDM-PON. The simulation was conducted according to Ref [8]. In the simulation, the receiver sensitivity, equivalent input noise current, and extinction ratio were 0.8 A/W, 4.5 pA/$\sqrt{\text{Hz}}$, and 10 dB, respectively. When we set target to

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BER of 10^{-12}, the receiver noise was dominated by the RIN noise in the simulation. Figure 1(b) represents calculated (dashed lines) and measured (hollow circles) power penalties as a function of the RIN at the BER of 10^{-12} in case of the 1.25 Gb/s transmission. It should be noted that the penalties with FECs are estimated value at the theoretical FEC thresholds for BER of 10^{-12}. The power penalty is dramatically surged as the RIN increases over −110 dB/Hz when we do not utilize the FEC. On the other hand, the easing of the required RIN with the same penalty is possible through using an FEC. In this study, the 1st generation FEC is RS (255, 239) code and the 2nd generation FEC is RS (1901, 1855) with Extended Hamming Product Code (512,502) × (510,500) [10]. Both FECs require 6.69% overhead for coding. It may be noted that the BER thresholds to get the BER of 10^{-12} are 1.8×10^{-4} and 4.6×10^{-3} for the 1st generation and the 2nd generation, respectively. When we accept 2 dB penalty compared with clean source (RIN < −120 dB/Hz), the required RIN values of received signal can be reduced to −104.9 and −102.2 dB from −110 dB/Hz for the 1st generation and the 2nd generation FECs, respectively. These values should be compared with the input RIN of −104.4 dB/Hz in Fig. 1(a).

3. Experimental setup and results

Figure 2 shows the experimental setup for investigating 25 GHz-spaced DWDM-PON based on ASE injection seeding. The 25 GHz-spaced arrayed waveguide grating (AWG) was emulated by combining a 25 GHz-spaced interleaver with a 50 GHz-spaced AWG. The insertion loss of the emulated AWG was 7.5 dB. The pass-band was presented at the inset of the Fig. 2. The pass-band type was flat-top, and its 3-dB bandwidth was 0.17 nm (≈21.3 GHz). Thus, the input RIN was about −104.4 dB/Hz for an unpolarized ASE. An average loss of used single mode fiber was around 0.23 dB/km. And the output power of employed C band broadband light source (BLS) was about 24 dBm. A variable optical attenuator (VOA) was utilized between the BLS and the circulator to adjust the total seed power (P_{seed}) into the feeder fiber. The spectrum-sliced ASE is injected to the reflective modulator, which would be an RSOA or an F-P LD, at the optical network terminal (ONT). The polarized F-P LD/RSOA were made by a quantum well active medium while the unpolarized ones were made by a tensile strained InGaAsP bulk active medium [9]. A cavity length of the F-P LD was around 600 µm, where its mode spacing (0.56 nm) is 3.3 times wider than the emulated AWG bandwidth (0.17 nm).

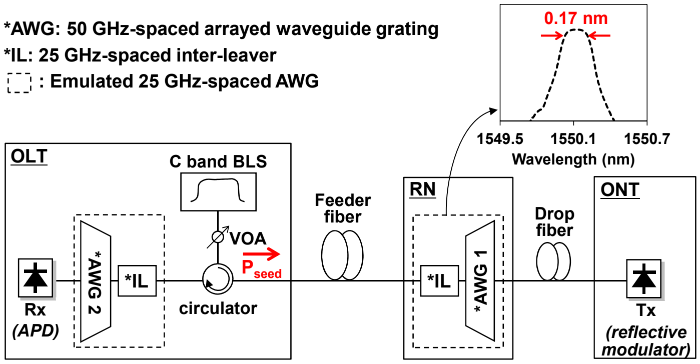

Fig. 2. Experimental configuration of 25 GHz-spaced seeded DWDM-PON.

To characterize the reflective modulator, we measured the gain as shown in Fig. 3. The gain decreases as we increase the injection power, referring to this as gain saturation, which leads to the RIN suppression [8,9]. The polarized optical sources have usually higher gain than unpolarized sources. The gain of F-P LD varies with the wavelength detuning

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($= \lambda_{Injection} - \lambda_{Mode}$) due to the spectral ripple at the constant injection power. Thus, we represented the minimum gain for the worst case.

The optical output from the reflective modulator gets to the receiver after passing through two AWGs and optical fiber. The RIN of the received signal in back-to-back (B-t-B) condition is represented in Fig. 4. In case using F-P LDs, we represented the worst RIN values, because the F-P LD has varied RIN value due to the spectral ripple, like the gain. When the injection power is low, the RSOAs operate in linear region and the F-P LDs operate as lasers. The unpolarized RSOA shows less RIN than polarized RSOA (The difference is not 3 dB due to nonzero polarization dependent gain [9].). However, the F-P LDs show higher RIN arisen from mode partition noise. The RINs were decreased as we increased the injection power because of the gain saturation. It may be noted that the effects of gain saturation are more pronounced in F-P LDs due to decrease of both the mode partition noise and the intensity noise of the injected light. At high injection power, difference of RIN between RSOA and F-P LD becomes very small. It can be explained from the deeply saturated gain. In other words, the F-P LD operates as a saturated regenerative amplifier [9]. As seen in Fig. 4, the RSOA shows less RIN over a wide range of injection power. Thus we selected RSOA for transmission experiment. Nevertheless, it should be noted that the RIN performance of the F-P LD will be enhanced when the cavity length increases so that the mode spacing is comparable to or narrower than the AWG bandwidth as seen in Ref [9]. It may be noted that if we match the input wavelength to the lasing wavelength, the RIN of F-P LD becomes less than the ROSA [11].

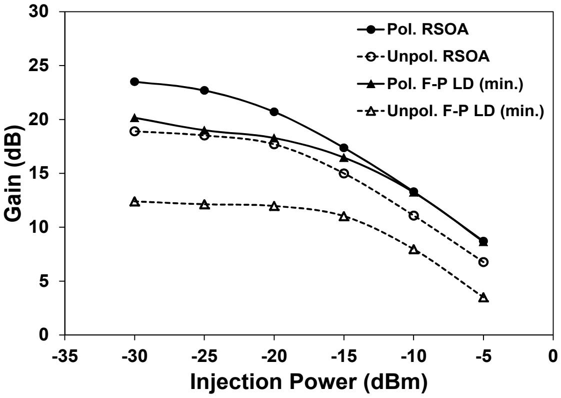

Fig. 3. Measured fiber-to-fiber gain of reflective modulators as a function of injection power.

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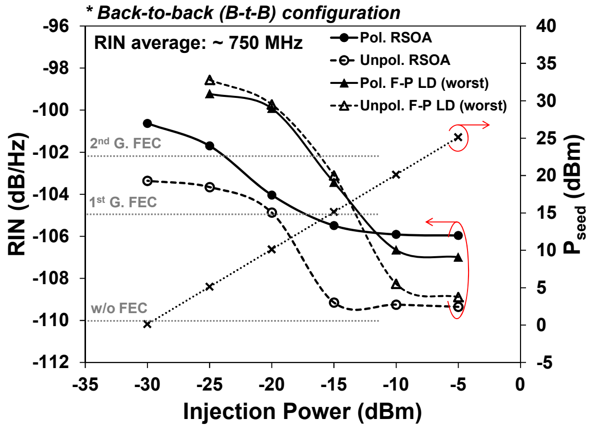

Fig. 4. Measured RIN of received signal and required seed power (P_{seed}) as a function of injection power (under B-t-B condition).

We measured BER curves in B-t-B configuration as seen in Fig. 5(a). The RSOAs were modulated by non-return-to-zero (NRZ) signal where data rate is 1.25 Gb/s and pattern length of pseudorandom binary sequence (PRBS) is 2^{31}-1. In the unpolarized RSOA case, we obtain the BER that is better than the 1st generation FEC threshold at both −20 and −25 dBm injection power. However, in case of the polarized RSOA, the BER was worse than the 1st generation FEC threshold. This can be explained from the higher RIN and poor extinction ratio. The extinction ratios of polarized RSOA and unpolarized RSOA were 7 dB and 10 dB, respectively. The bad extinction ratio is attributed to the limited modulation bandwidth of the polarized RSOA.

To investigate upstream transmission performance, we measured the power and BER of the received optical signal as a function of the length of the transmission fiber, as shown in Fig. 6. When the transmission length is increased the seed power is increased to maintain the constant injection power. As the received power is decreased by the increase in the fiber length (Fig. 6(a)), the BER is degraded (Fig. 6(b)). The inclination of BER degradation by the fiber transmission is more moderate when the polarized RSOA is employed. This is because the polarized RSOA features about 3-4 dB higher power due to the higher gain than the unpolarized one. The BER threshold of the 2nd generation FEC was achieved up to 60 km transmission when the injection power was −20 dBm with both polarized and unpolarized RSOAs. For the 60 km upstream transmission with the −20 dBm injection power, the seed power at OLT was 24 dBm which is commercially available. It should be commented that the 24 dBm seed power is beyond the range of the eye-safety that is 21.34 dBm without fast power shut down given the class 1M laser. Therefore, the fast power shut down is required in this case. But, 5 dB reduction of seed power is possible when the transmission length is 50 km.

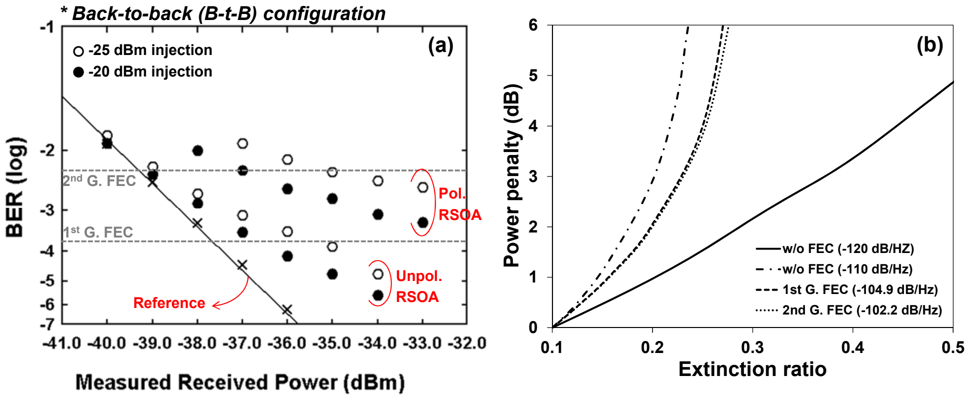

Fig. 5. (a) Measured BER curves in B-t-B condition and (b) calculated extinction ratio penalty.

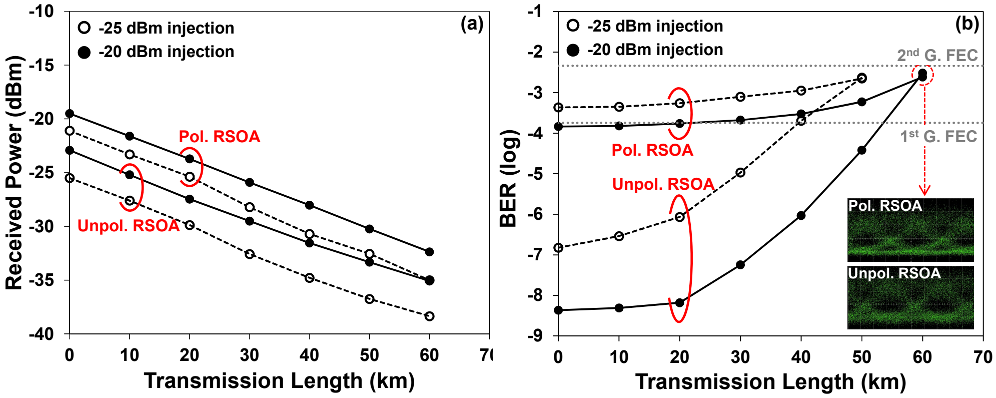

Fig. 6. (a) Measured received power and (b) BER curves as a function of transmission length.

Since the back reflection is the main factor of performance degradation for the upstream transmission, we investigate the effect of back reflection on the system performance. In Fig. 7(a), the crosstalk (ratio of back reflection power to signal power) level by back reflection varies with the transmission length and the injection power [12]. To be specific, since the polarized RSOA has a higher gain than that of the unpolarized RSOA, the crosstalk level is lower even after transmission of the same distance. Also the lower injection power results in the higher gain and consequently, the lower crosstalk. Then the crosstalk by back reflections with 60 km fiber were −7.4 (polarized RSOA) and −4.2 dB (unpolarized RSOA) as seen in Fig. 7 (a). Figure 7(b) shows the measured power penalties by back reflection as a function of the crosstalk. For the same devices, the performance degradation was higher at low injection power on account of the worse RIN. The unpolarized RSOA provides the better back reflection immunity since it features better noise characteristic and extinction ratio. The measured penalties at 60 km fiber transmission were 1.5 (polarized) and 2 dB (unpolarized), respectively. We expect that the distance would be extended by around 10 km if the polarized RSOA has a sufficient modulation bandwidth.

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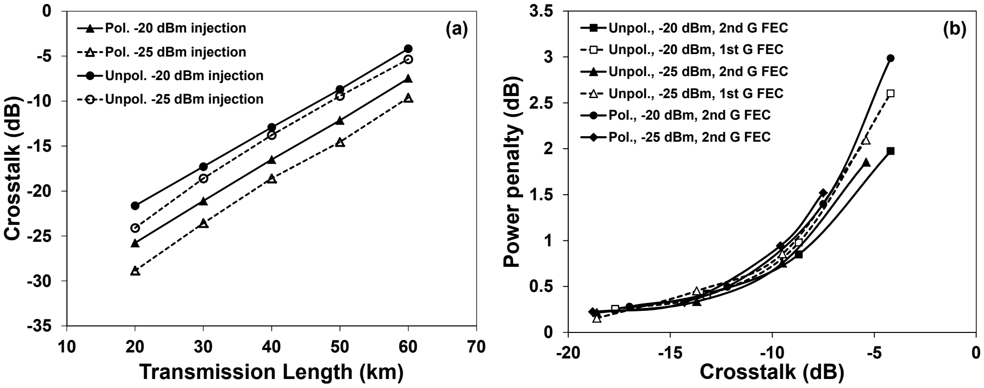

Fig. 7. (a) Back-reflection induced crosstalk as a function of fiber length and (b) measured power penalties as a function of the crosstalk.

It should be noted that the penalty by dispersion induced pulse broadening is less than 1 dB. Thus, it is possible to have longer transmission distance as seen in Fig. 8, if we relocate the BLS to the remote node (RN) [13]. At the maximum injection power of −6 dBm, where the BLS output at the RN is 24 dBm, the transmission length was limited to 80 and 90 km with unpolarized and polarized RSOAs, respectively. Compared with the previous cases, the RIN of the optical signal is improved and there is no degradation of the RIN and extinction ratio by back scattering. Although the maximum injection power was increased by 14 dB compared to the previous cases, the increase in the output power of the RSOA was only 3-4 dB due to the gain saturation. Thus the improvement of transmission distance is limited even though the receiver sensitivity was improved due to the reduced noise. Since the polarized RSOA has a higher gain than the unpolarized RSOA by about 2 dB, it could provide 10 km longer reach than un-polarized one. A reduction of injection power of 10 dB (−16 dBm injection) brought about the decrease in the reach by 10 km as seen in Fig. 8(b). It should be noted that the dispersion induced power penalty was less than 1.5 dB in all cases.

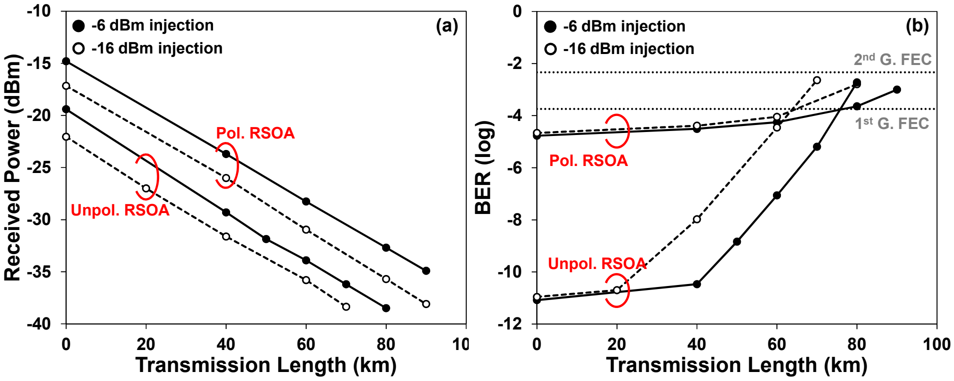

Fig. 8. (a) Measured received power and (b) BER curves as a function of transmission length after relocating the BLS to RN.

4. Conclusion

We experimentally demonstrated a 60 km reach DWDM-PON based on ASE injection seeding. The channel spacing was 25 GHz. Thus it is possible to accommodate more than 160 channels within C-band. The achieved link budget was 27.3 dB including the loss at the OLT. If we utilize a 25 GHz-spaced AWG, the interleaver with 2.5 dB loss will be replaced by the additional 10 km fiber, with an insignificant dispersion penalty. The reach was increased to 90 km by changing the location of the BLS to remote node. Further increase in transmission distance can be achieved by high gain reflective modulator.