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A 240 km Reach DWDM-PON of 8-Gb/s Capacity using an Optical Amplifier

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We demonstrate a 240 km reach DWDM-PON at 8-Gb/s capacity based on wavelength-locked Fabry-Perot laser diodes and a bidirectional EDFA. We achieve a packet-error-free transmission in both the 64 upstream and 64 downstream channels, guaranteeing a 125 Mb/s symmetric data rate per user. There is no noticeable dispersion penalty. The power penalty due to the crosstalk induced by the DWDM transmission and detuning between AWGs is less than 1.2 dB, when the detuning is within ±0.12 nm.

OCIS codes : 060.0060, 060.4230, 060.4250, 060.4510

I. INTRODUCTION

Fiber-to-the-home (FTTH) based on a passive optical network (PON) is attractive as the ultimate broadband access network [1]. In particular, the long-reach PON has been studied in an effort to reduce capital equipment and operation costs by consolidating a metro network and an access network [2-4]. It also enhances the quality of service (QoS) by directly connecting the customer premises to an edge switch of a long-haul backbone network. The service coverage with a central office (CO) is proportional to the square of the transmission length. As a result, the QoS is enhanced and the service coverage is enlarged as the transmission length increases. In terms of dedicated bandwidth per home, more than 100 Mb/s is expected to support future video centric services with high definition quality [5]. In addition, a symmetric bandwidth is preferred due to rapid increase of upstream video traffic.

Recently, a long-reach dense wavelength division multiplexing-PON (DWDM-PON) has been demonstrated based on wavelength-locked Fabry-Perot laser diodes (F-P LDs) using a 50 GHz channel spacing without an optical amplifier [4]. In this system, the transmission length is limited to approximately 70 km due to lack of the injection power of a broadband light source (BLS). The transmission bit rate is limited to approximately 155 Mb/s as a result of the beat noise between the upstream signal and the Rayleigh-backscattered BLS. This limitation can be overcome by replacing the BLS to a CO located near by the remote node (RN) [6].

In this paper, we demonstrate a 240 km reach 64-channel bidirectional DWDM-PON of 8-Gb/s capacity based on wavelength-locked F-P LDs with a 50 GHz channel spacing. The BLS for upstream channels is located a CO near by the remote node (RN) and a bidirectional optical amplifier is employed. However, we do not need any dispersion compensation. The crosstalk effects induced by DWDM transmission and detuning between arrayed waveguide gratings (AWGs) are negligibly small. Further enhancement of capacity can be achieved by upgrading the transmission bit rate or the split ratio.

II. EXPERIMENTAL RESULTS

The experimental setup to demonstrate high capacity long reach (8-Gb/s capacity with the 240 km reach) 64-channel DWDM-PON based on a wavelength-locked F-P LD is shown in Fig. 1. It is composed of an optical line termination (OLT) at CO1, a 120 km single mode fiber (SMF) as the first feeder fiber, a bidirectional Erbium-doped Fiber Amplifier (EDFA) at CO2, a 120 km SMF as the second feeder fiber, a RN, and 64 optical network terminations (ONTs). The BLS is the amplified spontaneous emission (ASE) generated by a pumped Erbium-doped fiber. The C-band BLS to be injected for the upstream channel is located at CO3 near by the RN, while the L-band BLS to be injected for the downstream channel is located at the OLT.

Each BLS is coupled into the transmission fiber through BLS coupling devices, which consist of a circulator and two C/L band separating wavelength division multiplexers (C/L WDMs).

Transistor outlook (TO)-can packaged F-P LDs with a typical mode spacing of 0.6 nm were used. The front-facet of the F-P LD was anti-reflection coated and the temperature of the F-P LD was controlled by a thermo-electric cooler (TEC) to have a high signal power [4]. Although we use the TEC, the transmission wavelength of the each channel is locked to the AWG's transmission wavelength. This feature offers a possibility of color-free (wavelength independent) operation of the ONT [7]. The injection power density of spectrum-sliced BLS from the L-band BLS at the OLT into the downstream F-P LDs was -14 dBm/0.2 nm (total power: -12 dBm). That from the C-band BLS at the RN into the upstream F-P LDs at the ONT was -23 dBm/0.2 nm (total power: -20 dBm). A different injection power was used to check the dynamic range of the injection power. Both 64 upstream and 64 downstream channels were directly modulated by 100 Base-x Ethernet packets (data rate = 125 Mb/s) with various packet lengths and amplified by the bidirectional EDFA on the feeder fiber.

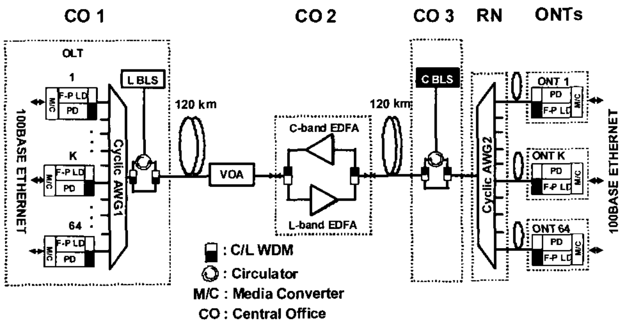

FIG. 1. Experimental setup of the 240 km reach 64-channel DWDM-PON.

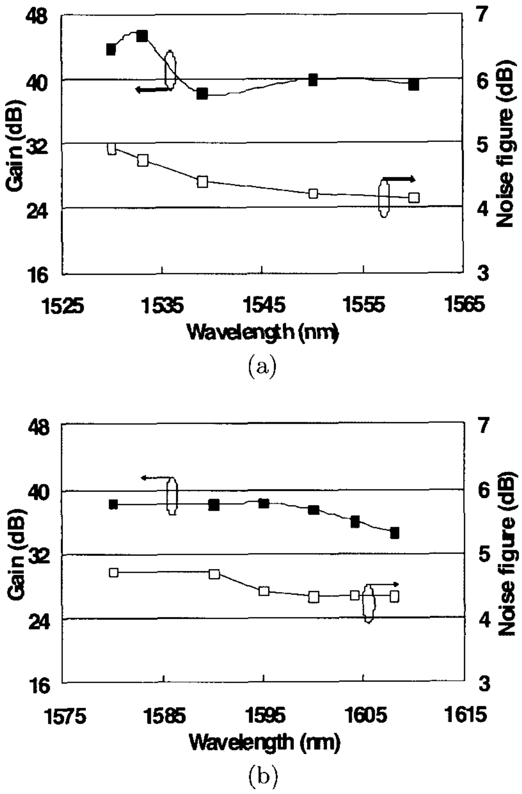

FIG. 2. (a) Measured gain and noise figure of the C-band EDFA. (b) Measured gain and noise figure of the L-band EDFA.

The bidirectional EDFA consists of a unidirectional C-band EDFA, a unidirectional L-band EDFA and two C/L WDMs. The first stage EDFA was forward pumped by a 980 nm LD with 120 mW and the second stage EDFA was bidirectionally pumped by 980 nm LDs at 350 mW/120 mW. The measured gain and noise figure (NF) are shown in Fig. 2. These were 38.3~45.4 dB (34.7~38.8 dB) and 4.17~4.94 dB (4.35~4.73 dB), respectively, for C-band (L-band) EDFA.

Fast Ethernet packets (100 Base-x) generated by a data quality analyzer (Anritsu MD1230A) were transmitted as upstream and downstream data. Both 64 upstream and 64 downstream channels were directly modulated with the Ethernet packets simultaneously. We confirmed error-free transmission for more than a day. Then, the packet error rate (PER) was measured for both the upstream and downstream signals in order to investigate system performance. To do that we inserted a variable optical attenuator (VOA) between the first 120 km feeder fiber and the bidirectional EDFA as shown in Fig. 1.

The measured PERs as a function of VOA attenuation are shown in Fig. 3. As a packet is lost as soon as a single bit in a packet is in error, the relationship between the PER and bit error rate is given as [8]

$$\mathrm{PER} = 1-(1-\mathrm{BER})^{\mathrm{Nb}} \tag{1}$$

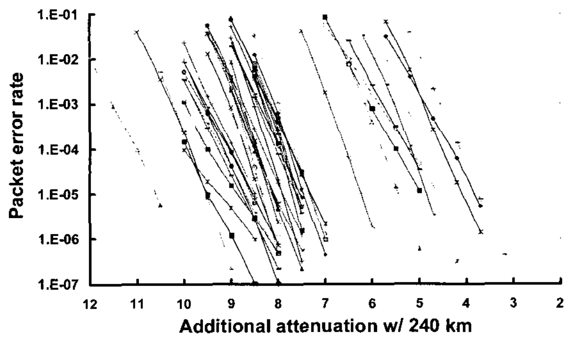

FIG. 3. Measured packet error rates of the upstream channels.

where Nb is the average number of bits in a packet. In the experiment, Nb was 6291 ; thus, a PER of 10^{-6} corresponds to a BER of 10^{-10}, approximately. A PER for less than 10^{-6} was observed up to 3 dB attenuation. In other words, we can accommodate 3 dB more loss on top of the loss of the 240 km transmission fiber. The scattering of PER curves can be explained as difference of the front facet reflectivity of the F-P LDs and detuning between the injection wavelength and the lasing wavelength at each channel. The downstream signals showed similar or better PERs compared with the upstream signals. It may be noted that we do not use any dispersion compensation for 8-Gb/s transmission capacity.

The temperature dependent transmission characteristic of the AWG2 is one of the key issues in deploying the proposed DWDM-PON, as the AWG2 is installed in the outside plant. To investigate how much tolerance exists, detuning between the AWG1 and the AWG2 was induced by changing the temperature of the AWG2. Here, detuning is defined as the difference in the peak transmission wavelength of two AWGs at the same channel. The detuning range was varied from -0.12 nm to +0.12 nm. The measured PERs of the upstream channels according to the detuning value are shown in Fig. 4. Both a single channel transmission and 64-channel DWDM transmission were conducted to check the crosstalk effect induced by the DWDM transmission.

The power penalty due to the crosstalk induced by only the DWDM transmission at 0 nm detuning is nearly 0.5 dB at a PER of 10^{-6}. The crosstalk induced by the DWDM transmission increases as the detuning increases. The total power penalty is less than 2 dB within ±0.12 nm detuning of the AWGs. It should be noted that a single channel transmission penalty of 0.8 dB is included in the total penalty. Thus the network may support ±0.12 nm of wavelength variation of the AWG2. To understand the measured results, the total crosstalk power entering into a channel was measured in terms of the detuning. The penalty induced by WDM transmission was then plotted as a function of the crosstalk, as shown in Fig. 5. The experimental results (markers) are in good agreement with theoretical prediction (dotted line) based on the power addition [9]. A state-of-the-art athermal AWG with 50 GHz channel spacing can maintain detuning less than ±0.015 nm over a temperature range of -5℃ to 70℃ [10]. Therefore, when an athermal AWG is used for the AWG2, it is not necessary to consider the temperature dependence of the RN located in the field.

To investigate the dynamic range of the distribution fiber, the maximum distribution fiber length was analyzed and measured. The measured crosstalk of the upstream channel was -13 dB at the worst case. As the crosstalk that brings about a 1 dB power penalty is -7 dB, the maximum allowable loss differences between the RN and the ONT are 6 dB. Therefore, the distribution fiber can be 0 to 20 km. It was confirmed that the power penalty was approximately 0.8 dB when inserting 20 km of distribution fiber.

III. DISCUSSION AND CONCLUSION

In this experiment, the transmission bit rate per channel was 125 Mb/s for Ethernet connection between the OLT and ONT. In our previous results, we confirmed a 155 Mb/s per channel transmission [11]. That means this WDM-PON can guarantee 10 Gb/s capacity with 240 km reach. In addition, the proposed long-reach DWDM-PON using conventional EDFA-based BLSs can accommodate 80 subscribers (or channels), as the bandwidth of the BLS is nearly 32 nm. The capacity of the DWDM-PON then becomes 12.4 Gb/s in a single direction. A further expansion of the capacity will be possible either by using semiconductor-based BLSs with a wider bandwidth or by upgrading the bit rate per channel.

When the proposed long-reach DWDM-PON is

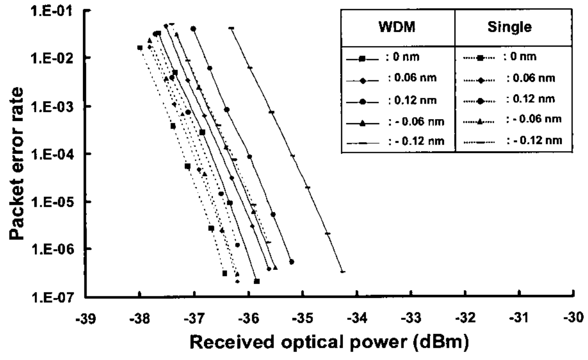

FIG. 4. Measured PER of the upstream channel according to AWG detuning.

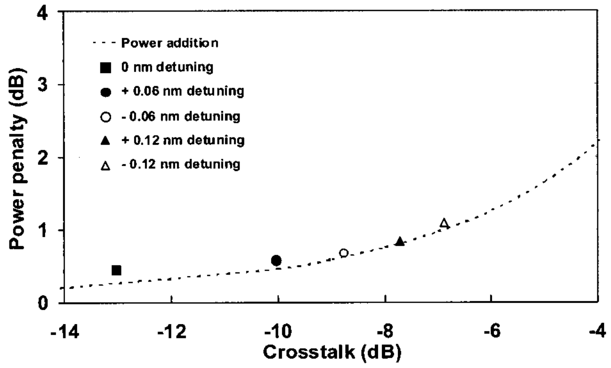

FIG. 5. Power penalty due to the crosstalk.

deployed, it is necessary to supply electric power to the bidirectional EDFA as well as to the C-band BLS. However, this is simple because the EDFA and the BLS can be located at conventional COs around the feeder fiber path. As discussed in the previous paper [4], a color-free (wavelength independent) operation of the ONT can be realized by using several different methods. Thus management issues of the ONT can be solved.

In conclusion, a 240 km reach DWDM-PON based on wavelength-locked F-P LDs with 50 GHz channel spacing was demonstrated by employing a bidirectional EDFA without dispersion compensation. Packet-error-free transmission is obtained, guaranteeing 8-Gb/s capacity (125 Mb/s symmetric data rate per user). Based on a crosstalk experiment and the reported temperature dependency of the AWG, the proposed long-reach DWDM-PON can be deployable at the field.

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