Dense WDM-PON Based on Wavelength-Locked Fabry–Pérot Laser Diodes

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***Abstract*—We demonstrate a bidirectional 12-channel wavelength-division-multiplexing passive optical network (WDM-PON) with 50-GHz channel spacing based on wavelength-locked Fabry–Pérot laser diodes. The maximum transmission length is 30 km including 20 km of feeder fiber and 10 km of distribution fiber. The proposed WDM-PON system can accommodate 80 channels with erbium-doped fiber amplifier-based broad-band light sources. We also propose a few methods for the wavelength-independent operation of an optical network termination.**

***Index Terms*—Fabry–Pérot (F-P) laser, passive optical network (PON), wavelength-division multiplexing (WDM), wavelength-independent operation, wavelength locking.**

I. INTRODUCTION

THE wavelength-division-multiplexing passive optical network (WDM-PON) has been considered as an ultimate broad-band access network due to its large guaranteed bandwidth, high security, easy upgradeability, bit rate, and protocol transparencies. However, it requires expensive wavelength specified light sources and wavelength management of the optical transmitters in the subscribers' side.

Several types of WDM-PON have been proposed to solve these problems. The WDM-PON using spectrum-sliced incoherent light sources such as light-emitting diodes (LEDs) or amplified spontaneous emission (ASE) sources was proposed [1]–[3]. However, the output power of LED is insufficient because of spectrum slicing. Although the spectrum-sliced ASE source provides much higher output power than the LED, it requires an expensive external modulator. Recently, a wavelength-locked Fabry–Pérot laser diode (F-P LD) to an injected spectrum-spliced ASE light was proposed for a low-cost WDM source [4]. The injected ASE light forces the F-P LD to operate in a quasi-single mode and suppresses the mode partition noise [4]–[6]. Therefore, we can use the wavelength-locked F-P LD as a WDM light source.

In this letter, we demonstrate 12-ch WDM-PON with 50-GHz channel spacing using the wavelength-locked F-P LDs. We transmit 155-Mb/s upstream and downstream data bidirectionally over 20 km of a single-mode fiber. We estimate the maximum transmission length at 30 km including 20 km of feeder fiber and 10 km of distribution fiber. The proposed WDM-PON can accommodate 80 channels with erbium-doped fiber amplifier (EDFA)-based broad-band light sources (BLSs). We also propose a few methods for the wavelength-independent operation of an optical network termination (ONT) that is essential for a field deployable WDM-PON.

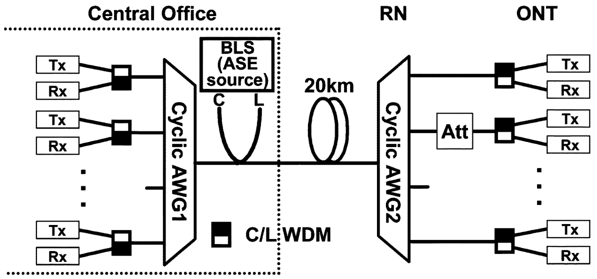

Fig. 1. Experimental setup of 12-ch WDM-PON with 50-GHz channel spacing based on wavelength-locked F-P LDs.

II. EXPERIMENTAL RESULTS

The experimental setup is shown in Fig. 1. The BLS is the ASE light generated by a pumped erbium-doped fiber. Two BLSs at different bands (C- and L-band) are located at the central office (CO) for injection of broad-band light into lasers located at the CO and the ONTs. The C/L-band separating wavelength-division multiplexers (C/L WDMs) are used to separate the different band signals. The arrayed waveguide gratings (AWGs) with Gaussian-type passband are used at the CO and at the remote node (RN). The channel spacing and 3-dB bandwidth of the AWG are 50 and 22 GHz, respectively. To use a single AWG for both transmission bands (multiplexing of a band and demultiplexing of the other band or vice versa), we take advantage of periodic property of the AWG. We may need an athermal AWG for operation over wide temperature range. However, we used a conventional AWG for experimental purpose.

The transmitter includes a TO-can packaged F-P LD. Typical mode spacing and the front facet reflectivity of the F-P LD are 0.6 nm and 1%, respectively. We use a heater to reduce the wavelength variation of the F-P LD induced by the ambient temperature variation. The wavelength variation of the laser with the heater is about 0.05 nm/10 °C when system operating ambient temperature is below the heater setting temperature of 55 °C. We use conventional C-band (1548.9–1553.3 nm) for the upstream data transmissions and L-band (1581.3–1585.8 nm) for the downstream data transmissions. The F-P LDs are directly modulated at 155 Mb/s with a $2^{31}-1$ pseudorandom bit sequence (PRBS) pattern. The feeder fiber length between the CO and the RN is 20 km. It may be noted that an F-P LD, a C/L WDM, a photodiode, and a transimpedance amplifier can be

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Manuscript received January 21, 2005; revised March 21, 2005. This work was supported by the Korea Ministry of Science and Technology under the National Research Laboratory.

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Digital Object Identifier 10.1109/LPT.2005.848558

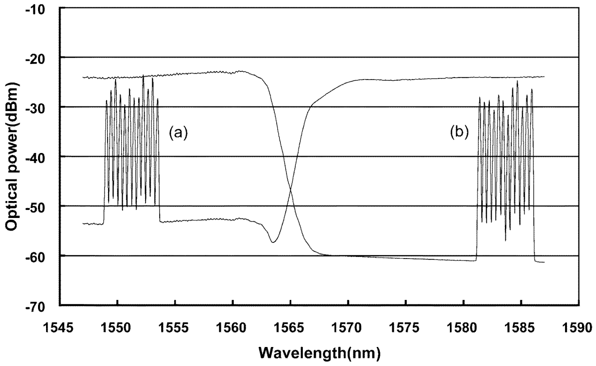

Fig. 2. Measured spectra. (a) Upstream signal. (b) Downstream signal.

packaged in a small form factor module (BiDi module) or hybrid integrated in a single platform.

The broad-band light from C-band BLS was coupled into the transmission fiber and sent to the AWG2. Then, it was spectrally sliced by the AWG2 and injected into an F-P LD located at an ONT of each subscriber premises. The injection power into the F-P LD was −14 dBm/0.2 nm at peak. The upstream wavelength of each subscriber is determined by the wavelength of the injected spectrum-sliced BLS, since a mode of F-P LD that is the nearest to the peak wavelength of the injected BLS is locked to the wavelength of the injected BLS. The upstream signals were multiplexed by the AWG2. The multiplexed signals were transmitted through the transmission fiber. At the CO, the received signals were demultiplexed by the AWG1. Then, the receiver recovered the upstream data. For the downstream data transmission, L-band BLS output was coupled into the AWG1. It was spectrally sliced and injected into the F-P LDs located at the CO. The injected power was −14 dBm/0.2 nm at peak. The rest of the processes are similar to the upstream signal.

The measured upstream and downstream spectra are shown in Fig. 2. The upstream spectrum [Fig. 2(a)] and downstream spectrum [Fig. 2(b)] were measured at the input of the AWG1 and AWG2 with a tap coupler, respectively. Each spectrum shows multiplexed 12-ch signals and the BLS output. It may be noted that we do not try to match the output power of each channel.

We measured the bit-error rate (BER) for a single-channel transmission and for 12-ch WDM transmission to investigate the crosstalk. Typical sensitivity of the receivers ranged from −37.5 to −36 dBm in back-to-back operation. We measured the same sensitivity with a single-channel transmission, i.e., there is no measurable dispersion penalty. As shown in Fig. 3, the measured BER curves of 24 channels with WDM transmission show no measurable error floor. For WDM transmission, we modulated all 24 channels simultaneously. The inset of Fig. 3 shows the power penalties due to WDM transmission which are between −0.3 and 0.5 dB.

To investigate the system dependency on the distribution fiber that is the transmission fiber between the RN and the ONT, we inserted a variable attenuator between the RN and the upstream Channel 5, as shown in Fig. 1. It may be noted that Channel 5 has a minimum output power. The measured BER curves according to the attenuation values are shown in Fig. 4. The power penalty at the BER of 10^{-10} is less than 1 dB within 2.4-dB attenuation. In this case, the maximum power difference between channels was about 10 dB. In the case of 3.5-dB attenuation, the power penalty induced by the reduction of the injection power was 1.5 dB and the power penalty induced by crosstalk was 0.5 dB. Based on the result, we estimate that the proposed WDM-PON can support about 10 km of distribution fiber length difference.

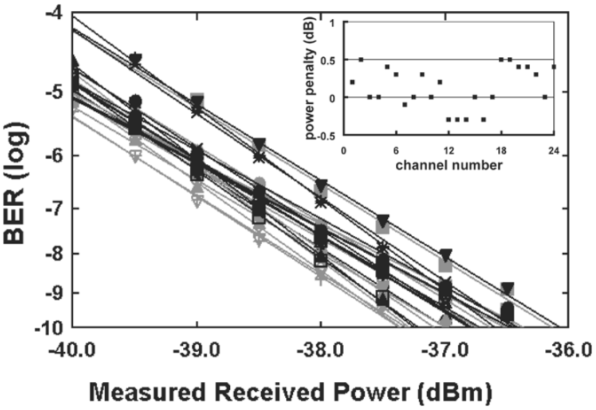

Fig. 3. Measured BER after 12-ch WDM transmission.

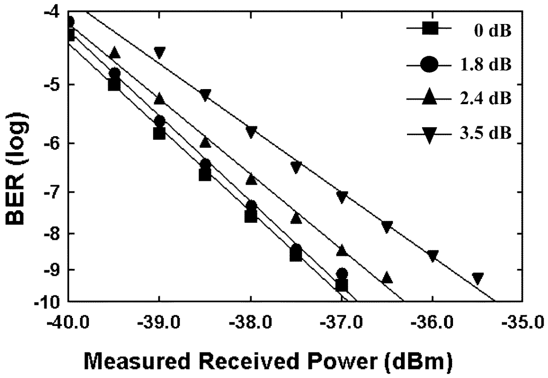

Fig. 4. Measured BER at different distribution fiber losses.

To investigate the effects of detuning between the injection wavelength and the upstream laser mode, we measured BER curve as a function of the detuning. The detuning is defined as $\lambda_{\mathrm{ASE}} - \lambda_{\mathrm{LD}}$. We induced the detuning by changing the temperature of two AWGs for experimental convenience. However, we can generate the same effects by changing the laser temperature. As we increase the detuning from the optimum value, the sensitivity degrades and its slope of the BER curve decreases, as shown in Fig. 5. We can achieve BER of 10^{-10}, when the power penalty from the best case is about 2 dB. It corresponds to about 0.08-nm detuning range. Then, the ONT operating temperature range is about 16 °C, since the wavelength tuning coefficient of the F-P LD with the heater is 0.05 nm/10 °C.

When −14 dBm/0.2 nm (−12.5-dBm total power) injection power was injected into a F-P LD, the minimum output power of the wavelength-locked F-P LDs was about −11 dBm. From Fig. 3, the measured worst channel sensitivity at the BER of 10^{-10} was −36 dBm at 155 Mb/s. When we consider 1-dB power penalty due to the distribution fiber and 2-dB power penalty due to the detuning range of the F-P LD, the worst sensitivity would be −33 dBm at the BER of 10^{-10}. We expect a very small dispersion penalty, because the bit rate distance product of this system is BL $<$ 54 Gb/s · km. Thus, we can accommodate 22-dB link loss between the transmitter and the receiver. The transmission link consists of two-AWG

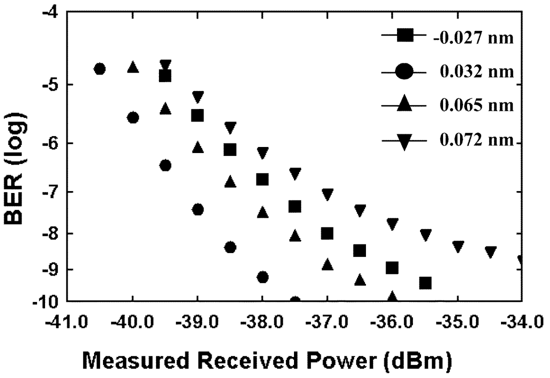

Fig. 5. Measured BER at different detuning values.

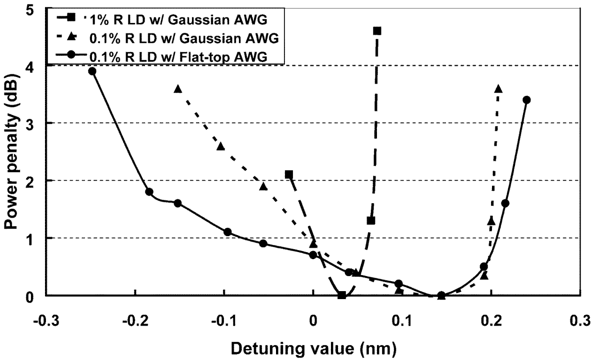

Fig. 6. Measured power penalty at the BER of 10^{-10}.

[total 10-dB insertion loss (5 dB $\times 2$)], transmission fiber, and coupling devices for BLSs (1.5-dB insertion loss). We also have a C/L WDM (1-dB insertion loss) in front of the transmitter–receiver module at both the CO and the ONT. Thus, total insertion loss except the transmission fiber is 13.5 dB. If we allocate 1-dB path penalty, we have 7.5 dB for fiber loss. It implies about 30-km transmission length when loss of the fiber is 0.23 dB/km.

Based on experimental results, we can estimate the total capacity of this WDM-PON system. For an EDFA-based BLS, the typical bandwidth is about 32 nm. Then, we can accommodate maximum 80 channels with 50-GHz channel spacing using the EDFA-based BLSs. This gives about 12.4 Gb/s of total capacity in a single direction.

III. DISCUSSION

We can use a single type laser for all ONTs. However, it does not mean colorless operation of the ONT. To investigate a feasibility of the colorless operation of the ONT, we reduced the front facet reflectivity of the F-P LD to 0.1%. We also increased 3-dB bandwidth of the AWG by using a flat-top passband AWG to 34 GHz. The measured power penalty at BER of 10^{-10} as a function of detuning is shown in Fig. 6. The acceptable detuning range of the F-P LD increases from 0.08 to 0.26 nm, when we use the laser with 0.1% reflectivity. It is increased to 0.4 nm, when we use the laser with 0.1% reflectivity and the flat-top AWG. In this case, the system operating temperature range can be 80 °C. In other words, when we match the wavelength of a lasing mode to that of the spectrum-sliced BLS at 10 °C of ambient temperature, the system operates properly from -30 °C to 50 °C of ambient temperature. However, it does not mean the complete colorless operation of the ONT, since we still have a large penalty in some detuning range.

To achieve colorless operation of the ONT, we need to match mode spacing of the laser to channel spacing of the AWG. If the mode spacing of the laser is two times the channel spacing, we need two different types of ONTs for even and odd channels. We also can achieve colorless ONT by maximizing the output power from the F-P LD, since it is maximal when the injection wavelength matches with a lasing mode. In this case, we may need a control loop in the ONT. By increasing the cavity length of the F-P LD (i.e., decreasing the mode spacing of the F-P LD from 0.6 to 0.4 nm), we can have at least one of lasing modes within 0.4-nm detuning range. Then, we will be able to achieve colorless ONT.

Since two wavelengths for the downstream and the upstream are allocated to each subscriber, the subscriber can communicate with the CO regardless of the status of the others. In other words, the system supports dedicated connectivity between the CO and the subscribers. This feature is important when we try to provide video services that require high bandwidth, a long connection time, and high quality of services.

IV. CONCLUSION

We have demonstrated 50-GHz-spaced 12-channel WDM-PON based on the wavelength-locked F-P LD with a heater. The upstream and downstream signals are transmitted bidirectionally at the bit rate of 155-Mb/s. The crosstalk induced by WDM transmission was less than 0.5 dB. We also investigated the effect of the distribution fiber. The maximum transmission length is 30 km including about 10 km of distribution fiber. We can accommodate maximum 80 channels with conventional EDFA based BLSs. We also proposed several methods for the colorless operation of the ONT.

REFERENCES

[1] M. Zirngibl, C. R. Doerr, and L. W. Stulz, "Study of spectral slicing for local access applications," *IEEE Photon. Technol. Lett.*, vol. 8, no. 5, pp. 721–723, May 1996.

[2] R. D. Feldman, E. E. Harstead, S. Jiang, T. H. Wood, and M. Zirngibl, "An evaluation of architectures incorporating wavelength division multiplexing for broad-band fiber access," *J. Lightw. Technol.*, vol. 16, no. 9, pp. 1546–1559, Sep. 1998.

[3] D. K. Jung, H. Kim, K. H. Han, and Y. C. Chung, "Spectrum-sliced bidirectional passive optical network for simultaneous transmission of WDM and digital broadcast video signals," *Electron. Lett.*, vol. 37, pp. 308–309, 2001.

[4] H. D. Kim, S.-G. Kang, and C.-H. Lee, "A low-cost WDM source with an ASE injected Fabry–Pérot semiconductor laser," *IEEE Photon. Technol. Lett.*, vol. 12, no. 8, pp. 1067–1069, Aug. 2000.

[5] D. J. Shin *et al.*, "Transmission of HDTV and ethernet data over a WDM-PON employing ASE-injected Fabry–Pérot laser diodes," in *Proc. Conf. Optical Fiber Commun. (OFC 2004)*, Los Angeles, CA, Feb. 2004, Paper WO3.

[6] S.-J. Park, C.-H. Lee, K.-T. Jeong, H.-J. Park, J.-G. Ahn, and K.-H. Song, "Fiber-to-the-hone services based on wavelength-division-multiplexing passive optical network," *J. Lightw. Technol.*, vol. 22, no. 11, pp. 2582–2591, Nov. 2004.