Bidirectional Hybrid DWDM-PON for HDTV/Gigabit Ethernet/CATV Applications

Hai-Han Lu, Wen-Shing Tsai, Tzu-Shen Chien, Shih-Hung Chen, Yu-Chieh Chi, and Che-Wei Liao

A new scheme for bi-directional HDTV/Gigabit Ethernet/CATV transmission over a hybrid dense-wavelength-division-multiplexing passive optical network (DWDM-PON) is proposed and demonstrated. It is based on injection-locked vertical-cavity surface-emitting lasers and distributed-feedback laser diodes as transmitters. Services with 129 HDTV channels, a 1.25 Gbps Gigabit Ethernet connection, and 77 CATV channels are successfully demonstrated over 40 km single-mode fiber links. Good performance of bit error rate, carrier-to-noise ratio, composite second order, and composite triple beat is achieved in our proposed bidirectional DWDM-PON.

Keywords: Dense-wavelength-division-multiplexing, injection-locked, passive optical network, vertical cavity surface emitting laser.

I. Introduction

A hybrid dense-wavelength-division-multiplexing (DWDM) system can fully utilize the fiber bandwidth and increase the transmission capacity of a fiber link. A hybrid DWDM system that uses different optical channels to carry combined signals of HDTV, Gigabit Ethernet, and CATV would be quite useful for a fiber transmission network providing Internet access and video service. A passive optical network (PON) is a promising means to obtain low-cost optical access. The use of DWDM in combination with PON has received considerable attention in many fields; it is the most promising candidate for a lightwave transport system due to its large capacity, network security, easy management, and upgradeability [1]-[4]. For the practical implementation of a DWDM-PON, finding a cost-effective light source is the key issue. Previous studies have focused on distributed-feedback (DFB) laser diodes as a light source for DWDM-PONs; however, this approach has failed to attract attention from industries due to its high cost. In terms of cost-effectiveness, the use of vertical-cavity surface-emitting lasers (VCSELs) with injection locking [5], [6] seems more promising. In recent years, VCSEL technology has advanced enough that VCSELs can be designed to operate in the 1.55 µm wavelength window which is required for VCSELs to operate in a single transverse mode [7]. Moreover, directly modulated VCSELs show potential for application in high-speed digital optical communication systems. Such VCSELs operating in a single mode with narrow linewidth could be employed to replace DFB laser diodes in a DWDM-PON.

The feasibility of employing DFB laser diodes in a WDM-PON was previously discussed in [3] and [8], and the feasibility of employing injection-locked VCSELs in radio-on-

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Hai-Han Lu (phone: + 886 2 27712171 ext. 4621, email: hhlu@ntut.edu.tw), Wen-Shing Tsai (email: s2669016@ntut.edu.tw), Tzu-Shen Chien (email: s3658003@ntut.edu.tw), Shih-Hung Chen (email: s3658034@ntut.edu.tw), Yu-Chieh Chi (email: s0310368@ntut.edu.tw), and Che-Wei Liao (email: s4658010@ntut.edu.tw) are with Institute of Electro-Optical Engineering, National Taipei University of Technology, Taipei, Taiwan.

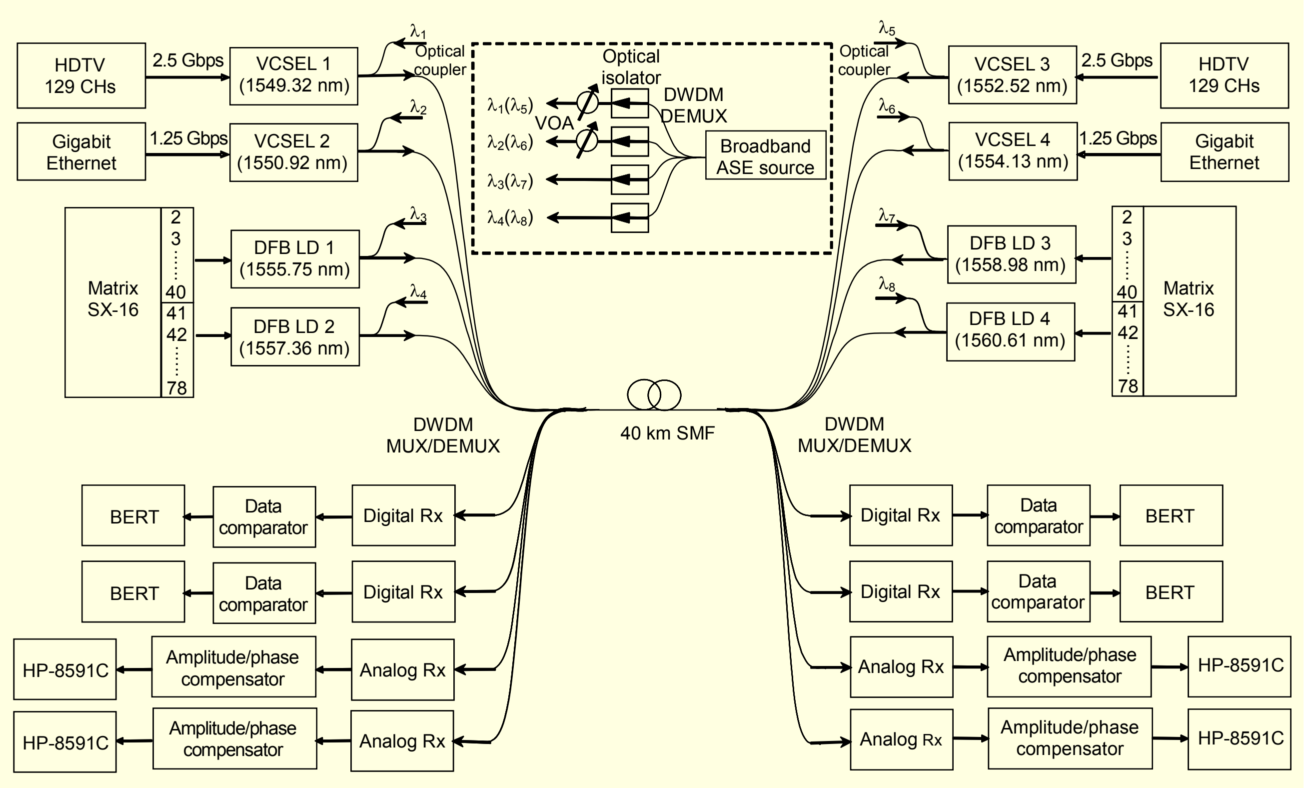


Fig. 1. Experimental configuration of our proposed HDTV/Gigabit Ethernet/CATV over bidirectional hybrid DWDM-PON.

DWDM transport systems was demonstrated in [9]. However, a bidirectional hybrid DWDM-PON with the heterogeneous traffic of HDTV, Gigabit Ethernet, and CATV based on injection-locked VCSELs and a data comparator incorporating injection-locked DFB laser diodes and an amplitude/phase compensator has not yet been reported. The injection-locking technique, which can enhance laser frequency response, is expected to lead to good performance in a bidirectional DWDM-PON. The use of a data comparator, which corrects data errors, is also expected to lead to improvements in system performance. Nonlinear distortion might be significant in a bidirectional hybrid DWDM-PON. An amplitude/phase compensator could track the variations and compensate the nonlinear distortion in the link. In this paper, we propose and demonstrate an HDTV/Gigabit Ethernet/ CATV over bidirectional hybrid DWDM-PON based on 4 injection-locked VCSELs and 4 injection-locked DFB laser diodes. Our system uses one wavelength for 129 HDTV channels at 2.5 Gbps, one wavelength for a 1.25 Gbps Gigabit Ethernet channel, and two wavelengths for 77 CATV channels on each transmitting site. Our proposed system is demonstrated to be more economically advantageous compared to a bidirectional hybrid DWDM-PON based on 8 injection-locked DFB laser diodes. Transmission performance over 40 km of a standard single-mode fiber (SMF) was investigated. Improved performance in bit error rate (BER), carrier-to-noise ratio (CNR), composite second order (CSO), and composite triple beat (CTB) was achieved in our proposed bidirectional hybrid DWDM-PON. Due to the limitation of the inherent linearity characteristic, the performance of DWDM-PON-DFB is better than that of the DWDM-PON-VCSEL. The DWDM-PON-DFB system can be used to transmit both analog and digital signals; however, the DWDM-PON-VCSEL system can only be used to transmit digital signals. Despite the performance advantages, the DFB laser diode is a high-cost light source. For practical implementation of DWDM-PON systems, it is necessary to consider the cost. For this reason, we propose a system in which injection-locked DFB laser diodes are employed to transmit analog signals (CATV) and injection-locked VCSELs are employed to transmit digital signals (HDTV and Gigabit Ethernet).

II. Experimental Setup

Figure 1 shows the experimental configuration of our proposed system. The transmitting sites consist of two HDTV multiple-signal generators, two Gigabit Ethernet generators, two CATV multiple-signal generators (Matrix SX-16), four VCSELs, and four DFB laser diodes. The four VCSELs were selected with wavelengths of 1549.32, 1550.92, 1552.52, and 1554.13 nm. In addition, four DFB laser diodes were selected with wavelengths of 1555.75, 1557.36, 1558.98, and 1560.61

nm. Both VCSELs 1 and 3 were directly modulated at 2.5 Gbps with 129 HDTV channels (19.39 Mbps/channel × 129 channels). Both VCSELs 2 and 4 were directly modulated at 1.25 Gbps with 1 Gigabit Ethernet channel. Channels 2 to 40 were directly fed into DFB LDs 1 and 3, and channels 41 to 78 were directly fed into DFB LDs 2 and 4, with an optical modulation index (OMI) of approximately 3.5% per channel. For light injection, two broadband amplified spontaneous emission (ASE) sources were employed as light injection sources (also shown in Fig. 1). One broadband ASE light source is efficiently split into λ_1, λ_2, λ_3, and λ_4 optical channels, while the other light source is efficiently split into λ_5, λ_6, λ_7, and λ_8 optical channels by a DWDM demultiplexer (DEMUX) with a side mode suppression ratio (SMSR) greater than 40 dB. Optical isolators are placed between the broadband ASE source and the DWDM DEMUX optical channels, which prevent reflected light from getting into the injection light source. Light is injected in the counter-propagation direction through an optical coupler. The power level injected into the VCSEL (-5 dBm) is lower than that injected into the DFB LD (0 dBm) through a variable optical attenuator (VOA). Within the locking range, the frequency of the slave laser is locked nearly to the frequency of the master laser. The λ_1 is injected through an optical coupler, and the output of the injection-locked VCSEL 1 is launched into a 40 km SMF link through a 1×8 DWDM multiplexer (MUX)/DEMUX. The 1×8 DWDM MUX/DEMUX is used to launch the downstream wavelengths λ_1, λ_2, λ_3, and λ_4 (λ_5, λ_6, λ_7, and λ_8) into the fiber link, and to receive the upstream wavelengths λ_5, λ_6, λ_7, and λ_8 (λ_1, λ_2, λ_3, and λ_4) simultaneously. Both the DWDM MUX/DEMUX have 200 GHz (1.6 nm) channel spacing, 0.4 nm channel passband width, and higher than 40 dB adjacent channel isolation. Such high adjacent channel isolation, characteristic of the DWDM MUX/DEMUX, provides excellent demultiplexing ability to prevent linear crosstalk, which can result from the phenomenon of optical-beat interference (OBI). High adjacent channel isolation results in low linear crosstalk; therefore, the OBI parameter only has a minor influence on the system. Over a fiber link of 40 km, the combined optical wavelengths are split by a DWDM DEMUX, and detected by two digital optical receivers and two analog receivers in each receiving site. The output of the digital optical receiver is passed through a data comparator, and then fed into a BER tester for analysis. The output of the analog optical receiver is passed through an amplitude/phase compensator, and then fed into an HP-8591C CATV analyzer for CNR/CSO/CTB performance evaluation.

III. Experimental Results and Discussion

The bidirectional hybrid DWDM-PON employing the injection-locking technique on VCSELs and DFB laser diodes is envisioned to have a number of master lasers which are wavelength-selected for each channel and controlled to operate at specific wavelengths. This process will increase the cost and complexity of the systems. There have been a few techniques to overcome these problems, such as using a spectrum-sliced optical source. Spectrum slicing is a feasible approach, in which a narrow wavelength is filtered from a broadband optical source and injected into the slave lasers. It is attractive because it avoids the need for multiple master lasers with selected wavelengths. In this experiment, the broadband ASE is efficiently divided into four optical channels as injection sources by using a DWDM DEMUX, instead of the conventional multiple master lasers.

Wavelength stabilization is critical for VCSELs and injection-locked DFB laser diodes. Injection locking occurs when an injection-source laser is slightly detuned to a frequency lower than that of the injection-locked laser. The outer boundary of the locking range for a laser under light injection is given by [10] as

$$d < \pm\frac{k_c}{2\pi}\sqrt{\frac{S_i}{S}(1+\alpha^2)}, \tag{1}$$

where the frequency detuning $d = f_{\text{inj}} - f_{\text{free}}$ (f_{inj} is the frequency of the master laser, f_{free} is the frequency of free-running slave laser), k_c is the coupling coefficient, S_i/S is the injection ratio, and α is the linewidth enhancement factor. An optimum locking can be achieved if the frequency of the master laser is lower than that of the free-running slave laser (negative detuning). Within the locking range, the frequency of the slave laser is locked nearly to that of the master laser. However, outside the locking range, severe oscillation occurs. When a VCSEL (DFB LD) is injection-locked, its optical spectrum shifts to a slightly longer wavelength and becomes narrower in linewidth. The optimal injection locking condition is found when the detuning between the slave laser and the master laser is 0.14 nm. Because the detuning is 0.14 nm, the system has the best transmission performance in terms of the lowest received optical power level (BER is 10^{-9}) for HDTV/Gigabit Ethernet digital channels, and the best CNR/CSO/CTB performance for the CATV analog channel.

A block diagram of the data comparator is illustrated in Fig. 2, including a fast comparator. If data signal $d(n)$ is available at the transmitting site without any distortion, then the distortion of the received data signal $d_{er}(n)$ is due to the fiber link. The function of the data comparator is to estimate $d(n)$ from $d_{er}(n)$ by error feedback. For data comparison, the output of the fast comparator is compared with memorized data of $d(n)$ to create an error. A fast feedback updates the error every time so that

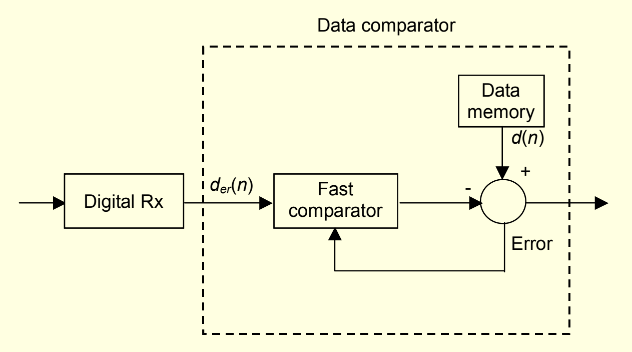


Fig. 2. Block diagram of the data comparator.

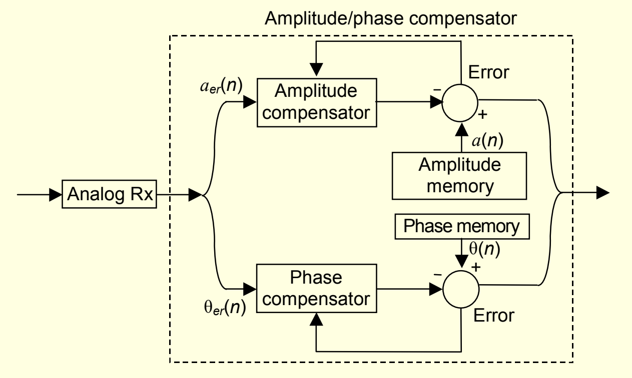


Fig. 3. Functional block of the amplitude/phase compensator.

the error is minimized. A functional block of the amplitude/phase compensator is shown in Fig. 3. The $Sig(n)$ has an amplitude of $a(n)$ and a phase of $\theta(n)$. After transmission through the fiber link, the received signal $Sig_{er}(n)$ has a distorted amplitude of $a_{er}(n)$ and a distorted phase of $\theta_{er}(n)$. The amplitude/phase compensator has to achieve $Sig(n)$ from $Sig_{er}(n)$ by error feedback. For amplitude compensation, the output of the amplitude compensator is compared with a memorized amplitude of $a(n)$ to create an error. For phase compensation, the output of the phase compensator is compared with a memorized phase of $\theta(n)$ to create an error. The use of an amplitude/phase compensator offers significant error compensations. The data comparator has a stored copy of data signal in the data memory before starting communication. The amplitude/phase compensator also has a stored copy of amplitude/phase signal in the amplitude/phase memory before starting communication. The critical issues are that there must be data/amplitude/phase memory chips to store the memorized data/amplitude/phase at the receiving site. In an optical network unit (ONU), the potential disaster of a power outage can be anticipated. In this case, the data/amplitude/phase memory chips must be initialized to refresh the memorized data/amplitude/phase. However, the data comparator and amplitude/phase compensator are worth using due to BER and CSO/CTB performance improvements.

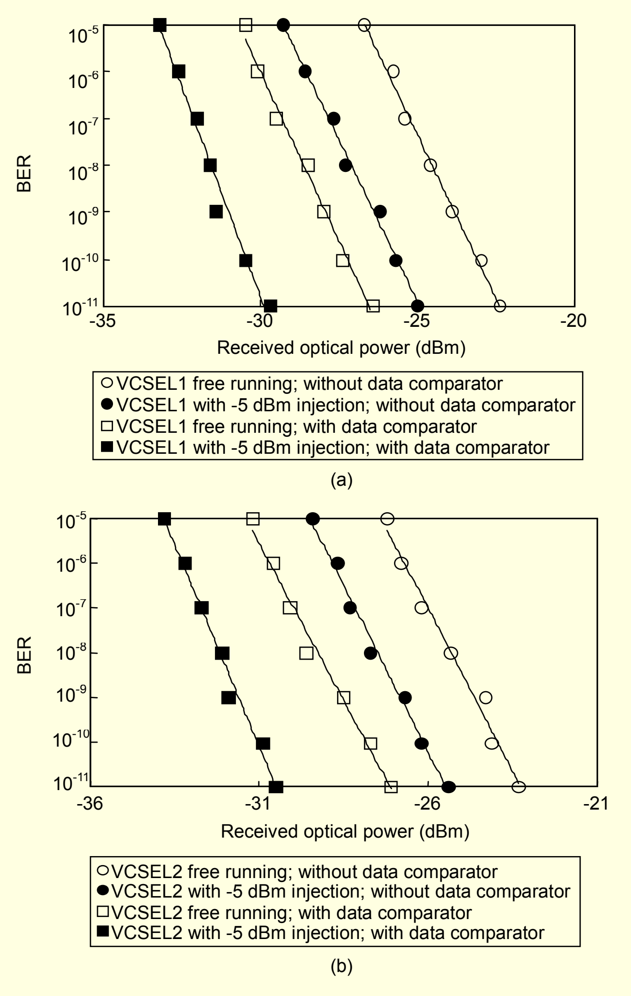


Fig. 4. Measured BER curves as a function of the received optical power: (a) VCSEL 1 and (b) VCSEL 2.

The measured BER curves, as a function of the received optical power, are plotted in Fig. 4. For VCSEL 1 at a BER of 10^{-9}, in the free-running case, the received optical power is -23.9 dBm; with -5 dBm light injection and a data comparator, the received optical power is -31.4 dBm. A large 7.5 dB received optical power reduction is achieved when the light injection technique and data comparator are employed simultaneously. For VCSEL 2 at a BER of 10^{-9}, in the free-running case, the received optical power is -24.3 dBm; with -5 dBm light injection and data comparator, the received optical power is -31.9 dBm. A large 7.6 dB received optical power reduction is achieved when the light injection technique and data comparator are employed simultaneously. To ascertain how much power penalty improvement is related to each of the schemes, one system using -5 dBm light injection technique alone and another using the data comparator alone have been employed to measure the received optical power. Using the -5

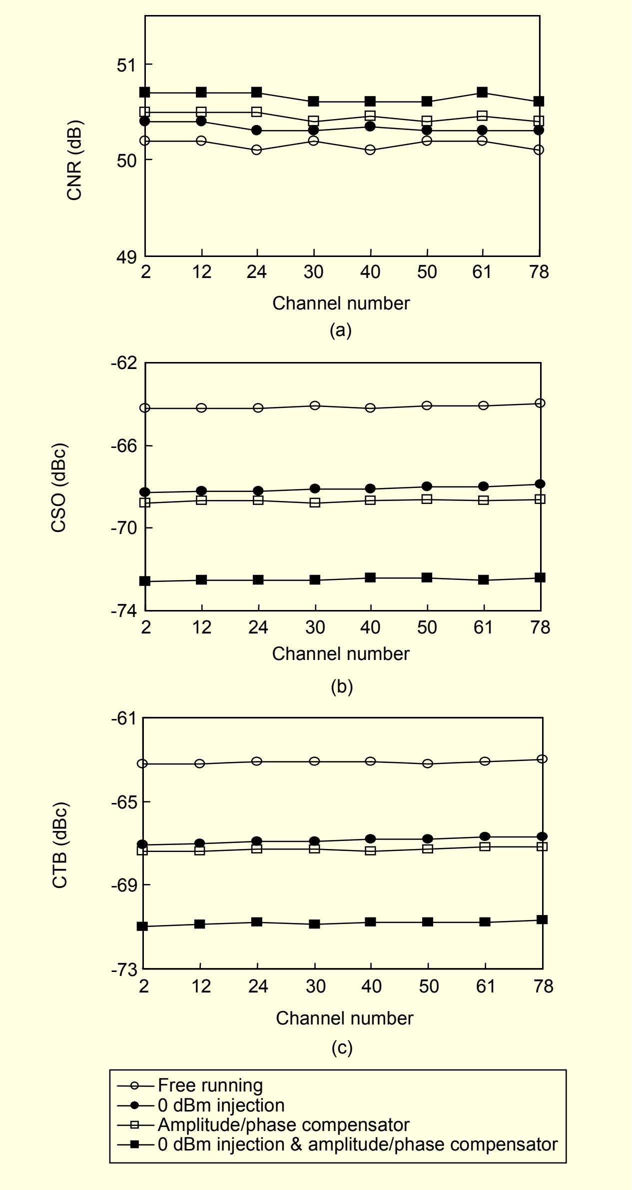


Fig. 5. (a) Measured CNR values under NTSC channel number, (b) measured CSO values under NTSC channel number, and (c) measured CTB values under NTSC channel number.

dBm light-injection technique alone, for VCSEL 1 and VCSEL 2 at a BER of 10^{-9}, the received optical powers are -26.2 and -26.7 dBm, respectively. Using the system with the data comparator alone, for VCSEL 1 and VCSEL 2 at a BER of 10^{-9}, the received optical powers are -28 and -28.5 dBm, respectively. This demonstrates that with either systems, the received power penalty improvement is limited.

Figure 5 shows the measured CNR, CSO, and CTB values in relation to NTSC channel number, respectively. It can be seen that the CNR value (>50 dB) increases when light is injected and an amplitude/phase compensator is employed. Regarding the CSO/CTB performance, in the free-running case, the CSO/CTB values are less than -64/-63 dBc, respectively; with 0 dBm light injection and amplitude/phase compensator, the CSO/CTB values are less than -72/-70 dBc, respectively. A huge CSO/CTB performance improvement of 8 and 7 dB is obtained when the light-injection technique and amplitude/phase compensator are employed simultaneously. Light injection reduces the threshold current of the DFB laser diode, thus, increasing the optical output power of the DFB laser diode. The higher the optical power launched into the fiber, the better the CNR performance obtained in the system. In a direct modulation system, second-order harmonic distortion-to-carrier ratio (HD_2/C) and third-order intermodulation distortion-to-carrier ratio (IMD_3/C) can be expressed as in [11] by

$$HD_2/C \cong 10\log\left\{ m\frac{(\frac{f}{f_r})^2}{g(2f)} \right\}, \tag{2}$$

$$IMD_3/C \cong 10\log\left\{ \frac{m^2}{2}\frac{(\frac{f}{f_r})^4 - \frac{1}{2}(\frac{f}{f_r})^2}{g(f)g(2f)} \right\}, \tag{3}$$

where m is the OMI, f_r is the laser resonance frequency, and $g(f)$ is the gain of the laser medium as a function of frequency. From (2) and (3), it is obvious that both HD_2/C and IMD_3/C can be very small when f_r is very large. The injection-locking technique increases the laser resonance frequency, resulting in a system with lower HD_2/C and IMD_3/C, and leading to an improvement of CSO/CTB performance. The use of an amplitude compensator decreases the amplitude error of the system, which causes the system to have a higher CNR value. The CSO and CTB distortions are given as in [12] by

$$CSO = 10\log\left[\frac{mD\lambda_c^2 Lf}{4c}\sqrt{16(\Delta\tau)^2 + \frac{4\lambda_c^4 L^2 \pi^2 f^6}{c^2}} \right] + 10\log N_{\mathrm{CSO}} + 6, \tag{4}$$

$$CTB = 10\log\left[\frac{9m^2 D^2 \lambda_c^4 L^2 f^2}{4c}(4(\Delta\tau)^2 + 4\pi^2 f) \right] + 10\log N_{\mathrm{CTB}} + 6, \tag{5}$$

where D is the dispersion coefficient, λ_c is the optical carrier wavelength, L is the fiber length, f is the RF frequency, $\Delta\tau$ is the phase noise, and N_{CSO} and N_{CTB} are the product counts of CSO and CTB. The use of a phase compensator decreases the phase noise of the system, which causes the system to show better CSO/CTB performance.

To ascertain how much CSO/CTB performance improvement is related to each of the schemes, one system using the 0 dBm light-injection technique alone has been employed to measure the CSO/CTB values (<-68/-66.7 dBc), while another system using the amplitude/phase compensator alone has been employed to measure the same CSO/CTB values (<-68.6/-67 dBc). The results demonstrate that with either system, the CSO/CTB performance improvement is limited.

Transmission of HDTV and Ethernet data over a WDM-PON has been reported previously in [13], in which 162 Mbps data frames containing 2 HDTV channels (19.39 Mbps × 2) and 1 Ethernet connection (100 Mbps) were used. Our proposed DWDM-PON compares well with this, using bidirectional transport is instead of unidirectional transport, a high transmission data rate (3.75 Gbps) instead of a low transmission data rate (162 Mbps), and a hybrid signal format (analog and digital) rather than the solely digital signal format. To the best of our knowledge, this is the first overall performance improvement of a bidirectional hybrid DWDM-PON using injection-locked DFB laser diodes and injection-locked VCSELs simultaneously.

IV. Conclusion

We proposed an HDTV/Gigabit Ethernet/CATV transmission system over a bidirectional hybrid DWDM-PON based on injection-locked VCSELs and DFB laser diodes as transmitters. Services with 129 HDTV channels, a 1.25 Gbps Gigabit Ethernet connection, and 77 CATV channels were successfully demonstrated over 40 km SMF links. Compared with the previously proposed WDM-PON technologies, it is the most promising and economically advantageous approach. Cheap VCSELs are employed to replace expensive DFB laser diodes to transmit digital signals, and sophisticated arrayed-waveguide gratings (AWGs) are not used.

References

[1] K.M. Choi, J.S. Baik, and C.H. Lee, “Broadband Light Source Using Mutually Injected Fabry-Perot Laser Diodes for WDM-PON,” *IEEE Photon. Technol. Lett.*, vol. 17, 2005, pp. 2529-2531.

[2] W. Lee, M.Y. Park, S.H. Cho, J. Lee, C. Kim, G. Jeong, and B.W. Kim, “Bi-Directional WDM-PON Based on Gain-Saturated Reflective Semiconductor Optical Amplifiers,” *IEEE Photon. Technol. Lett.*, vol. 17, 2005, pp. 2460-2462.

[3] M. Khanal, C.J. Chae, and R.S. Tucker, “Selective Broadcasting of Digital Video Signals over a WDM Passive Optical Network,” *IEEE Photon. Technol. Lett.*, vol. 17, 2005, pp. 1992-1994.

[4] S. Hann, D.H. Kim, and C.S. Park, “Uni-Lambda Bidirectional 10/1.25 GbE Access Service Based on WDM-PON,” *Electron. Lett.*, vol. 40, 2004, pp. 194-195.

[5] W.S. Tsai, H.H. Lu, S.H. Chen, T.S. Chien, W.N. Chen, and M.H. Tu, “Improvement of IEEE 802.11a Systems over Radio-on-Multimode Fiber Applications,” *IEEE Photon. Technol. Lett.*, vol. 17, 2005, pp. 2230-2232.

[6] C.H. Chang, L. Chrostowski, C.J. Chang-Hasnain, and W.W. Chow, “Study of Long-Wavelength VCSEl-VCSEL Injection Locking for 2.5 Gb/s Transmission,” *IEEE Photon. Technol. Lett.*, vol. 14, 2002, pp. 1635-1637.

[7] S. Zhang, N. Margalit, T. Reynolds, and J. Bowers, “1.54 μm Vertical-Cavity Surface-Emitting Laser Transmission at 2.5 Gb/s,” *IEEE Photon. Technol. Lett.*, vol. 9, 1997, pp. 374-376.

[8] E.S. Son, K.H. Han, J.K. Kim, and Y.C. Chung, “Bidirectional WDM Passive Optical Network for Simultaneous Transmission of Data and Digital Broadcast Video Service,” *J. Lightwave Technol.*, vol. 21, 2003, pp. 1723-1727.

[9] H.H. Lu, W.S. Tsai, W.J. Wang, and Y.L. Lui, “Employing Double External Light Injection Techniques to Improve Radio-on-DWDM System Performance,” *IEEE Photon. Technol. Lett.*, vol. 17, 2005, pp. 672-674.

[10] S. Mohrdiek, H. Burkhard, and H. Walter, “Chirp Reduction of Directly Modulated Semiconductor Lasers at 10 Gb/s by Strong CW Light Injection,” *J. Lightwave Technol.*, vol. 12, 1994, pp. 418-424.

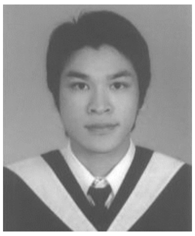
[11] H.H. Lu, Y.W. Chuang, G.L. Chen, C.W. Liao, and Y.C. Chi, “Fiber-Optical Cable Television System Performance Improvement Employing Light Injection and Optoelectronic Feedback Techniques,” *IEEE Photon. Technol. Lett.*, vol. 18, 2006, pp. 1789-1791.

[12] W.I. Way, *Broadband Hybrid Fiber/Coax Access System Technologies*, Academic Press, San Diego, 1998.

[13] D.J. Shin, D.K. Jung, J.K. Lee, Y.K. Oh, J.H. Lee, H.S. Kim, C.H. Lee, S.T. Hwang, J.H. Ko, Y.J. Oh, T.I. Kim, and C.S. Shim, “Transmission of HDTV and Ethernet Data over a WDM-PON Employing ASE-Injected Fabry-Perot Laser Diodes,” *Opt. Fiber Commun. Conference*, vol. 1, 2004.

Hai-Han Lu received the BS from the Electro-Physics Department of the National Chiao-Tung University, Taiwan, in 1987. He received the MS and PhD degrees from the Institute of Optical Sciences of the National Central University, Taiwan, in 1991 and 2000, respectively. He joined the Institute of Electro-Optical Engineering, National Taipei University of Technology, as an Associate Professor in 2001. He has become a Full Professor in 2003. His current research interests include the applications of the lightwave communication, ROF transport systems, and WDM-PON.

Wen-Shing Tsai was born in Taipei, Taiwan. He received the BS, MS, and PhD degrees from National Taipei University of Technology, Taiwan, in 1995, 2003, and 2006, respectively. He joined the Department of Electrical Engineering, Mingchi University of Technology, as an Assistant Professor in 2006. His current research interests include the applications of DWDM-PON and ROF transport systems.



Tzu-Shen Chien received his MS degree from the Institute of Electro-Optical Engineering, National Taipei University of Technology, in 2006. His current research interests include the applications of fiber optical CATV systems and WDM-PON.

Shih-Hung Chen received his MS degree from the Institute of Electro-Optical Engineering, National Taipei University of Technology, in 2006. His current research interests include the applications of lightwave communication and ROF transport systems.

Yu-Chieh Chi has been working toward his MS degree in the Institute of Electro-Optical Engineering, National Taipei University of Technology, since 2005. His current research interests include the applications of fiber optical CATV transport systems and the characteristics of WDM-PON.

Che-Wei Liao has been working toward his MS degree in the Institute of Electro-Optical Engineering, National Taipei University of Technology, since 2005. His current research interests include the applications of fiber optical CATV and ROF transport systems**.**