Self-Seeding Injection of Anti-Reflection Coated FP Laser Amplifier Based Transmitters for Wavelength Division Multiplexing PON

Gong-Cheng Lin[a], Sun-Chien Ko[a], Yin-Hsun Huang[a], Hai-Lin Wang[a],
Yu-Sheng Liao[b], and Gong-Ru Lin[c*]

[a]Advanced Tech. Ressearch Lab, Telecommunication Laboratories, Chunghwa Telecom Co., Ltd.
12, Lane 551, Min-Tsu Road Sec.5, Yang-Mei, Taoyuan, Taiwan 32617, R.O.C
[b]Department of Photonics & Institute of Electro-Optical Engineering,
National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan
[c*]Graduate Institute of Electro-Optical Engineering and Department of Electrical Engineering,
National Taiwan University
No.1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan, Republic of China
E-mail: grlin@ntu.edu.tw

ABSTRACT

We experimentally demonstrate a directly modulated 1% AR-FPLA based ONU under side-mode injection-locking for 1.25Gbits/s DWDM-PON application. With side-mode injection of this device, the characterizes of 34-channel detuning capacity under self seeding and its corresponding to a wavelength locking range of 30 nm is a potential candidate to achieve the cost effective and high capability 1.25 Gbits/s DWDM-PON systems. The effects of the front-facet reflectivity in the AR-FPLA on injection locking range, spontaneous emission, and Q-factor are interpreted from our results. A BER of <10^{-12} is obtained for the nearest 17 channels and a 10^{-10} error rate can be achieved for all of the 34 injection-locked channels with SMSR >35dB, providing a negative power penalty of -0.7 dB.

Keywords: FP Laser diode, side-mode injection, fiber-to-the-home, injection locking, DWDM

1. INTRODUCTION

Recently, the wavelength division multiplexed-passive optical network (WDM-PON) has attracted great attention as one of the solutions for future broadband subscriber networks because WDM-PON is point-to-point connected through the dedicated wavelength without sacrificing bandwidth. How to obtain a low-cost and wavelength-stable light source is the key point for WDM-PON. The WDM-PON based on amplified spontaneous emission (ASE) injection-locked FP-LD does not need to maintain assigned wavelength and decrease management and installation costs simultaneously. WDM-PON is promising as low-cost subscriber networks to fiber-to-the-home

Optical Transmission, Switching, and Subsystems V,
edited by Dominique Chiaroni, Wanyi Gu, Ken-ichi Kitayama, Chang-Soo Park,
Proc. of SPIE Vol. 6783, 67832W, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.745046

systems by reason of far greater capacity and flexibility, which is one possible solution for access networks over 1 Gbit/s. Recently, lots of efforts have been focused on a cost effective and high performance transmitter in every optical network unit (ONU) including spectral slicing of light-emitting diodes [1, 2] or amplified spontaneous emission (ASE), wavelength-seeded reflective semiconductor optical amplifiers (RSOA) [3, 4], and ASE-injected Fabry–Perot laser diodes (FPLDs). Especially, the most promising approach in an economical point of view is employing FPLDs under injection locking, where single-mode output is achievable from an FP-LD by externally injected FPLD with EDFA amplified [5, 6]. In low-cost transmitters termed "colorless," optical light originating from the OLT is fed into the ONUs to injection-lock Fabry–Perot laser diodes (FPLDs) [7-10] or to wavelength-seed reflective semiconductor optical amplifiers (RSOAs). The injection-locked wavelength-seeding light may be furnished by spectrally sliced light from a centralized broadband source located at the CO. The scheme of injection-locking FPLD succeeds in removing the need for centralized broadband sources to provide the injection locking light, but it does not tolerate a wavelength drift between the FP-LDs, FBGs, and AWGs. The self-seeding RSOAs as colorless upstream ONU transmitters were achieved by using AWG spectrally sliced ASE in the RN and fed back via a passive reflective path to seed itself without requiring centralized broadband sources. However, these approaches have trade-off with wavelength tolerate of FPLD scheme and high cost of RSOA. In this work, we propose a 1.25-Gbit/s DWDM-PON light source of the novel anti-reflection coated FP laser amplifier (AR-FPLA) with self-seeding injection lock. The including injected locking performance, eye diagram, and bit error rate (BER) of the AR-FPLA with a cost-effective TO-56 can-package are determined.

2. EXPERIMENTAL SETUP

Figure 1 schematically illustrates a DWDM-PON system based on the selfseeding injection-locked AR-FPLAs. The reflectivity of the front facet was lowered to below 1% using antireflection coating, while reflectivity of the rear facet was enhanced to about 85% using high-reflection coating. This highly asymmetric cavity allowed efficient injection of ASE into the chip and reduced undesirable backward reflection at the front facet and power waste to the rear. The F-PLD was modified for an injection-locking scheme without significant increase in cost. The measured threshold of the AR-FPLA is 12.5 mA.

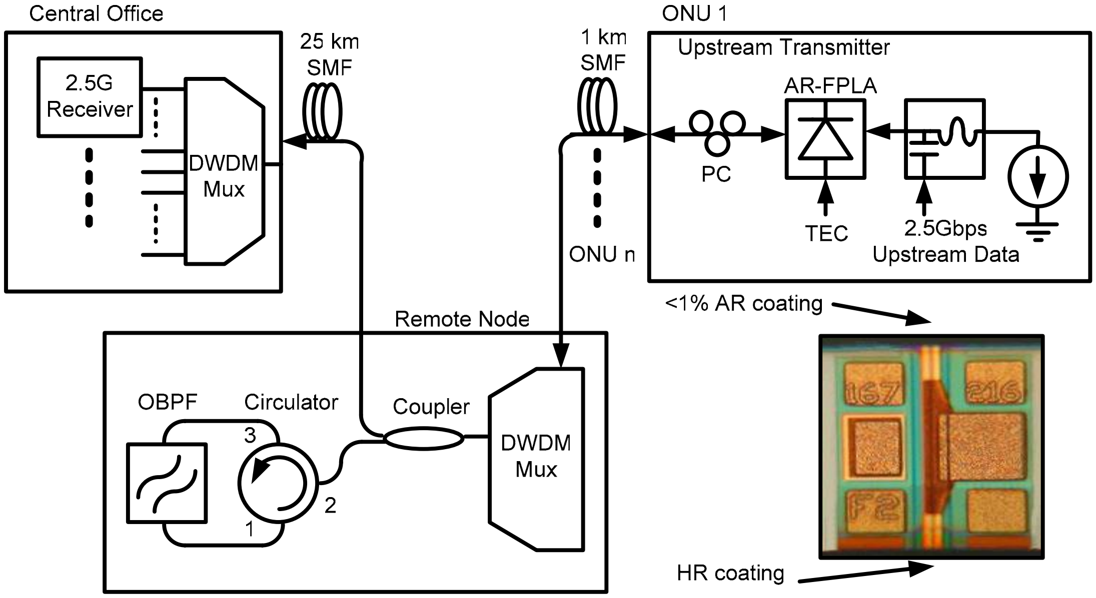

Fig. 1 Setup of the experiment of self-seeding AR-FPLAs as upstream transmitters in a WDM-PON.

Each ONU transmitter comprised an AR-FPLA, a polarization controller (PC) that was adjusted to maximize the seeding efficiency of the AR-FPLA. The broadband ASE of AR-FPLA is sent upstream toward the RN in initiation. The AWG in the RN spectrally slices the ASE of AR-FPLA from each ONU into a narrowband spectrally sliced light which is reflected back to the RSOA to initiate injection lock. When the externally injection-locking condition between the self-seeding source and slave FPLD is matched, the slave one can be operated as high side-mode suppression ratio (SMSR). Each slave AR-FPLA is directly modulated by a 1.25 Gbit/s PRBS data stream for transmission performance diagnosis.

3. RESULTS AND DISCUSSIONS

Compared to conventional FPLDs, the mode spacing was reduced to ensure that at least one lasing mode can spectrally overlap with the injected narrowband ASE to maintain wavelength locking regardless of the thermally drifting lasing wavelengths. Since the passband of the arrayed waveguide gratings (AWGs) was nearly rectangular and 0.6 nm wide, the mode spacing of the FPLD was chosen to be 0.6 nm. Figure 2 shows optical spectrum of the AR-FPLA with threshold of 14 mA at free-run condition of 20, 30, 40 mA and injection locking condition of 30 mA. At around threshold current, the luminance spectrum from thin and thick wells merges and becomes broad. At above threshold current, the FWHM of the luminance spectrum is above 35 nm and no significant peaks can be obtained. Note that there is only one high reflectivity of the rear facet was enhanced to about 90%, and the Fabry–Perot effect in the chip exhibits but it can not build the major wavelength peak.

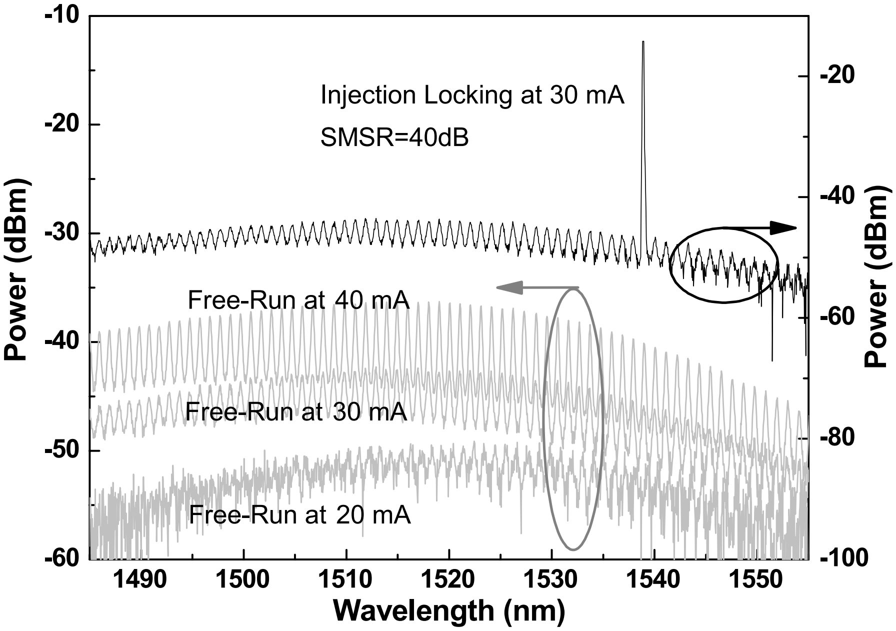

Fig. 2 Optical spectrum of the AR-FPLA at free-run condition of Ith+ 5 to Ith+25mA and injection locking condition of Ith +15mA.

In our approach, the AR-FPLA exhibits wide injected-locking range which can cover 1510 nm to 1540 nm by using an AR-FPLA. As the wavelength of the filtered and amplified FPLD light source exactly matches that of a longitudinal mode in AR-FPLA, the AR-FPLA exhibits the largest peak power and the lowest noise, the slave AR-FPLA exhibits the largest peak power and the lowest noise. The maximum SMSR of the master light source injected FPLD is up to 40 dB when the wavelengths of master light source and AR-FPLA mode are coincident each other. The detuning wavelength is the wavelength shift of the injected signal from the master FPLD with respect to the free-running wavelength of one longitudinal mode of the slave AR-FPLA. As a result, the wavelength locking range of the slave AR-FPLA measured by the adopted modified delayed self-homodyne (MDSH) scheme is shown in Fig. 3. The locking range was defined as the wavelength tunable range for remaining the SMSR of the AR-FPLA lasing mode at >35 dB. Narrower locking ranges were measured for the AR-FPLA with lower injection power and the injection power is required maintaining the AR-FPLA within the locking range. The injection ratio is defined as the power ratio of the injected signal to the free-running optical signal inside AR-FPLA cavity. The stable injection-locking region is found to be bounded by two solid curves. Under such conditions of injection larger than that of the AR-FPLA, the AR-FPLA is operated at larger injection ratio and has larger locking range. In addition, a relatively weak signal with considerable noise has also been found as the injection wavelength is detuned away from the slave AR-FPLA's longitudinal mode by 0.6 nm. The injected-locking cover range was limited by the gain profile of its material inside the chip of AR-FPLA. Almost the other longitudinal mode had been restrained and the selected wavelength was raised as the black line of Fig. 3. Most gain of the AR-FPLA was been cached by the selected wavelength and the SMSR can be obtained up to 40 dB. The directly current-modulated AR-FPLA controls the upstream signal from the ONU. As comparing with the commercial FPLD, our AR-FPLA provides an up to 10-times flexible locking range.

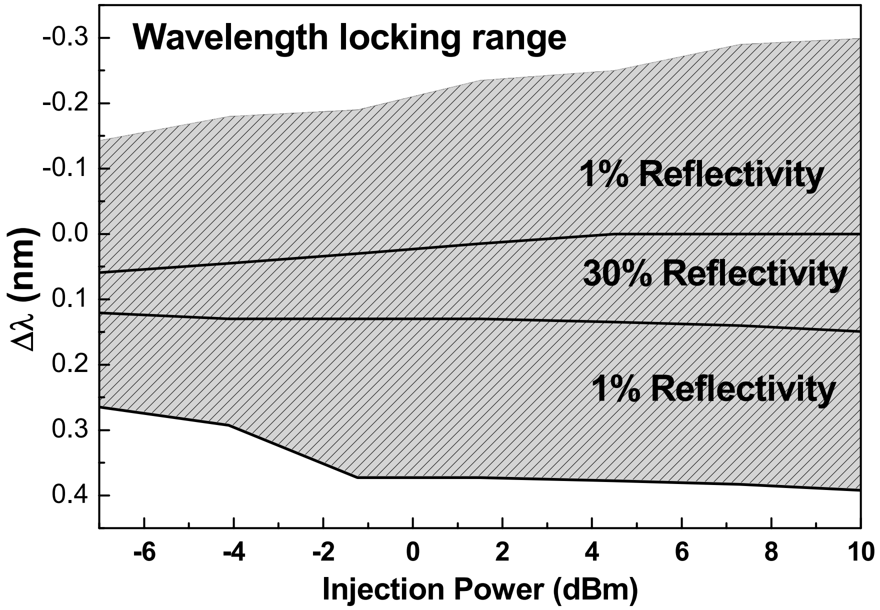

Fig. 3 Wavelength locking range of a side-mode in the slave AR-FPLA at ONU end as a function of injection-locked power.

The dynamics of an AR-FPLD with the external injected light can be described with the following rate equations. A traveling-wave rate-equation model [11, 12] is constructed to simulate the AR-FPLA initiating from the amplified spontaneous emission. However, the opposite-direction parts of the traveling-wave equations are neglected since the unidirectionally propagated AR-FPLA has high reflectivity at the rear facet. Both the ASE and injection locking induced gain-depletion effects are considered during simulation. The asymmetric gain characteristic was taking into account and the differential rate equation of carrier density and the propagation equations which describe the time-varied powers of the injection locked AR-FPLA and the injected signals. The measured BER of the data-stream received by the AR-FPLA can be accurately calculated from the recorded Q factor of the received eye pattern at a desired data rate. Figure 4 shows the calculated Q factor and locking range of the injection locking AR-FPLA with different reflectivity. The figure shows that high reflectivity bring good quality transmission signal, but the expense is the narrow locking range. As detuning the injection wavelength near the FP-etalon gain peak, the injected can not get much gain because the etalon restrains the optical confinement factor in the cavity. In order to drop this effect, the reflectivity of the front facet should be reduced. Previously, the wavelength-locked FP-LD by the spectrum-sliced incoherent lights had been usually adopted for a low capacity WDM PON. They have shown great cost-effective performance to any other components in terms of practical WDM-PON realization, but the data rate of a single channel is limited at the data rate of 622 Mbits/s due to its high RIN. The performance of the directly-modulated, wavelength-locked AR-FPLA based DWDM PON operating at a data rate of 1.25 Gbits/s was been investigated. As comparing with spectrum-sliced ASE source, the intensity noise of wavelength-locked AR-FPLA was suppressed efficiently at high frequency. The spectrum-sliced ASE injection is a detrimental source to FPLDs due to its random polarization characterizes.

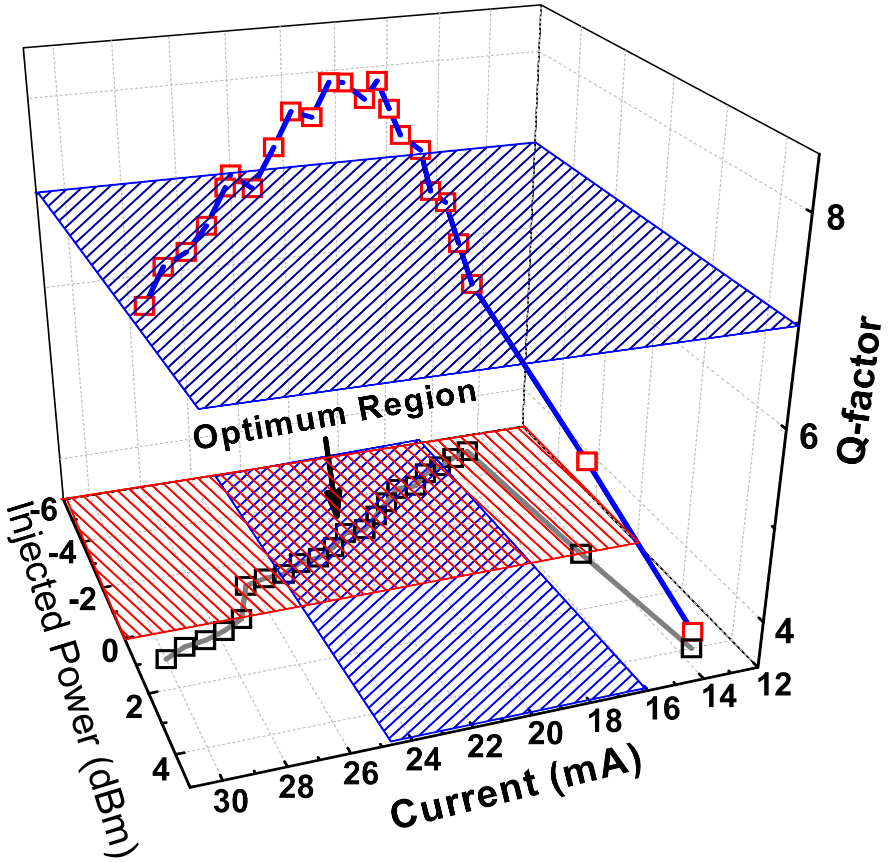

Fig. 4 Injected power (hollow markers) and measured Q (solid markers) of the driving current at a wavelength locked longitudinal mode.

The wavelength-locked AR-FPLA could provide better performance than the spectrum-sliced ASE source for above gigabit signal transmission. With optimized injection, the measured Q factor can be as high as 9.2, providing a reachable BER of 1.8×10^{-20} at the data rate of 1.25 Gbits/s. By increasing the dc biasing current of the slave AR-FPLA to 20 mA, the wavelength locking at the data rate of >2.5 Gbits/s can be achieved, which is eventually limited by the transient gain contribution of ever longitudinal mode of the FPLD. Effective transmission is obtainable within blue-shaped region of an estimated Q > 7 corresponding to a BER of about 10^{-12} as shown in the Fig. 6. On the other hand, the red-shaped region represents the practical implementation of such an injection-locked FPLD system at an injecting power below -1 dBm. That is, the optimized operating parameters for concurrently achieving high-Q and low-injection are determined with at a FPLD driving current between 16 mA and 25 mA.

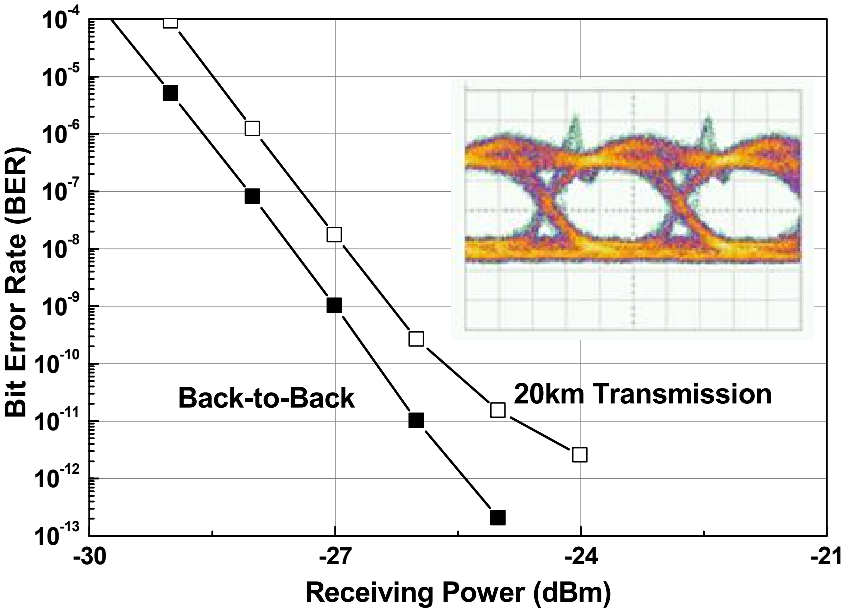

Fig. 6 BER analysis of wavelength injection locked FPLD at different longitudinal modes and measured eye diagrams (inset) with

The other structure of WDMPON is based on the directly modulated SOA which operating in gain-saturation regime, but it requests of using extra optical amplifier. An RSOA operating in the linear regime has been proposed as a low-cost ONU [3,10], but the allowable extinction ratio (ER) in the downstream transmission is limited to be less than around 3 dB even with higher optical gain in the linear regime. As comparing with RSOA, our proposed with better ER and adaptable driving region. The AR-FPLA also provides slight gain to injection source, and this helps low injected locking power of master source. To characterize the data transmitting performance of directly modulated FPLD with wavelength locking in a simulated 1.25-Gbits/s WDM-PON fiber-optic network, the eye diagram analysis at 1.25 Gbits/s is also performed. A well-opened eye pattern can be obtained with a relatively large dynamic range as shown in inset of Fig. 6. The rising time and falling time (defined as the duration between 20% and 80% of on-level amplitude) are 118 ps and 125 ps, respectively. The nearly error-free (BER < 10^{-12}) back-to-back with and without optical injection can be detected at received optical power of larger than -24.4 and -23.7 dBm with the pattern length of Pseudo Random Binary Sequence 2^{31}-1 (PRBS), respectively. A negative power penalty of -0.7 dB as comparing with non-injection is measured at a BER of 10^{-12}, which is attributed to the reduction of the relaxation oscillation of the FPLD and increasing bandwidth by the competition of every longitudinal mode. As the transient situation of carrier density changing from the bit 0 to bit 1, the photon density of this desired longitudinal mode gets a stable gain by external optical injection. The carrier density was depleted continuously by external optical injection, which can not form the relaxation oscillation with photon density.

4. CONCLUSION

We experimental demonstrate and theoretically analyze the effect of the front-facet reflectivity in the AR-FPLA on injection locking rage, spontaneous emission, and Q-factor. In order to obtain wide gain spectrum width and low gain extinction ratio, the effect of front-facet reflectivity of AR-FPLA is theoretically analyzed. A 30 nm cover-range capacity of a directly modulated 1% AR-FPLA based ONU under side-mode injection-locking for 1.25Gbits/s DWDM-PON application is experimentally demonstrated. Such a wavelength injection-locked 1% AR-FPLA can be operated at a data rate up to 1.25 Gbits/s to show a largest SMSR of 40 dB and a Q factor ranging from 9.2 to 7.5 as the injection-locked channel extends to the 12th side-mode with respect to the central carrier. The maximum usable ONU channels of the side-mode injection-locking AR-FPLA are 34, corresponding to a wavelength locking range of 30 nm. A BER of $<10^{-12}$ is obtained for the nearest 17 channels and a 10^{-10} error rate can be achieved for all of the 34 injection-locked channels, providing a negative power penalty of -0.7 dB due to the reduction on relaxation oscillation of the AR-FPLA. These results indicates that the demonstrated side-mode injection-locked AR-FPLA is a potential candidate to achieve the cost effective and high capability 1.25 Gbits/s DWDM-PON systems for low operation and maintenance cost.

ACKNOWLEDGMENT

The authors thank the National Science Council of Republic of China for financially supporting this research under grants NSC95-2221-E-002-448 and NSC95-2752-E-009-007-PAE. Gong-Ru Lin is the corresponding author with E-mail: grlin@ntu.edu.tw.

REFERENCES

1. 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, pp. 1067–1069, 2000.
2. K. Lee, J.-H. Song, H.-K. Lee, and W.-V. Sorin, “Multistage access network for bidirectional DWDM transmission using ASE-injected FP-LD,” IEEE Photon. Technol. Lett., vol. 18, pp. 761-763, 2006.
3. W. Lee, M.-Y. Park, S.-H. Cho, J. Lee, C. Kim, G. Jeong, and B.-W. Kim, “Bidirectional WDM-PON Based on Gain-Saturated Reflective Semiconductor Optical Amplifiers,” IEEE Photon. Technol. Lett., pp. 2460-2462, vol. 17, 2005.
4. P. Healey, P. Townsend, C. Ford, L. Johnston, P. Townley, I. Lealman, L. Rivers, S. Perrin and R. Moore, “Spectral slicing WDM-PON using wavelength-seeded reflective SOAs,” Electron. Lett., vol. 5, pp. 1181-1182, 2001.
5. K.-M. Choi, J.-S. Baik, and C.-H. Lee, “Color-free operation of dense WDM-PON based on the wavelength-locked Fabry–Pérot laser diodes injecting a low-noise BLS,” IEEE Photon. Technol. Lett., vol. 18, pp. 1167-1169, 2006.
6. H.-C. Kwon, and S-K. Han, “Performance analysis of a wavelength-locked Fabry-Perot laser diode by light injection of an external spectrally sliced Fabry-Perot laser diode,” Applied Optics, vol. 45, pp. 6175-6179, 2006.

7. D. J. Shin, D. K. Jung, H. S. Shin, J. W. Kwon, S. Hwang, Y. Oh, and C. Shim, "Hybrid WDM/TDM-PON with wavelength-selectionfree transmitters," IEEE J. Lightw. Technol., vol. 23, pp. 187–195, 2005.
8. X. J. Meng, T. Chau, and M. C. Wu, "Improved intrinsic dynamic distortions in directly modulated semiconductor lasers by optical injection locking," IEEE Trans. Microwave Theory and Techniques, vol. 47, pp. 1172-1176, 1999
9. G.-R. Lin, Y.-H. Lin, and Y.-C. Chang, "Theory and experiments of a mode-beating noise-suppressed and mutually injection-locked Fabry–Pérot laser diode and erbium-doped fiber amplifier link," IEEE J. Quantum Electron., vol. 40, pp. 1014-1022, 2004.
10. S.-M. Lee, K.-M. Choi, S.-G. Mun, J.-H. Moon, and C.-H. Lee, "Dense WDM-PON based on wavelength-locked Fabry-Pérot laser diodes," IEEE Photon. Technol. Lett., vol. 17, pp. 1579-1581, 2005.
11. K.-Y. Park, S.-G. Mun, K.-M. Choi, and C.-H. Lee, "A Theoretical Model of a Wavelength-Locked Fabry–Pérot Laser Diode to the Externally Injected Narrow-Band ASE," IEEE Photon. Technol. Lett., vol. 17, pp. 1797-1799, 2005.
12. G.-R. Lin, Y.-S. Liao, and G.-Q. Xia, "Dynamics of optical backward-injection-induced gain-depletion modulation and mode locking in semiconductor optical amplifier fiber lasers," Opt. Express, vol 12, pp. 2017-2026, 2004.
13. N. S. Bergano, F. W. Kerfoot, C. R. Davidsion, "Margin measurements in optical amplifier system," IEEE Photon. Technol. Lett., vol. 5, pp. 304-306, 1992.