22-Channel Capacity of 2.5Gbit/s DWDM-PON ONU Transmitter by Direct-Modularly Side-Mode Injection Locked FPLD

Yu-Sheng Liao[a], Yung-Jui Chen[b], and Gong-Ru Lin[c*]

[a] Department of Photonics & Institute of Electro-Optical Engineering,
National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan
[b]Department of Computer Science and Electrical Engineering University of Maryland, Baltimore County
1000 Hilltop Circle, Baltimore, MD 21250, Maryland, USA
[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

22-channel detuning capacity of a 2.5Gbit/s directly modulated FPLD based ONU under side-mode injection-locking for DWDM-PON is demonstrated with SMSR >35dB, Q-factor 6.8-9.2, locking range of 24nm, power penalty of -0.7dB, and BER of 10^{-10} *at -17dBm. The demonstrated side-mode injection-locked FPLD is a potential candidate to achieve the cost effective and high capability 2.5Gbit/s DWDM-PON systems. The maximum usable ONU channels of the side-mode injection-locking FPLD are 22, corresponding to a wavelength locking range of 24 nm. Direct modulation of the upstream channels was successfully obtained and shows high quality eye diagram at ONU transmission.*

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

1. INTRODUCTION

The growth of e-businesses and multimedia applications are accelerating strong requirements for broadband services over gigabit for business users. The wide-area broadband access networks are required to offer high-speed connection services between several local area networks. Dense wavelength-division-multiplexed passive optical network (DWDM-PON) is promising as low-cost subscriber networks to fiber-to-the-home 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). The Several methods have been proposed to reduce the cost of DWDM systems such as spectral slicing of

Optical Transmission, Switching, and Subsystems V,
edited by Dominique Chiaroni, Wanyi Gu, Ken-ichi Kitayama, Chang-Soo Park,
Proc. of SPIE Vol. 6783, 67832L, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.745282

light-emitting diodes [1] or amplified spontaneous emission (ASE), wavelength-seeded reflective semiconductor optical amplifiers [2], and ASE-injected Fabry–Perot laser diodes (FPLDs). However, they are limited by low bandwidth, power budget in optical link, and high intensity noise. 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 [3]. In this work, we study the maximum channel detuning capacity for operation of ONUs of directly modulated 2.5Gbit/s DWDM-PON was demonstrated by mutually side-mode injection-locking FPLD. The corresponding relationship of bias current, external injection power, and longitudinal number to optimize the operation of wavelength injection locked FPLD was analyzed.

2. EXPERIMENTAL SETUP

Figure 1 schematically illustrates a DWDM-PON system based on the side-mode injection-locked FPLDs. A FPLD with an integrated optical isolator is employed as the master laser for injection-locking the other FPLDs at the ONU end. The RIN of this master FPLD operated at a bias current of 40 mA was measured by Agilent 71401C Lightwave Signal Analyzers as low as -150dB/Hz. The master FPLD currently used in our system is commercially, which will be replaced by a specially designed long-cavity one for obtaining the 50-GHz longitudinal mode spacing. The longitudinal mode of the master FP-LD is temperature detuned to match the ITU-T DWDM channel, which is further amplified by an EDFA at the central office for obtaining higher modal power.

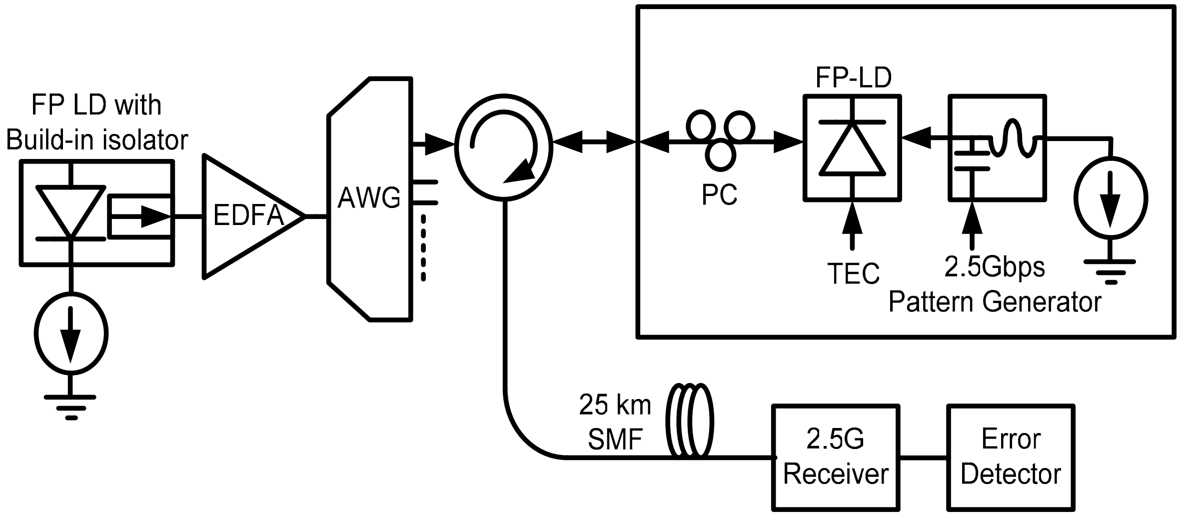

Fig. 1(a) The configuration a DWDM-PON system with FPLD at ONU end that is side-mode injection-locked by a wavelength-sliced master FPLD.

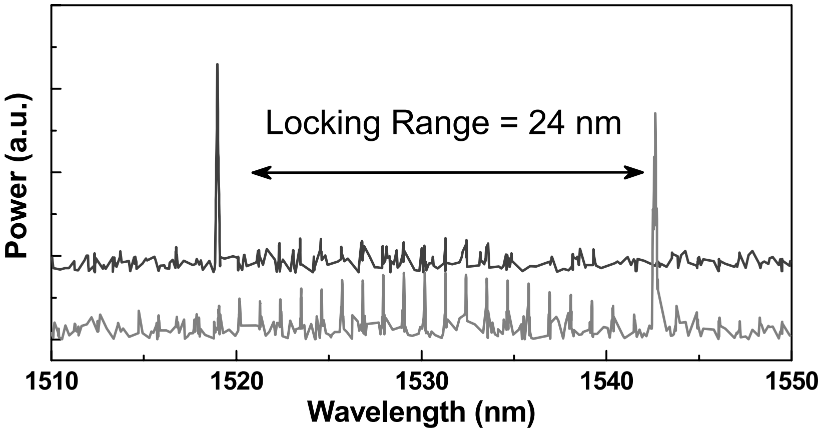

Fig. 1(b) The locking range of the FPLD at ONU end that is side-mode injection-locked

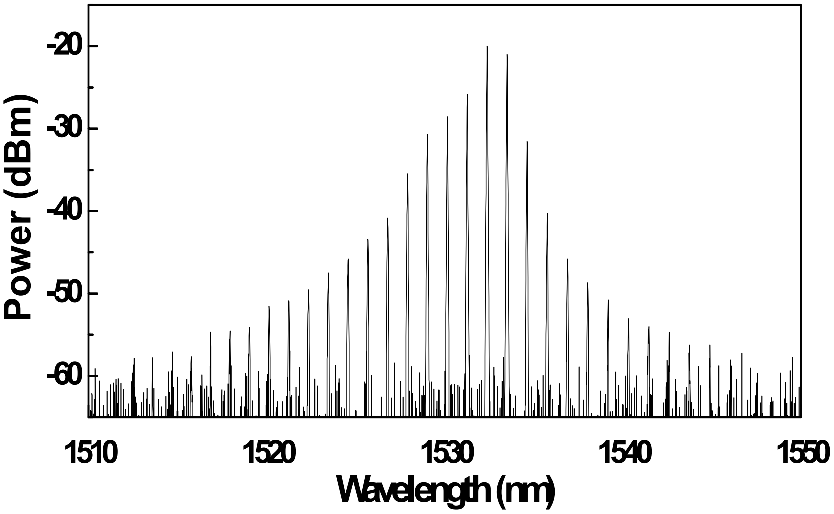

Fig. 1(c) The spectrum of the FPLD at ONU end that is side-mode injection-locked

The slave FP-LD exhibits threshold current of 8.5 mA, longitudinal mode spacing of 1.1 nm, and front facet reflectivity of 0.1%. The temperature of all FPLDs are controlled at 25°C with a fluctuation of <0.1 °C to prevent the wavelength drift on longitudinal modes. The master FPLD output is filtered by a DWDM multiplexer built-in with the DWDM-PON before injecting into each FPLD at ONU end, which consequently causes a reduction on threshold current of the slave FPLD. When the externally injection-locking condition between the wavelength-sliced master and slave FPLD is precisely matched, the slave one can be operated just as a single longitudinal mode optical source with high side-mode suppression ratio (SMSR). Each slave FPLD is directly modulated by a 2.5 Gbit/s PRBS data stream for transmission performance diagnosis. As shown in Fig. 2, the spectrum of the slave FPLD after injection-locking shows a 3dB linewidth of 0.024 nm, which is slightly broadened after direct modulation.

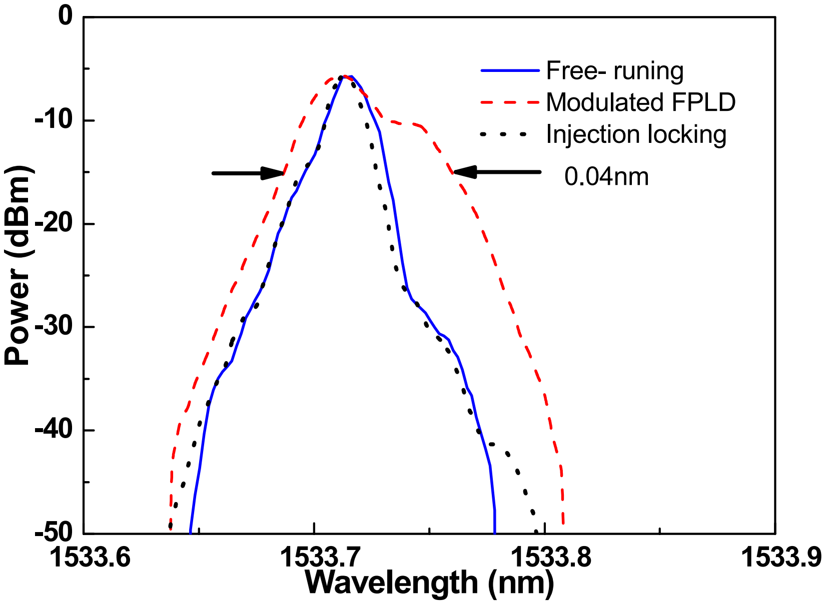

Fig. 2 Spectral linewidths of injection-locked FPLD before (red line) and after (blue line) modulation as compared to a reference laser source (black).

3. RESULTS AND DISCUSSIONS

As a result, the wavelength locking range of the slave FPLD measured by the adopted modified delayed self-homodyne (MDSH) scheme is shown in Fig. 3. The injection ratio is defined as the power ratio of the injected signal to the free-running optical signal inside FP-LD cavity [4, 5]. 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 FPLD. The stable injection-locking region is found to be bounded by two solid curves. The FPLD is injection-locked by bit “1” whose power is much larger than that of the FPLD. Under such conditions, the FP-LD 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 FPLD’s longitudinal mode by 0.4 nm.

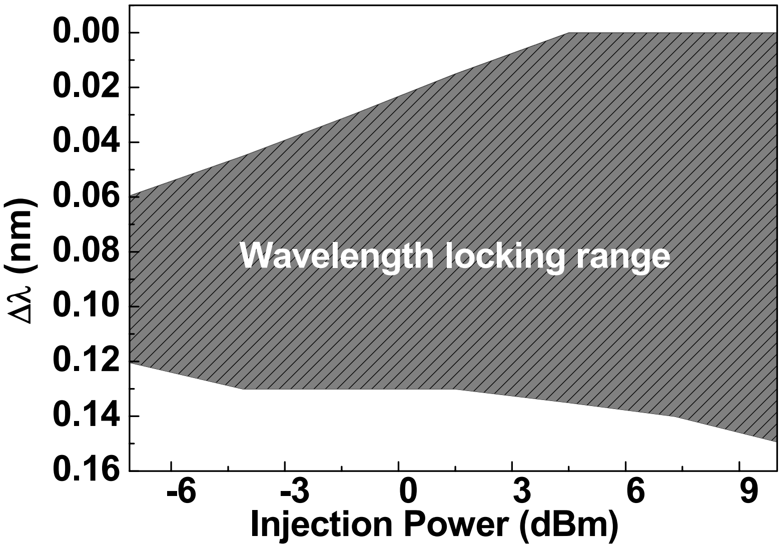

Fig. 3 Wavelength locking range of a side-mode in the slave FPLD at ONU end as a function of injection-locked power.

The measured 3-dB spectral linewidth for one longitudinal mode of the CW free-running and directly modulated FPLD are 0.024 and 0.04 nm, respectively. This result correlates well with the theory that the transient variation in carrier density simultaneously affects the refractive index and mode linewidth of the slave FPLD. However, under injection locking the linewidth of the CW free-running and directly modulated FPLD are reduced to 0.018 and 0.022 nm, respectively. After injecting the single wavelength from master FPLD into the Slave FPLD, the SMSR was shown in Fig. 4 as a function of detuning external injection power and longitudinal modes. Note that longer longitudinal mode need higher external injection power to achieve SMSR > 35 dB. Figure 3 illustrated the behavior of slave FPLD, and it provides the minimum optical injected power at all longitudinal modes to initial wavelength locking.

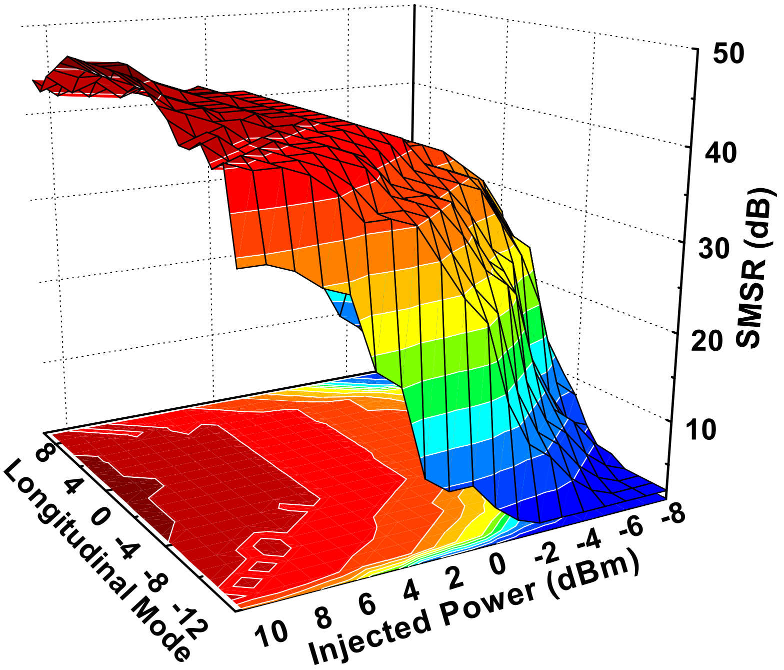

Fig. 4 Measured SMSR curve on adjacent injected longitudinal mode and external optical power.

Bergano *et al.* have previously demonstrated a BER evaluation method by measuring the signal-to-noise ratio at decision circuit of an optical transmission and receiving system [5]. The measured BER of the optical transmitting eye diagram can be accurately calculated from the recorded Q factor at a desired data rate. The equivalent mean and sigma of the marks and spaces are determined by fitting this data to Gaussian characteristic. The measured Q factor with optimized injection can be as high as 9.2, providing a reachable BER of 1.8×10^{-20} at the data rate of 2.5 Gbit/s. By increasing the dc biasing current of the slave FPLD to 20 mA, the wavelength locking at the data rate of >2.5 Gbit/s can be achieved, which is eventually limited by the transient gain contribution of ever longitudinal mode of the FPLD. The locking range was defined as the wavelength tunable range for remaining the SMSR of the slave FPLD lasing mode at >35 dB. Narrower locking ranges were measured for the slave FPLD with lower injection power, as shown in Fig. 3. On the other hand, the injection power required maintaining the FPLD within the locking range as a function of different bias current, and the corresponding Q factors are also measured and shown in Fig. 5. We illustrated the calculated Q-factor of the injection-locked FP-LD based WDM-PON transmitter at different driving currents and injection powers. Effective transmission is obtainable within blue-shaped region of an estimated Q > 7 corresponding to a BER of about 10^{-12}. On the other hand, the red-shaped region represents the practical implementation of such an injection-locked FPLD system at an injecting power below 2 dBm. That is, the optimized operating parameters for concurrently achieving high-Q and low-injection are determined with at a FPLD driving current between 12mA and 17 mA.

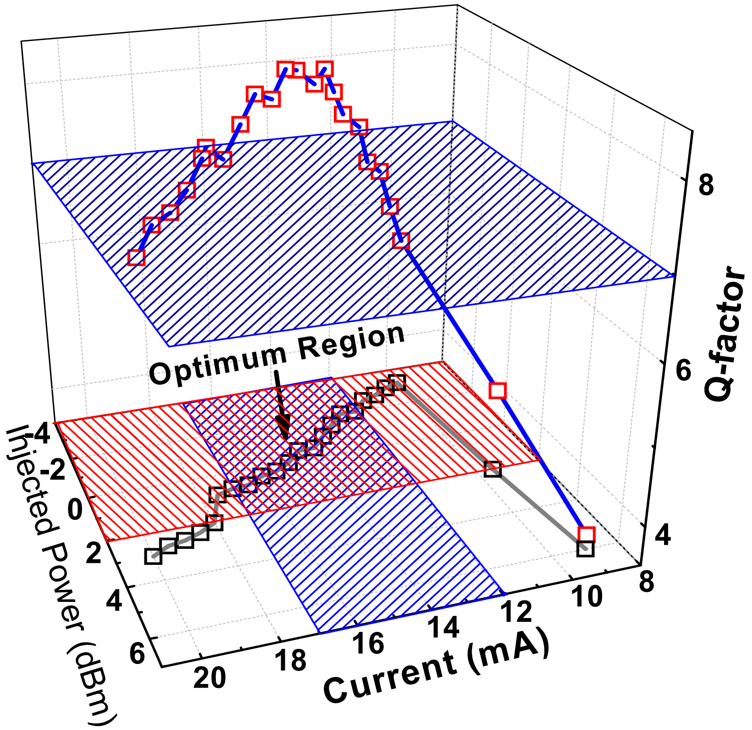

Fig. 5 Injected power (hollow markers) and measured Q2 (solid markers) of the driving current at a wavelength locked longitudinal mode.

Later on, the eye diagram analysis at 2.5 Gbit/s is also performed to characterize the data transmitting performance of directly modulated FPLD with wavelength locking in a simulated 2.5-Gbit/s WDM-PON fiber-optic network. This is done with an electronic time division multiplexing experiment using a 2.5 Gbit/s Pseudo Random Binary Sequence (PRBS) data-stream. Besides, 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 -23.7dBm, respectively. A positive power penalty of 0.7 dB is measured at a BER of 10^{-12}, which is attributed to the reduction of the relaxation oscillation of the FPLD 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.

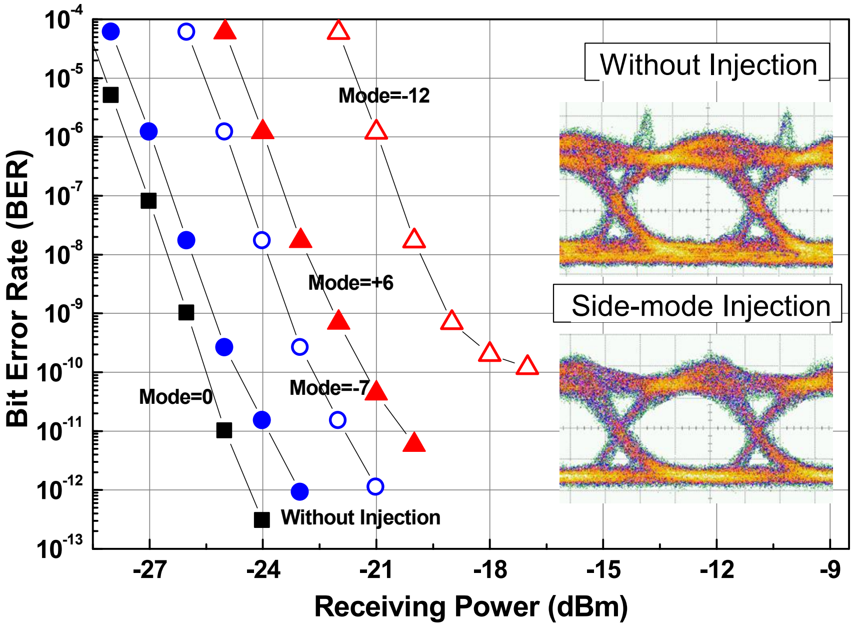

Fig. 6 BER analysis of wavelength injection locked FPLD at different longitudinal modes and measured eye diagrams (inset) with and without injection

4. CONCLUSION

A 22-channel detuning capacity of a directly modulated FPLD based ONU under side-mode injection-locking for 2.5Gbit/s DWDM-PON application is demonstrated. Such a wavelength injection-locked FPLD can be operated at a data rate up to 2.5Gbit/s to show a largest SMSR of 35 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 FPLD are 22, corresponding to a wavelength locking range of 24 nm. A BER of $<10^{-12}$ is obtained for the nearest 13 channels and a 10^{-10} error rate can be achieved for all of the 22 injection-locked channels, providing a negative power penalty of -0.7 dB due to the reduction on relaxation oscillation of the FPLD. These results indicates that the demonstrated side-mode injection-locked FPLD is a potential candidate to achieve the cost effective and high capability 2.5Gbit/s DWDM-PON systems.

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. 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, 761-763 (2006).
2. E. Wong, K.-L. Lee and T. Anderson, “Low-cost WDM passive optical network with directly-modulated self-seeding reflective SOA,” Electron. Lett., Vol. 42, (2006).
3. 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, 1167-1169 (2006).
4. 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 Techniques, Vol. 47, pp. 1172-1176, 1999.
5. G.-R. Lin, Y.-H. Lin, and Y.-C. Chang, "Theory and Experiments of a Mode Beating Noise Suppressed and Mutually Injection-Locked Fabry-Perot Laser Diode and Erbium-Doped Fiber Amplifier Link" Vol. 40, 1014-1022, (2004).
6. Y.-C. Chang, Y.-H. Lin, and G.-R. Lin, “All-optical NRZ-to-PRZ format transformer with an injection-locked Fabry-Perot laser diode at unlasing condition,” Optics Express, Vol. 12, 4449-4456, (2004).
7. 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, 6175-6179, (2006).
8. N. S. Bergano, F. W. Kerfoot, C. R. Davidsion, “Margin measurements in optical amplifier system,” IEEE Photon. Technol. Lett., Vol. 5, 304-306, (1992)