# Side-mode transmission diagnosis of a multi-channel selectable injection-locked Fabry-Perot Laser Diode with anti-reflection coated front facet

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**Abstract:** Theory and experiments on the side-mode-suppression-ratio (SMSR) enhancement and the linewidth reduction of a Fabry-Perot laser diode (FPLD) side-mode-injection-locked by using another FPLD are demonstrated to realize its potential application as a DWDM transmitter source. The SMSR, the spectral linewidth and the linewidth enhancement factor are simulated to realize the limitation of the FPLD-FPLD link under side-mode injection-locking condition. A degradation of the linewidth enhancement factor from 1.5 to 2.1 is observed due to the slave FPLD injection-locked at principle- and side-mode conditions. Up to 22-channel selectability of the 2.5 Gbit/s directly modulated FPLD based transmitter under side-mode injection-locking is demonstrated with a SMSR >35 dB, a Q-factor 6.8-9.2, a locking range of 24 nm, a power penalty of -0.7 dB, and a BER of $10^{-10}$ at -17 dBm. The side-mode injection-locked FPLD shows high-quality transmission performance and meet the demand for cost-effective and high-capability 2.5 Gbit/s WDM systems.



**OCIS codes:** (140.3520) Lasers, injection-locked; (060.2330) Fiber optics communication.

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## 1. Introduction

Recently, there are increasing interests on the economic subcarrier multiplexed (SCM) fiber-optic networks with multi-channel selectable carriers from one unified optical source to support a wide wavelength range of the analog and digital broadband services. To meet this demand, the single-longitudinal-mode and low-noise operation of the laser sources with selectable channel wavelengths [1-6] are critical issues for such a wavelength-division-multiplexing (WDM) optical access system. Some of the previous works focused on developing the specific broadcasting architectures to release the cost issue of the rather expensive DFB laser transmitters by sharing over a large customer base. One solution is the use of 1.5-μm DFB in conjunction with optical amplifiers to achieve larger link budgets [1]. Alternatively, a high-power diode-pumped erbium-doped fiber amplifier (EDFA) based ring laser using an intra-cavity liquid-crystal fiber etalon filter was proposed with its output wavelength electrically tunable from 1525 to 1586 nm.[2] In particular, a transmission experiment at 2.5 Gbit/s over 30 km using a wavelength-locked Fabry–Perot laser diode (FPLD) externally controlled by another spectrally sliced Fabry–Perot laser diode was also performed [3]. Under such kind of injection-locking, the suppression on second/third harmonic distortion and third-order intermodulation distortion was demonstrated.[4] Moreover, a distinguished and cost-effective method for generation a channel-selectable single-mode FPLD by self-seeding it with low-level injection power was ever reported.[5] Nearly single-mode source with side-mode suppressing ratio (SMSR) of higher than 40 dB over all selectable channels with a wavelength tuning range covering 11.5 nm was demonstrated with such a self-seeding FPLD.[6] Typically, the aforementioned technology is achieved by use of a tunable linearly-chirped fiber Bragg grating or an active Fabry–Perot filter to provide wavelength-selective injection and output filtering function. Alternatively, the other approaches using an FPLD injection-locked with a coherent optical source have also been presented in previous works. For example, a spectrally sliced amplified-spontaneous–emission (ASE) light source and a spectrally sliced FPLD have also been proposed as the WDM optical sources,[7] which were in connection with the add–drop modules that are composed of "4skip0" and add-drop filters. The experiments in a novel optical distribution network for multistage access with multiple remote nodes (RNs) have shown error-free transmission with simultaneous bidirectional 1.25 Gbit/s per channel up to 20 km. Not long ago, we have also demonstrated a single-longitudinal-mode optical source generated using a mode-beating noise-suppressed FPLD-EDFA link under mutually injection–locking condition [8]. Similar FPLD-FPLD injection-locked sources were emerged as the WDM passive optical network (PON) transmitters,[9] and the high-speed-uplink WDM-PON architecture at 10 Gbit/s with 15-km transmission capability has been demonstrated using the injection-locked FPLDs.[10] Up to now, most researching efforts are focused on the injecting architectures of the FPLD at its principle longitudinal mode under high-gain competition. Nonetheless, it was seldom addressed that the FPLD under side-mode injection-locking condition can also be

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approached as a high-quality optical light source in particular conditions. Although most of the transmission performances have been comprehensively investigated, some of the important parameters such as the SMSR, the spectral linewidth and its enhancement factor, and the bit-error-rate (BER) power penalty of the optical carrier based on the injection-locked side modes were never discussed. In this paper, we analyze the performances of a side-mode injection-locked FPLD by externally injecting with another spectrally sliced FPLD. The effects of the biased current and the external injection power on the optimization of a side-mode injection-locked FPLD at different longitudinal modes are discussed. The transmission performances such as extinction ratio, Q factor, and BER at 2.5 Gbit/s over 25 km are also characterized.

## 2. Experimental setup

Figure 1 schematically illustrates the WDM-PON system based on the side-mode injection-locked FPLDs. A FPLD with an integrated isolator is employed as the master laser for injection-locking the other slave FPLDs used as WM-PON transmitters. The master FPLD is a commercially available one with mode spacing of 1.1~1.2 nm (corresponding to 150 GHz), which could be replaced by a specially designed long-cavity one for obtaining the 50-GHz longitudinal mode spacing. The relative intensity noise (RIN) of the master FPLD as low as -140 dBm/Hz at biased current of 40 mA was measured with a lightwave signal analyzer (Agilent 71401C). The longitudinal mode of the master FPLD is detuned to match the ITU-T DWDM channel by adjusting its temperature, which is further amplified by an EDFA at the central office for obtaining higher modal power. The master FPLD output is filtered by arrayed waveguide grating (AWG) multiplexer with the channel spacing of 100 GHz.

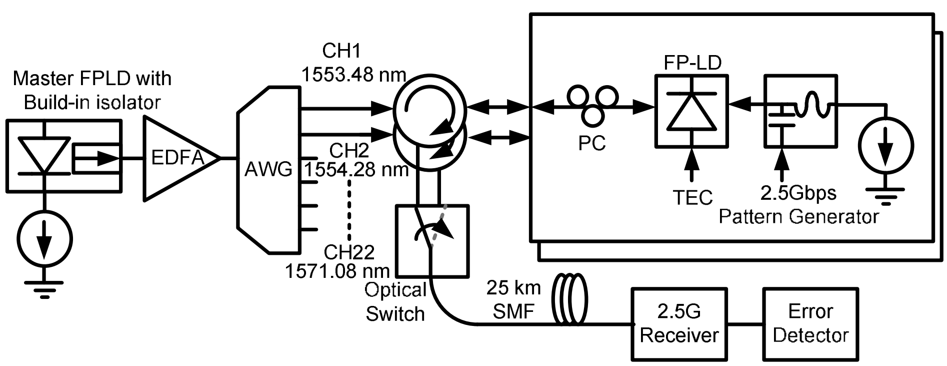


Fig. 1. The configuration of an experimental system with slave FPLD is side-mode injection-locked by a wavelength-sliced master FPLD.

The side-mode injection-locking transmissions of the multi-channel selectable FPLD up to 22 wavelengths from 1553.48 nm (CH 1) to 1571.08 nm (CH 22) are demonstrated. The slave FPLD exhibits a threshold current of 8.5 mA, a longitudinal mode spacing of 1.1 nm, and a cavity length of 250 μm. The temperature of all FPLDs are controlled at 25°C with a fluctuation of <0.1°C to prevent any wavelength drift on the longitudinal modes. The total insertion loss of the injection-locked FPLD-FPLD link during transmission is 18 dB coming from the AWG (4 dB), the 25-km single-mode fiber (SMF) (6 dB), and the other excessive loss (8 dB). When the externally injection-locking condition between the wavelength-sliced master FPLD and the slave FPLDs is achieved, the slave one can be operated just as a single-longitudinal-mode optical source with high SMSR. Each slave FPLD is directly modulated by a 2.5 Gbit/s PRBS data stream with a pattern length of $2^{31}$-1 for transmission diagnosis.

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## 3. Results and discussions

*3.1 Side-mode suppressing ratio analysis*

The wavelength locking range of the slave FPLD measured by using a modified delayed-self-homodyne (MDSH) scheme is shown in Fig. 2, which is defined as the wavelength injection-locking range for one specific longitudinal mode of the slave FPLD with its SMSR >35 dB. The detuning wavelength is defined as the wavelength shift on the longitudinal mode of the master FPLD with respect to that of the slave FPLD. The stable injection-locking region is bounded by two solid curves and the slave FPLD is operated at higher injection ratio to reach larger injection-locking range under such conditions, where the injection ratio is defined as the power ratio of the injected signal to the free-running optical signal inside FPLD cavity. In addition, a relatively weak signal with considerable noise has also been observed as the injection wavelength is detuned away from the slave FPLD's longitudinal mode by 0.15 nm. After injection-locking with the master FPLD, the SMSR of the slave FPLD as a function of the detuning external injection power and the order of the side longitudinal mode is shown in Fig. 3. This figure provides the minimum optical power at all longitudinal modes to initiate the wavelength injection-locking. Note that a higher ordered longitudinal mode acquires larger injecting power to achieve a SMSR > 35 dB. In more detail, the SMSR of the slave FPLD with the seeding from the master FPLD is theoretically discussed as below.

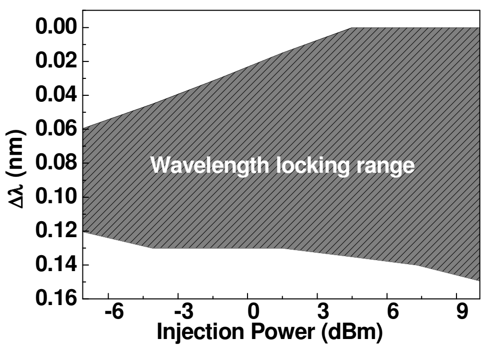


Fig. 2. Wavelength locking range of the injection-locked mode in slave FPLD versus injection power.

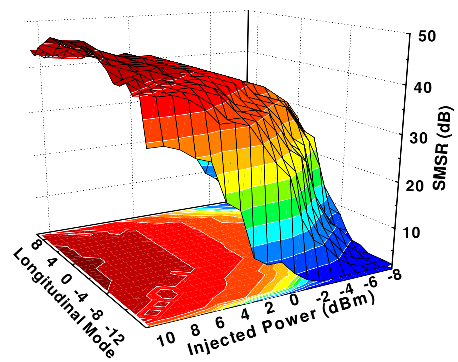


Fig. 3. Measured SMSR curve on adjacent injected longitudinal mode and external optical power.

Typically, the SMSR of the FPLD longitudinal mode under external injection-locking condition can be expressed by [11]

$$SMSR = \frac{I_m}{I_0} = \frac{g_m}{(\Gamma'_m - g_m)} \times \frac{(\Gamma'_0 - g_0)}{g_0} = \frac{\dfrac{g_m}{(1+\dfrac{I_m}{I_S(m)})}}{\Gamma'_m - \dfrac{g_m}{(1+\dfrac{I_m}{I_S(m)})}} \times \frac{\Gamma'_0 - \dfrac{g_0}{(1+\dfrac{I_0}{I_S(0)})}}{\dfrac{g_0}{(1+\dfrac{I_0}{I_S(0)})}}, \quad (1)$$

where the optical intensity of the fundamental (the largest) mode and the desired side-mode to be injection-locked in the slave FPLD are denoted as $I_0$ and $I_m$, the index j defines each parameter, $g_j$ denotes the gain coefficient, $\Gamma_j$ denotes the loss coefficient, and $I_S$ denotes the saturation intensity. We assume that only the intensities of the external injection at $\lambda_0$ (the central wavelength of principle mode) and $\lambda_m$ (the injection-locked side-mode) can contribute to the slave FPLD. In our case, a new parameter Δm is employed to describe the wavelength difference between the injection-locked $m^{th}$ side-mode and the principle mode (Δm=0) naturally lasing at the gain peak of the slave FPLD. The material gain spectrum is approximated by a Lorentzian shape function to model the spectral roll-off of the slave FPLD gain profile. The gain of each $m^{th}$ side-mode can thus be described by $g_m=g_0/[1+(\Delta m/M^2)]$,

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where $M$ denotes the total mode number related to the full-width-at-half-maximum of the slave FPLD gain spectrum. If we assume that the saturation conditions of the principle and side modes are equivalent (i.e. $I_s(0) = I_s(m)$), the SMSR, $I_0/I_m$, can thus be described as a function of the ratio of loss coefficients.

$$SMSR = \frac{I_m}{I_0} = \frac{C_1(\Gamma_0^{'}/(1+\Delta m/M^2) - C_2\Gamma_m^{'})}{\Gamma_m^{'}} = \frac{C_1(1 - C_2\Gamma_m^{'}(1+\Delta m/M^2)/\Gamma_0^{'})}{\Gamma_m^{'}(1+\Delta m/M^2)/\Gamma_0^{'}}$$
$$= \frac{C_1\left[1 - C_2 \ln\left(R_{eff,m}^{'}\right)(1+\Delta m/M^2)/\ln\left(R_{eff,0}^{'}\right)\right]}{\ln\left(R_{eff,m}^{'}\right)(1+\Delta m/M^2)/\ln\left(R_{eff,0}^{'}\right)}, \qquad (2)$$

where $C_1$ and $C_2$ are constants. In addition, the relationship between the loss coefficient $\Gamma$ and the reflectivity R can be correlated each other by writing the following formula $\Gamma_j = -\ln(R'_{eff,j})/2L$, where $R'_{eff}$ denotes the effective reflectivity of the slave FPLD cavity under external injection. Hereafter, we define the reflectivity change ($\Delta$R) in term of external injection power as

$$\Delta R = \frac{I_{ext}}{\Gamma_F} \Big/ \frac{I_o}{1-R}, \qquad (3)$$

where $I_{ext}$ is the optical intensity of the external injection, and the $\Gamma_F$ is the coupling loss between the slave FPLD and the coupled SMF. Thus, the change of the loss coefficient for the slave FPLD can be described as

$$\Delta\Gamma = -\frac{\partial}{\partial R}\left[\frac{\ln\left(R_{eff}^{'}\right)}{2L}\right]\cdot\Delta R = -\frac{\Delta R}{2LR_{eff}^{'}}. \qquad (4)$$

Consequently, the SMSR of the slave FPLD under external injection-locking can be re-written as a function of the reflectivity change. The ratio of loss coefficients $\Gamma_0'/\Gamma_m'$ can be represented as

$$\frac{\Gamma_m'}{\Gamma_0'} \Rightarrow \frac{\Gamma_m + \Delta\Gamma_m}{\Gamma_0 + \Delta\Gamma_0} = \frac{\Gamma_m - \frac{\Delta R}{2LR_{eff,m}}}{\Gamma_0 - \frac{\Delta R}{2LR_{eff,0}}} = \frac{-\frac{\ln(R_{eff,m})}{2L} - \frac{\Delta R}{2LR_{eff,m}}}{-\frac{\ln(R_{eff,0})}{2L} - \frac{\Delta R}{2LR_{eff,0}}} \cong \frac{[\ln(R_{eff,m} + \frac{\Delta R_{eff,m}}{R_{eff,m}})]}{[\ln(R_{eff,0})]}, \qquad (5)$$

in which the effective reflectivity of the principle mode is assumed to be equivalent to the largest side mode, and the reflectivity change of the side mode is far stronger than that of the principle mode ($\Delta R_{eff,0} >> \Delta R_{eff,m} \cong 0$).

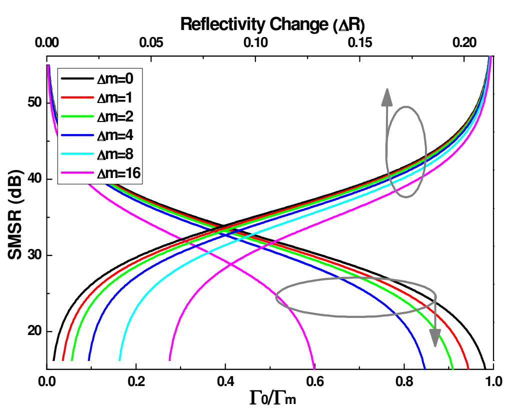


Fig. 4. (a) Theoretically simulated SMSR of the side-mode injection-locked FPLD as function of the reflectivity change ($\Delta$R) and the ratio of loss coefficient ($\Gamma_m/\Gamma_0$).

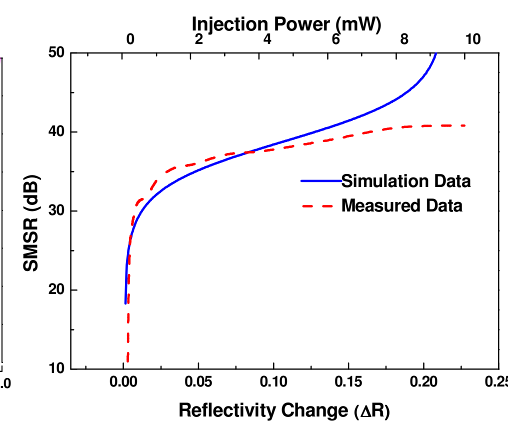


Fig. 4. (b) Comparison on the theoretical and experimental results of the SMSR for one specific FPLD injection-locked mode.

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By setting the output power of the slave FPLD as 0.1 mW under external injection, the cavity length (L) as 250 μm, the refractive index (n) as 3.5, and the photon lifetime ($T_R$) as 5.8 ps, the SMSR of the slave FPLD under external injection-locking is simulated and shown in Fig. 4. The SMSR of the slave FPLD as a function of the reflectivity change can also be obtained as shown in Fig. 4(a). Obviously, the SMSR of the slave FPLD can be up to 50 dB as the loss of the principle mode is far smaller than that of the injection-locked side-mode (i.e., the $\Gamma_m/\Gamma_0$ is infinitely small). To elucidate the injection-locking performance, we further compare the experimentally obtained and theoretical simulated SMSRs for one side-mode of the slave FPLD under external injection, as shown in Fig. 4(b). As illustrated in Fig. 3, we have already shown that the experimentally measured SMSR is well proportional to the externally injection-locking power. Since there is a linear relationship between the effective reflectivity change (ΔR) and the external injection power ($I_{ext}$), a relatively high injection could result in an increasing reflectivity change as well as an enhanced SMSR. We conclude that the experimental results on the obtained ΔR caused by an external injection into the slave FPLD are in good agreement with our simulation.

*3.2 Degradation of linewidth enhancement factor on injection-locked side-mode*

If we consider the Fabry-Perot etalon effect of the slave FPLD, the 3-dB linewidth of the lasing side-mode from the slave FPLD under external injection can thus be described as

$$\Delta\lambda = \frac{\lambda_m^2}{2\pi nL}\frac{\left(1-R_{eff}G_{eff}\right)}{\sqrt{R_{eff}}\sqrt{G_{eff}}}, \quad (6)$$

when the effective reflectivity of the slave FPLD is slightly changed due to the external injection-locking, this may give rise to a change in the longitudinal-mode linewidth of the slave FPLD. That is

$$\Delta\lambda = \frac{\lambda_m^2}{2\pi nL}\frac{\left[1-R'_{eff,m}G_{eff}\right]}{\sqrt{R'_{eff,m}}\sqrt{G_{eff}}} = \frac{\lambda_m^2}{2\pi nL}\frac{\left[1-(R_m+\Delta R)G_1/\left(1+\left(\Delta m/M^2\right)\right)\right]}{\sqrt{(R_m+\Delta R)}\sqrt{G_1/\left(1+\left(\Delta m/M^2\right)\right)}}. \quad (7)$$

Thus, the simulated linewidth of the FPLD can also be plotted as a function of the change in reflectivity for the slave FPLD due to the side-mode injection, as shown in Fig. 5. Therefore, the linewidth reduction and side-mode suppression of the slave FPLD can be understood through the theoretical modeling shown above. The measured 3-dB spectral linewidth for one longitudinal mode of the CW free-running and the directly modulated FPLD are 0.024 and 0.04 nm, respectively. These results correlate well with the theory since that the transient variation in carrier density simultaneously affects the refractive index and the linewidth of the slave FPLD. However, the linewidth of the directly modulated FPLD under external injection-locking are reduced from 0.04 to 0.018 nm, respectively, as shown in Fig. 6.

In particular, the linewidth reduction effect of the injection-locked side modes is significantly degraded with increasing side-mode order (Δm). That is, the side-mode exhibits greatly broadened spectrum as compared to the principle mode of the slave FPLD even under injection-locked condition. In digital communication systems, the product of the bit rate of $B$ and the full-width-at-half-maximum of the propagated data bit of $\Delta T$ must be under 1. If we consider the dispersion effect in fiber, the limitation on the side-mode linewidth of the injection-locked slave FPLD can be derived by using the equation of $B\Delta T<1 \Rightarrow BL|D|\Delta\lambda<1$, where L is the fiber length, D is the dispersion, and $\Delta\lambda$ is the spectral linewidth. Under a mode-linewidth of 0.025 nm, the transmission limitation of the injection-locked FPLD at the data rate of 2.5 Gbit/s can be over 1000 km. Nevertheless, even the side-mode with Δm up to 25, the degraded linewidth can still support the OC192 transmission over 80 km or longer.

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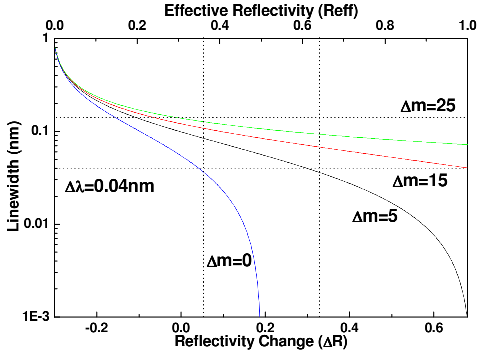


Fig. 5. The simulated linewidth of the injection-locked FPLD as a function of the reflectivity change (ΔR).

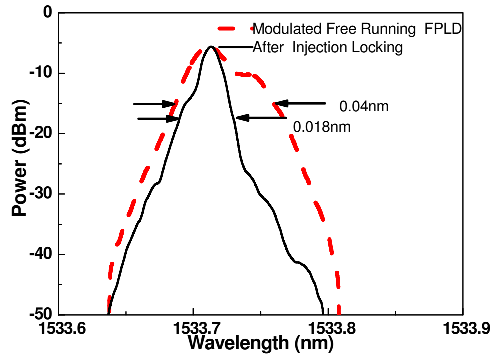


Fig. 6. Spectral linewidths of the injection-locked FPLD in principle mode with (red line), without (blue line) modulation, and a reference laser source (black).

In our case, the obtained linewidth of the side-mode injection-locked FPLD is 0.022 nm, which completely meets the requirement for the middle-short WDM optical access system even though the injection-locked side-mode is far from the principle mode of the FPLD (for example, $\Delta m > 15$).

By adopting the linewidth formula, the injection-locked side mode linewidth of the slave FPLD with side-mode order of Δm can thus be modified as [12]

$$\Delta\lambda = C\lambda^2 R_{sp,m}(1+\alpha^2)/(4\pi P) = \frac{C\lambda^2 R'_{sp,0}(1+\alpha^2)}{(4\pi P)\left(1+\left(\Delta m/M^2\right)\right)}, \tag{8}$$

where Δν denotes the linewidth of the slave FPLD under side-mode injection-locking condition, $R_{sp}$ is the rate of the spontaneous emission coupled into the lasing mode, α is the linewidth enhancement factor, P is the average power, Δm is the order of the side-mode away from the central wavelength, *M* is the total mode number where the gain has fallen to half of its peak value. Note that $R_{sp}$ is much smaller than the total spontaneous emission rate, since only a little part of the spontaneous emission is contributed to the injection-locked side-mode. The $R_{sp}$ can be modified as $R'_{sp,0}/(1+(\Delta m/M^2))$ by using the gain-profile approximation, and the linewidth is enhanced by $1+\alpha^2$ with a decreasing linewidth enhancement factor due to the amplitude-phase coupling. If the side mode with an increasing mode number Δm away from the principle mode is considered in our case, the rate of the spontaneous emission ($R_{sp}$) corresponding to the injection-locked side mode is gradually reduced due to the shift of the material gain profile. That is, the narrowest linewidth should be located at the peak of the material gain profile under injection-locking. By assuming the parameters of the slave FPLD as the optical power of 5 mW, the wavelength of 1550 nm, the spontaneous emission ($R_{sp}$) of $10^8$, the linewidth (Δλ) of 0.04 nm, we obtain the linewidth enhancement factor of 1.5 for the principle mode of the slave FPLD under injection-locking. In contrast, the linewidth enhancement factor for the injection-locked side mode of the slave FPLD in same condition is inevitably increasing up to 2.1.

### *3.3 Data transmission diagnosis of side-mode injection-locked FPLD*

We also evaluate the transmission performance with a BER evaluation method previously demonstrated by Bergano *et al.*, which is approached by measuring the signal-to-noise ratio at the decision circuit of an optical transmission and receiving system.[13] The equivalent mean value and standard deviation of the marks and spaces are determined by fitting this data to Gaussian function, and the measured BER of the optical transmitting eye-diagram can be accurately calculated from the recorded Q factor at a desired data rate. The measured Q factor

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of the slave FPLD with optimized injection-locking condition can be as high as 9.2, providing a reachable BER of $1.8\times10^{-20}$ at the data rate of 2.5 Gbit/s. By increasing the biased 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 to each longitudinal mode. On the other hand, the injection power required to maintain the slave FPLD within the injection-locking range as a function of the biased current, and the corresponding Q factor are also measured and shown in Fig. 7. The calculated Q-factor of the injection-locked slave FPLD based transmitter at different driving currents and injection-locking powers was illustrated. The effective transmission is obtainable within blue-shaped region of an estimated Q > 7 corresponding to a BER of about $10^{-12}$. The red-shaped region represents the practical implementation of such an injection-locked slave FPLD at an injecting power below 2 dBm. That is, the optimized operating parameters for concurrently achieving high-Q and low-injection are determined at the driving current for FPLD between 12 and 17 mA.

Later on, the BER analysis at 2.5 Gbit/s is also performed to characterize the data transmitting performance of a simulated multi-channel DWDM fiber-optic network using the directly NRZ-modulated FPLD under side-mode injection-locking regime. The PRBS data pattern length for modulating the injection-locked FPLD is $2^{31}$-1. Figure 8 shows the measured BER for the channels at $1^{st}$, $9^{th}$, $13^{th}$, $14^{th}$, $15^{th}$, and $21^{th}$ orders, which are corresponding to the mode number (Δm) of -12, -4, 0, 1, 2, and 8, respectively, away from the central mode. The power of the downstream signal injected into the slave FPLD was fixed to -3 dBm by using an optical attenuator, and the biased current of the injection-locked FPLD was fixed at 15 mA. The maximum usable channel of the side-mode injection-locking slave FPLD is 22, covering a wavelength range up to 24 nm. A BER of $<10^{-12}$ is obtained for the nearest 13 side-modes and a BER of $10^{-10}$ can be achieved for all of the 22 injection-locked side-modes. Without any chirping compensation, the data streams exhibit a power penalty of about 1.1 dB at a BER of $10^{-12}$ after 25-km transmission. In particular, there is a measured positive power penalty of 0.7 dB at a BER of $10^{-12}$, which is mostly attributed to the reduction of the relaxation oscillation of the slave FPLD from the competition among longitudinal modes as shown in the inset of Fig. 8. As the transient situation of the carrier density changing from the bit 0 to bit 1, the photon density of the desired longitudinal mode reaches a stable gain by external optical injection, whereas the carrier density continuously depletes and cannot form relaxation oscillation. Consequently, the rising time and falling time (defined as the duration between 20% and 80% of the on-level amplitude) are 118 ps and 125 ps, respectively, and a well-opened eye pattern can be obtained with a relatively large dynamic range as shown in inset of Fig. 8. Both the nearly error-free (BER < $10^{-12}$) back-to-back transmissions with and without optical injection can be detected at the received optical power of larger than -24.4 and -23.7 dBm, respectively. Up to 7 dB power penalty is observed at BER of $10^{-9}$ when changing the injection-locking from principle to the largest side mode, however, the corresponding receiving power level is still beyond the requirement for data communication.

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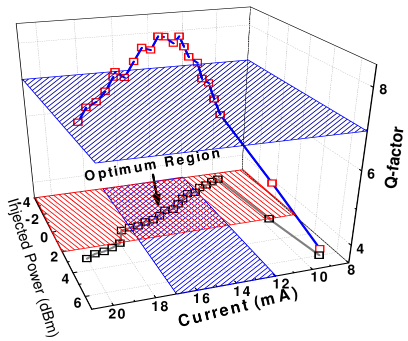


Fig. 7. Measured injected power (hollow markers) and measured Q (solid markers) of the driving current at the principle longitudinal mode.

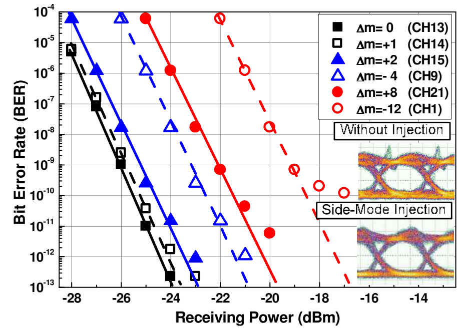


Fig. 8. BER analysis of wavelength injection-locked FPLD at different longitudinal modes and measured eye diagrams (inset) with and without injection

## 5. Conclusion

We theoretically analyzed the effect of the injection-locking power and side-longitudinal-mode order on the linewidth, SMSR, and BER characteristics of a slave FPLD injected by another spectrally sliced master FPLD. The SMSR and 3-dB linewidth of such a FPLD-FPLD link as a function of the injection-locking power dependent reflectivity change are simulated. The back-to-back and 25km-SMF transmission performances of the 2.5-Gbit/s directly modulated FPLD based WDM-PON transmitter under side-mode injection-locking is demonstrated. Such a wavelength injection-locked FPLD shows 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 12$^{th}$ side-mode with respect to the central carrier. Degradation on the linewidth enhancement factor from 1.5 to 2.1 corresponding to the principle- and side-mode injection-locking conditions of the slave FPLD injection-locked are observed. The maximum usable channels of the side-mode injection-locking FPLD are 22, covering a wavelength-locking range up to 24 nm. A BER of $<10^{-12}$ is obtained for the nearest 13 modes and a $10^{-10}$ error rate can be achieved for all of the 22 injection-locked modes, 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 can be a potential candidate of unified WDM-PON transmitter to achieve the cost effective and high-capability 2.5 Gbit/s WDM systems.

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