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Analysis of the regimes of feedback effects in quantum dot laser

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Abstract

We investigated the optical feedback effects on the static and dynamic characteristics of 1.3 μm quantum-dot (QD) Fabry–Pérot laser under reflection from -40 dB up to -8 dB. The onset of coherence collapse is determined as -14 dB from the optical and electrical spectra. Although the degradation in small signal modulation is reported above this critical feedback level, transmission operation with available eye diagram under higher feedback is demonstrated. Under 10 Gb s^{-1} modulation, there is no obvious degradation in eye diagram regarding the eye shape and extinction ratio up to feedback ratio of -8 dB. The higher feedback tolerance of QD laser under large signal modulation is attributed to the impact of gain compression. This high-speed feedback-resistant operation also indicates that QD laser is a promising light source for isolator-free photonic integrated circuits.

Keywords: quantum dot, feedback resistance, silicon photonics

(Some figures may appear in colour only in the online journal)

1. Introduction

The development of laser sources with extremely low-cost is in great demand due to the drastic extension of optical networks [1]. While the improved material quality together with the mature fabrication processes allows for the mass production of semiconductor devices and photonic integrated circuits, its packaging cost remains to be a bottleneck. Moreover, the optical feedback, generated by reflection from the facets of lasers and other optical devices, mainly causes deleterious effects on laser performances, including spectral broadening, mode hopping, and increased intensity noise [2, 3]. Particularly, for the coherent optical communication systems such as Si-based photonic integrated circuits, the lasers are highly susceptible to the external reflection, thus requiring extra isolators to reduce the undesired reflection back into the laser cavity due to the requirements for the stabilization and narrow linewidth. In this regard, optical feedback-tolerant lasers, capable of avoiding the use of isolator, are advantageous for cost reduction as the use of isolator covers a large portion of the overall packaging expense. Several methods, in terms of material properties and device structure optimization, have been proposed in order to improve the feedback tolerance [4–11]. Recently, 12.5% reflection tolerance was achieved by 80 μm long distributed feedback (DFB) laser integrated with 120 μm long passive waveguide [7], and an improved suppression of coherence collapse was predicted in fano laser [8]. However, the complex grating and microscopic structure pose the limit of high cost for the massive production.

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Another type of laser for feedback-resistant operation is quantum-dot (QD) laser. Indeed, GaAs-based InAs QD lasers have been proved as a promising alternative for InP-based quantum well (QW) lasers for the O-band applications in data center [12–14]. Compared with QW gain medium, QD devices offer several fundamental advantages, such as ultra-low threshold and high characteristic temperature T_0, due to its discrete quantum confined energy level. Additionally, in terms of dynamic properties, the gain curve of QD devices is quite symmetric, resulting in a very small phase-amplitude coupling and lower linewidth enhancement factor (LEF) [15–17]. Since a large value of LEF results in detrimental effect related to the optical feedback, the QD lasers with very low LEF are considered as a potential light source for the low-cost isolator-free directly modulated lasers.

The effects caused by external feedback have been extensively examined in previous works [18, 19]. The full range of feedback effects was first carried out by Tkach and Chraplyvy [20], and five distinct regimes were identified with well-defined transition. The sudden broadening in linewidth as the external cavity coupling increases is commonly known as coherence collapse. This catastrophic change in laser brings excess noise during transmission, leading to large bit error rate degradation. Theoretical results based on rate equations and Green's functions, have been calculated for the onset of coherence collapse [21–24] with variations in light output-current characteristics [25], optical and electrical spectrum [15, 26], intensity noise [27, 28], modulation response [29] and transmission systems [30]. However, for the experimental results, the practical critical feedback level for static characteristic, small signal response and large signal modulation is not in good agreement. For example, a 2.5 Gb s^{-1} modulation was demonstrated with QD DFB laser with the signal-to-noise ratio starts to decrease at -30 dB reflected ratio while the critical level for coherence collapse was verified by spectral broadening as only -14 dB [31]. Recently, a 10 Gb s^{-1} 20 km feedback-resistant transmission was demonstrated by 1.3 μm directly modulated QD laser, although from the optical and relative intensity noise (RIN) spectra, the critical feedback level was extracted to be -9 dB [10]. In order to accurately estimate the feedback resistance of QD laser for the data transmission, we need to further distinguish the regimes of feedback effects regarding the critical level for static and dynamic characteristics, even subdivided into performance of small signal response and large signal modulation.

In this paper, the properties of QD laser under intentional external feedback are demonstrated, with a focus on the critical feedback level. The theoretical analysis and performances of laser diodes with the impact of undesired external optical reflection are briefly reviewed in the first place. Then, the feedback impact on the optical spectrum, noise characteristics and transmission performance is experimentally studied for several regimes: first in the low level starts -40 dB, then for -20 dB and finally under coherence collapse. The transition and definition of these feedback regimes are evident, which can be regarded as a convenient way of designing and predicting the operation of the optical communication system. However, the influences on the static and dynamic performance

are not always identical. This work aims at further evaluating the potential impact of optical feedback on different characteristics and systematically determining the simple relationship between the performance of static and dynamic under feedback.

2. Laser measurement and experimental setup

The laser device under study is a QD Fabry–Pérot (FP) laser emitting at 1.3 μm grown on a GaAs (001) substrate by solid-source molecular beam epitaxy system. The active layer contains an eight-fold stack of InAs QDs embedded in InGaAs/GaAs QWs and is p-type modulation doped. The active layer was situated in the center of lower n-type and upper p-type AlGaAs cladding layers. The cavity length of the device is 600 μm with a stripe width of 2.2 μm and asymmetrical coating. A high reflection coating of 90% reflectivity is applied on the rear facet to improve the efficiency, while 30% antireflection coating is placed on the front facet for protection purpose.

As shown in figure 1, the setup consists of a QD laser, a coupling circuit, a feedback circuit and a monitor system. About 90% of the laser output is directed into feedback loop by the optical coupler while the other 10% is used as monitor function. The optical output in the 10% arm is fed into the power meter for monitoring purpose, which are used to estimate the external feedback ratio defined as

$$\Gamma_{\mathrm{dB}} = P_1 - P_0 + C_{\mathrm{dB}}$$

where P_1 is the reflected power, P_0 is the output power from laser, C_{dB} is the coupling loss between laser diode and packaged fiber. Power meter 1 and 2 were used to determine the ratio between the emitted and reflected light.

The feedback loop contains a circulator which directs the output power back into the cavity. The polarization controller is adjusted to guarantee the same polarization between the reflected light and emitted light from laser. Then, a 3 dB coupler is used to split half of the light to a variable optical attenuator (VOA) and then send back to the circulator to direct it back to the cavity. Fibers involved in our test are polished with 100° angle to avoid errors caused by the excess uncontrolled feedback.

Another half of the power is coupled through an isolator to the diagnostic instruments to observe the optical and electrical spectra, modulation and transmission characteristics. The optical isolator is added between the monitor path and detection system in order to block the extraneous feedback. The optical spectrum was simply measured by using the high-resolution optical spectrum analyzer while the noise spectrum was displayed by the microwave analyzer with an electronic spectrum analyzer. Regarding the dynamic properties, the modulation response was detected by p–i–n photodetector, and the frequency response was determined by measuring the S21 scattering parameter.

All the following measurements were performed without temperature control. In the absence of feedback, the laser gives a threshold value of 8 mA and slope efficiency of 0.2 W A^{-1}. The measured light–current (*L–I*) and voltage–current (*V–I*)

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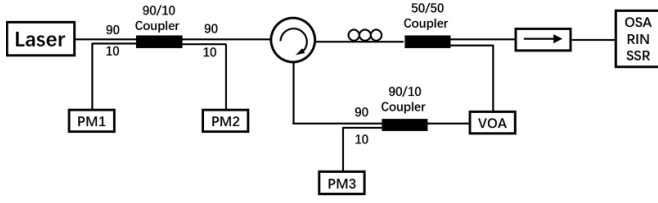
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Figure 1. Experiment setup of the QD laser with optical feedback.
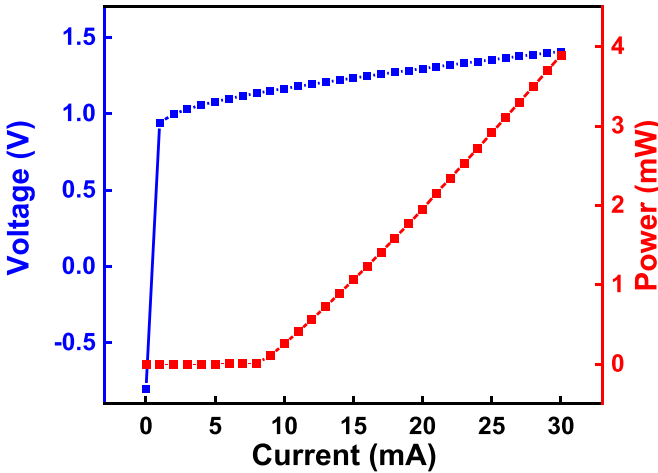
Figure 2. Measured *L–I* and *V–I* measurement of the QD FP laser measured at room temperature.
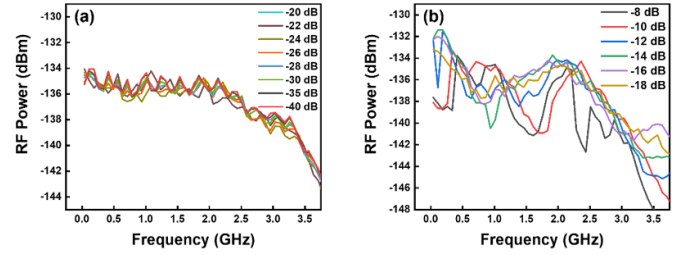

Figure 3. Electrical spectra of the QD laser under different reflected ratio with 100 mA injection current, (a) from −20 to −40 dB, (b) from −8 to −18 dB.

curves are shown in figure 2. The laser yields an output power of 8 mW under 100 mA biased current. Our feedback features are fixed at this injection current. The laser was coupled to the feedback loop by the fiber with about 4 mW power, and the coupling efficiency to the laser mode is thus estimated to be 3 dB. Additionally, the power loss in the loop is 3.5 dB while the variable attenuator can be finely set from 1.5 dB to 35 dB. As a result, the overall feedback ratio is controlled from −8 to −40 dB. The threshold for coherence collapse was determined by the sharp transition in the optical spectra and noise intensity while increasing the feedback ratio.

3. Results and analysis

Theoretical analysis and numerical results have been carried out to identify the important factor in determining the critical level for coherence collapse in lasers [21, 26, 32]. The most commonly used simple expression for the threshold of coherence collapse in laser is concluded by Helms and Petermann [21]. This expression correlates the behavior of laser under feedback to the LEF α, the relaxation oscillation damping rate Γ and cavity features including cavity length and facet reflectivity

$$f_{\mathrm{crit}} = \frac{\Gamma^2 \tau^2 \left(1 + a^2\right)}{16 |C_e|^2 \alpha^4}$$

where τ is the internal round-trip time and C_e is a coupling coefficient given as $|C_e| = \frac{1-R}{2\sqrt{R}}$.

Examining this formula, we can arrive at the idea that devices give better feedback tolerance with longer cavity length, high facet reflectivity, large damping factor and low LEF.

Figures 3(a) and (b) show noise spectra of the QD laser with feedback above and below coherence collapse threshold, respectively. In the curve of weak optical feedback ratio up to −20 dB, the microwave spectrum below 3 GHz is simple broadband noise and remains around −135 dBm. On the other hand, for the curve with higher reflected power, the sharp increases and fluctuations over 10 dB between −130 and −140 dBm are observed with groups of large spikes. Thus, these operating points could be classed as unstable. A typical value of $f_{\mathrm{crit}} = -14$ dB was found.

A more precise determination of critical feedback level is verified by the optical spectra. The reflection induces a change in longitudinal mode, corresponding to the effects of partition noise and dynamic mode chirp. Optical spectra of the QD FP laser with varying reflection ratio are displayed in figure 4. At room temperature, the FP laser provides multimode emission with the peak wavelength around 1303 nm at the biased current of 100 mA. In figure 4(a), at the low feedback levels region, the envelope of the laser spectrum is observed to be stable, while the envelope of the optical spectra is nearly superposed. The apparent destabilization starts to appear at feedback level of −18 dB and to increase dramatically from −14 dB, as shown in figure 4(b). The highest mode was found to be 1 dB higher than the nearest neighboring mode, and the fluctuation reaches 3 dB under −8 dB feedback ratio. Further details are depicted in the high-resolution spectra of the central mode. For a power reflection below −20 dB (figure 4(c)), the mode intensity distribution gives a moderate shift of 0.02 nm/10 dB with no sign of obvious spectral broadening. As the reflection becomes severe, the continuous red-shift is interrupted and down shifted when the reflected ratio increases from −25 to −20 dB, in figure 4(d). Then, the red-shift tendency recovers with the same rate. Additionally, the chaos in spectrum arises and the linewidth is broadened. The quantitative estimation is not provided in our description due to the resolution limit of the optical spectrum analyzer (OSA).

From the results of the optical and RF spectra, the critical feedback level of this QD laser is estimated to be −14 dB. To further verify the dynamic performance under external feedback, the small signal response of QD lasers was measured. Figure 5 shows the measured amplitude of the
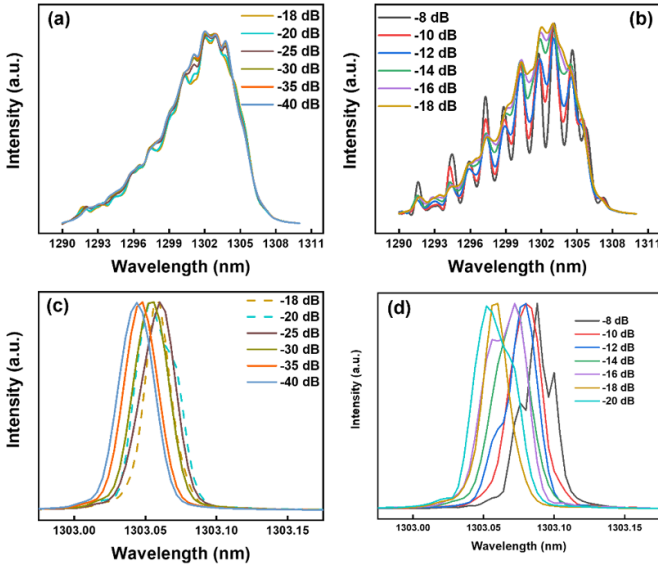
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Figure 4. Figures (a) and (b) are envelope of the optical spectra of laser under different feedback levels and (c) and (d) are high resolution spectra of the central mode.
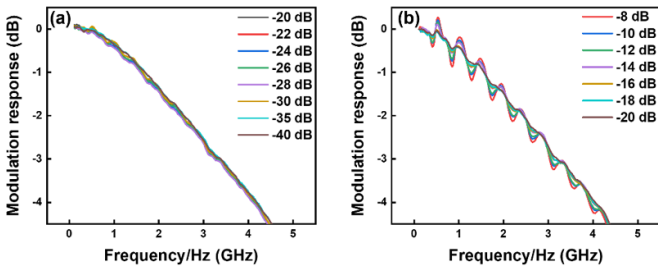

Figure 5. Small signal response of QD laser under 100 mA injection current with (a) lower feedback level and (b) higher feedback level.

transfer function. For the feedback ratios lower than −20 dB, the small signal response remains stable with a 3 dB bandwidth around 3.5 GHz, as shown in figure 5(a). In contrast, for the external feedback higher than −14 dB, large variations in $|S_{12}|$ of more than 0.3 dB occur (figure 5(b)). Although the impact of the reflection starts at around −18 dB feedback level and critical feedback level is verified to be −14 dB, such fluctuation does not necessarily mean coherence collapse in large signal modulation and transmission.

In order to further examine the feedback resistance in large signal transmission, the laser is modulated by non-return-to-zero format, and the loss of the fiber connection and systems is calibrated and compensated. Eye diagrams under 10 Gb s^{-1} modulation back-to-back transmission are shown in figures 6(a)–(d) for feedback levels of −8 dB, −14 dB, and −30 dB and without feedback, respectively. Regardless of the feedback level, no chaotic oscillation is observed on the eye diagram that remains clear with extinction ratio more than 4 dB.

Above the critical feedback level of −14 dB verified by the static performance, it is known for QD lasers that the large signal data transmission is theoretically impossible, but from
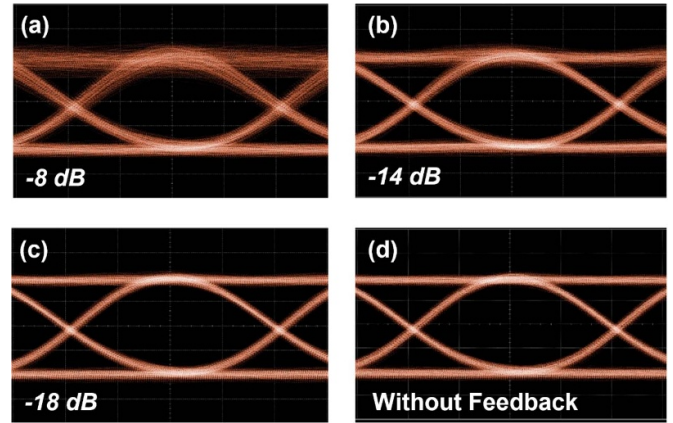

Figure 6. 10 Gb s^{-1} modulation eye diagram of 600 μm length laser under 100 mA injection current with different feedback levels.

the eye diagram in figure 6, the transmission performances slightly degrade with only the upper level of the eye diagram broadened when the feedback reaches −14 dB. The broadening of level one signal becomes worse as the reflected power gets stronger, but the whole eye diagram still remains quite stable. This discrepancy is due to the more complex mechanisms in the large signal modulation and the inherently underestimated digital modulation capability due to the large gain compression of QD structure [33].

For the 802.3ae 10 Gb s^{-1} Ethernet standard, the required feedback tolerance is up to −12 dB. Although the critical level of −14 dB is confirmed by the static and dynamic characteristics, based on the clear eye diagram of the QD laser under −8 dB together with the coupling losses, the QD FP laser should still be able to tolerance network feedback without an isolator.

Transmission performance with higher modulation rate is expected for QD laser with shorter cavity length. However, it is predicted that a short cavity causes greater cavity loss and sensitivity to feedback. This tradeoff is needed to be considered to design a higher speed operation laser with stronger feedback tolerance. It is also mentioned that the variation could be reduced by increasing the intensity modulation index.

4. Conclusion

In this paper, we have evaluated the effect of unintentional optical feedback on the static performance, small signal modulation and high-speed digital optical communication system with the 600 μm length QD FP laser. It is found that above −14 dB reflection, the chaotic behavior, which could be regarded as the onset of coherence collapse regime, is clearly observed in the optical/electrical spectra and small signal modulation. The feedback resistance is further examined in detail in the transmission system. Eye diagram under 10 Gb s^{-1} modulation back-to-back transmission remains clear with feedback power higher than the critical level of −14 dB. This discrepancy is mainly due to the large gain compression in QD laser. Based on the transmission result, this QD

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laser offers strong tolerance to the standard network feedback without an isolator.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

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