Sole Excited-State InAs Quantum Dot Laser on Silicon with Strong Feedback Resistance

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Abstract: We demonstrated first sole excited-state lasing InAs QD lasers on Si with 28 dB higher optical feedback resistance over both FP and DFB QW lasers, which propose QD DFB laser with potentially fully feedback tolerance.

1. Introduction

Photonic integrated circuit (PIC) on silicon is one of the most promising platforms for high density photonic integration. Over the past decade, many methodologies have been implemented to integrate III-V materials onto silicon substrate, which take advantages of III-V materials as active devices, such as lasers and photodetectors. But a major challenge impeding the heterogeneous integration is the external optical feedback (EOF) induced between laser and other photonic components or fiber connectors, which can lead the laser operating in a chaotic state. Within optical modules, optical isolators are normally utilized to suppress the side effect of EOF, while increase the overall cost and chip sizes. As a result, lasers with lower sensitivity to EOF would be desirable for high density integration of PICs.

It was proved that the ground state (GS) InAs/GaAs quantum dot (QD) lasers can stably operate up to optical feedback of -7.4 dB [1]. It is normally difficult to maintain sole GS in QD lasers at high injection current for higher output power, the stability of QD lasers is greatly affected by the mode competition between GS and excited state (ES) even when the GS still dominates. Especially at higher output power, the QD laser intend to operate in dual state. Therefore, ES QD lasers become an optimal choice for EOF insensitive optical source with high output power. The ES QD laser remains highly stable operation at high injection current, while exhibiting strong feedback insensitivity than dual state operation [2]. This paper investigates the feedback sensitivity of a InAs/GaAs QD laser epitaxially grown on Si (001) operating in sole excited state.

In this paper, the feedback sensitivities of QW and QD FP lasers are firstly compared. The critical feedback level of InAs QD FP laser on Si is -7.8 dB, which is significantly higher than the -36 dB of the QW FP laser. The great advance of feedback insensitive QD laser shows the significant potential of integrating on-chip lasers with silicon photonic components with absence of optical isolators. Furthermore, in the case of QW lasers, the critical feedback level increases by 22 dB as the laser structure switches from FP cavity to DFB structure, which is attributed to reflected light protection mechanism of DFB gratings. Therefore, we believe that InAs QD DFB laser could potentially exhibit fully feedback insensitivity against backreflection.

There have been analyses of feedback sensitivities of laser systems, our observations on QD lasers and lasers with different structures subjected to a well-designed experimental circuit give an accurate measurement of the feedback sensitivities and well supported by comprehensive characterizations. We feel the quantitative comparison are particularly significant for particular optical system integrations.

2. Results and Discussion

2.1 Optical spectral analysis
The evolution of optical spectral linewidth of sole excited-state QD laser on Si is achieved as shown in Figure 1. In Figure 1 (A), significant laser linewidth broadening of InAs QD laser on Si occurs at EOF of -7.8 dB, which leads to a clear coherence collapse. Besides, the isolated linewidths under EOF both below and above the critical feedback level are investigated to further confirm the evolution of optical spectra. Figure 1 (D) gives a clear demonstration of change of linewidth under different EOF. This broadening represents the start of chaotic state in QD laser shown in Figure 1 (A).

For comparison, both commercial QW FP laser and DFB laser are characterized here for optical spectral analysis. The optical spectral mapping of QW FP laser in Figure 1 (B) shows continuous broadening under EOF above -36 dB, which is confirmed by evolution of linewidth in Figure 1 (E). Simultaneously, we have measured the optical spectral evolution of QW DFB laser as shown in Figure 1 (C) and (F). In Figure 1 (C), optical spectrum shows coherence collapse at EOF of -14 dB, which is confirmed by the demonstration of linewidth evolution in Figure 1 (F). This result indicates that QW DFB laser exhibit stronger resistance against feedback with increased critical feedback level of 22 dB over FP structure with identical QW structures. The observed relatively high critical feedback level of QW DBF laser is benefitting from reduced feedback strength inside the laser cavity due to the DFB gratings. The overall optical spectral evolution analysis among all three types of lasers shows sole ES QD laser exhibits superior performance over QW laser with improved critical feedback level of 28.2 dB in identical FP structure.

2.2 Relative intensity noise (RIN) measurements

We have also performed relative intensity noise (RIN) measurements [3] for three different laser structures.
Usually, coherence collapse is defined as a collective phenomenon of broadening of laser spectrum with significant increased, such as abrupt increase of RIN. Here in this work, we analyze the RIN spectra with different EOF below and above the critical feedback level to understand the dynamics of semiconductor lasers with feedback.

In Figure 2(A), the QD laser shows relatively flat RIN spectra until -15 dB EOF, where the quasiperiodic RO frequency peaks arise, which however has no influence on coherent operation of the laser as the optical linewidth remains the same. By further increase EOF level towards -7.5 dB, a broad electrical signal noise peak appears, which represents the coherence collapse of QD laser. This behavior claims that the electrical noise peaks over the frequency range above 3 GHz represents the dominant noise frequency that influencing the optical feedback sensitivity.

For QW FP laser, even under weak EOF of -37 dB, multiple frequency noise peaks are already existing in the RIN diagram in Figure 2(B). The periodic peaks could be the high order harmonics of the fundamental RO frequency, which are caused by the intracavity resonance, and thus the coherence collapse follows in RIN diagram. With increasing EOF levels, the noise level continuously grows, which leads to significant optical spectral broadening.

The initial peak of RIN shows up at EOF of -13.7 dB, followed by broadening in QW DFB laser, which is shown in Figure 2(C).

From the above analysis, the QD laser and QW laser clearly undergo different routes into chaotic state. QD laser shows quasiperiodic oscillation of RO frequency to coherence collapse in the range of EOF from -15 dB to -7.5 dB. In comparison, QW laser goes through a high order harmonics of RO process before moving into chaotic states. Different chaotic route in QD lasers come from the unique quantum dots structure with higher confinement and thus reduced high order harmonics behavior in FP structure. The discrete energy state of QD lasers caused lower enhancement factor and higher damping factor are also the well accepted explanation for the higher feedback insensitivity of QD lasers than QW lasers. Lower enhancement factor suppresses the noise caused by EOF which otherwise can be amplified in the gain medium towards a chaotic operation.

The superior performance of DFB structure lies in the distributed feedback grating structure which can reduce the EOF strength entering the resonant cavity from the external circuits, while FP laser will be strongly affected by the entered optical feedback. The suppression of high order of harmonics in DFB which reduces the multimode competition in lasers is also a main mechanism for higher feedback resistance.

The results in this paper analyzed the critical EOF level in different materials and structures. The high feedback insensitivity of ES QD laser and the feedback noise suppression capability in DFB structure are confirmed. We believe these results bring a possibility to fabricate better EOF insensitive QD DFB laser, which can potentially achieve stable coherent operation with fully insensitivity against EOF for future photonic integrations.

3. Conclusion

To summarize, we have investigated the feedback sensitivity of ES InAs/GaAs QD laser on silicon in comparison with commercial QW lasers. The analyzed optical spectral mapping and RIN spectra confirm the superior performance of sole ES InAs QD laser on silicon over QW lasers, benefitting from the absence of mode competition. The measured maximum optical feedback tolerance is -7.8 dB for sole ES InAs QD laser on silicon, which is almost 28 dB higher than QW laser. In addition, the relatively better feedback insensitivity of QW DFB lasers suggests that DFB structure utilizing QD material is potentially resistant of 100% feedback, which could be promising for future on-chip photonic integration, where there are no on-chip optical isolators.

Reference
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