Numerical Study of the Single Mode Stability of Quantum Well and Quantum Dot DFB Laser Diodes Under External Optical Feedback

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***Abstract*—We numerically analysed the single mode stability of of multi quantum well and quantum dot DFB laser diodes in the presence of external optical feedback. Laser diodes which operate in a stable single mode in the absence of feedback were found to sometimes become multimode for external feedback levels below −30 dB. This is even the case for lasers with zero linewidth enhancement factor, even though such lasers are sometimes touted as feedback insensitive. The behavior depends strongly on the phase of the external reflection, as well as on the specific DFB laser structure.**

***Index Terms*—DFB laser diode, single mode stability, feedback sensitivity, quantum dot, quantum well.**

I. Introduction

SEMICONDUCTOR lasers have since long been known to be very sensitive to external optical feedback [1], [2] and in the past such optical feedback was usually suppressed by inserting an optical isolator in front of the semiconductor laser. Until now it has however turned out impossible to integrate optical isolators on the same chip as a laser diode, although there were several attempts (see e.g., [3], [4]), making the use of the isolator relatively costly.

In recent years there has been quite some attention for semiconductor lasers that would not require any isolator in front of them for a stable operation. This recent work relies on the article by Helms and Petermann [5], in which it is shown that the so-called coherence collapse of a semiconductor laser occurs for a feedback level that is inversely proportional to the fourth power of the linewidth enhancement factor α (or rather the effective linewidth enhancement factor α_{eff}). By using quantum dot active (QD) layers with low variation in the dot size and thus very small α [6], or alternatively, by using Distributed Feedback (DFB) or Distributed Bragg Reflector (DBR) laser structures with close to zero α_{eff} [7], one can realize laser diodes that don't exhibit coherence collapse, i.e., no dramatic increase in intensity noise and linewidth from a certain feedback level on.

However, avoiding this coherence collapse (and the dramatic increase in intensity and phase noise) is not the only thing that matters, not even when the laser diodes are meant as intensity modulated transmitters in short distance optical links with direct detection. For many applications such as optical communications and LIght Detection And Ranging (LIDAR), one should also have the guarantee that the lasers remain in a stable single mode regime. For laser diodes for coherent communications, also modest increases of linewidth are undesired. Even if no coherence collapse occurs, the laser linewidth might still increase by an order of magnitude due to external reflections if the feedback has the wrong phase.

Most, if not all theoretical derivations and modelling regarding the effect of external feedback on laser diodes are based on single mode rate equations. Very little is reported on how external feedback can affect the single mode operation of, e.g., DFB lasers. These laser types have been studied extensively since the early 1970's and it has been understood since then that their single mode behavior and gain margin are very sensitive to even small changes in amplitude and phase of the facet reflection [8], [9]. It is also clear that an external distant reflection can modify the amplitude and phase of the effective facet reflection and in a different manner for 2 different DFB modes.

We have found from numerical modelling that external feedback can indeed make a DFB laser multimode, even when the solitary laser has a stable single mode behavior and even when $\alpha = 0$ is assumed. The side mode that starts lasing is in this case not an external cavity mode, but another DFB mode. It is thus not so that quantum dot lasers, especially DFB lasers, can operate without isolator under any circumstance and for any application. When we used a value of 3 for α, as might be the case in multiple quantum well (MQW) lasers, there was an onset of coherence collapse at feedback levels lower than those giving the side mode onset for $\alpha = 0$.

Below we describe various simulation results on DFB lasers with both zero α-factor (as for QD lasers) and an α of 3 (as for, e.g., MQW lasers). The DFB lasers have a very good side mode suppression ratio (SMSR) without external feedback. We compare phase-shifted DFB lasers with zero facet reflection and DFB lasers with uniform grating with one HR-coated and a one AR-coated facet, and with the AR-coated facet facing the external reflection. Whether an isolated single mode DFB laser with $\alpha = 0$ becomes bimodal due to external reflections depends very much on the phase of that external reflection. By controlling that phase, e.g., with a phase shifter in front of the laser and a feedback loop, it should be possible to keep the laser single mode, provided that $\alpha = 0$.

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TABLE I
OVERVIEW OF THE LASER AND EXTERNAL CAVITY PARAMETERS USED IN THE SIMULATIONS

Parameter	Value [unit]
Width and thickness of active region	2.5 × 0.2 [μm^2]
Grating period	220 [nm]
Confinement factor	0.3
Internal loss	30 [cm^{-1}]
Differential gain	3 × 10^{-16} [cm^2]
Transparency carrier density	1.5 × 10^{18} [cm^{-3}]
Gain suppression	10^{-17} [cm^3]
Bimolecular recombination	10^{-10} [cm^{3}s^{-1}]
Auger recombination	1.3 × 10^{-29} [cm^{6}s^{-1}]
External cavity length	1 [cm]
Effective (and group) index external cavity	1.5
Inversion factor	2

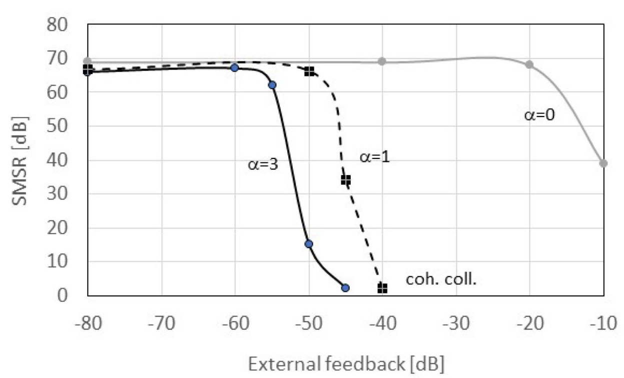

Fig. 1. SMSR vs. external feedback level for an AR-coated, λ/4-shifted DFB laser with $\alpha = 0$, $\alpha = 1$ and $\alpha = 3$.

II. Numerical Analysis

We simulated several DFB lasers with various levels of external feedback using the commercial software package VPI [10]. An overview of the main laser parameters used in the simulations is given in Table I. The gain and refractive index were assumed as independent of wavelength. The spontaneous emission (in W/s/cm/Hz) is modelled as the modal gain times the inversion factor times the photon energy hν.

We first considered a λ/4-shifted DFB laser with perfectly AR-coated facets (power facet reflectivities $R_1 = R_2 = 0$). The laser is 350 μm long and has a coupling coefficient of 30 cm^{-1}. The laser is biased at 150 mA and gives an output power of 15 mW.

Fig. 1 shows the side mode suppression ratio (SMSR) vs. feedback strength for this laser, for $\alpha = 0$, $\alpha = 1$ and $\alpha = 3$. For $\alpha = 0$, the λ/4-shifted DFB laser remains single mode with high SMSR up to feedback levels as high as – 10 dB, irrespective of the phase of the external reflection and there is no sign of coherence collapse. For $\alpha = 3$ on the other hand, coherence collapse (characterized by a wide optical spectrum, with a width of several GHz or tens of GHz) is appearing already at feedback levels of -50 dB. The feedback level at which the coherence collapse occurs increases with decreasing value of α and is already 10 dB higher for $\alpha = 1$ as compared to $\alpha = 3$. The feedback level at which the transition to coherence collapse occurs depends also on the gain suppression coefficient (in general the damping of the relaxation oscillation resonance, as is well known and, e.g., is described in [5]). E.g. raising the gain suppression to 3×10^{-17} cm^3 raises the feedback level where the transition to coherence collapse starts by 20 dB. We furthermore noted that the SMSR for $\alpha = 0$ and feedback levels of -10 dB or more depended on the feedback phase. The SMSR values given in Fig. 1 are the lowest for these feedback levels.

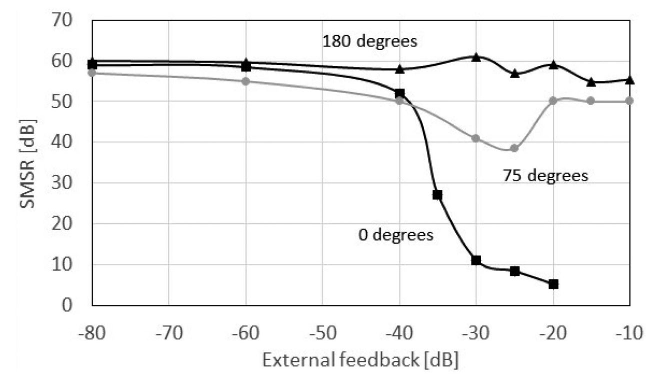

Fig. 2. SMSR vs. external feedback level for a DFB laser with one HR-coated facet and one AR-coated facet and with $\alpha = 0$, for 3 different reflection phases.

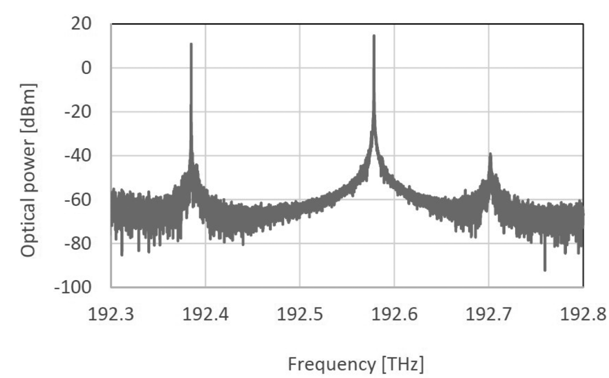

Fig. 3. Optical spectrum of the DFB laser with one HR-coated facet and one AR-coated facet and $\alpha = 0$, for an external reflection of -30 dB and phase of 0 degrees, after the side mode onset.

Next we consider a non-phase shifted DFB laser with same length and coupling coefficient and one 90% reflecting facet and one 5% reflecting facet. Facet reflection phases are $\phi_l = \pi$ and $\phi_r = 0.875\pi$.This laser is also biased at 150 mA and we now consider the cases $\alpha = 3$ and $\alpha = 0$. Fig. 2 shows the SMSR vs. external feedback level for the case α=0 and for three different phases of the reflector at a distance of 1 cm, namely 0, 75 and 180 degrees. It is stressed that the external reflector phases mentioned in this article are the phases at 1 cm from the laser. It is clear that the laser doesn't always remain single mode and that this depends on the phase of the reflection. Notice though there is never a coherence collapse, just a transition to bimodal operation for certain reflection phases. A typical optical spectrum after the onset of a side mode is shown in Fig. 3. The

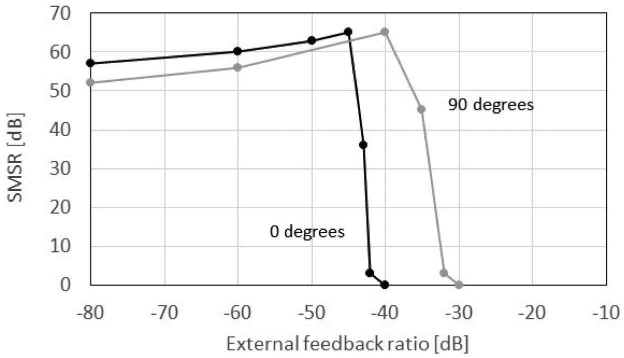

Fig. 4. SMSR vs. external feedback ratio for a DFB laser with one HR-coated facet and one AR-coated facet and with $\alpha = 3$, for the reflection phases of 0 and 90 degrees.

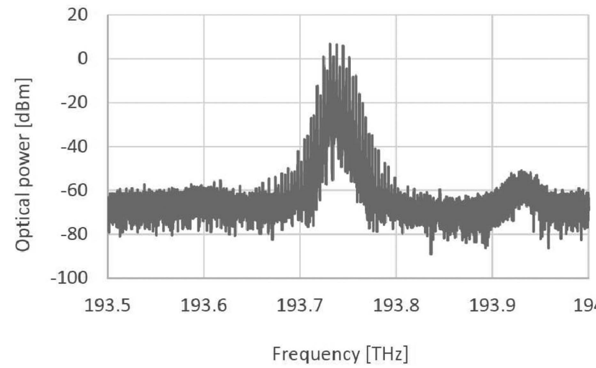

Fig. 5. Spectrum after coherence collapse of the HR-AR coated DFB laser with $\alpha = 3$.

SMSR was furthermore found to depend on the gain suppression coefficient ε.

Thus, even a QD DFB laser with $\alpha = 0$ will not necessarily remain in a stable single mode regime under external reflections with certain phase. It is well known that the single mode operation of an HR-AR coated DFB laser depends on the phase of both the facet reflections. A weak external reflection might change this phase in such a way as to render an originally single mode laser bimodal. For the phase of 0 degrees in Fig. 3, the onset of the side mode occurs already at a feedback level below −30 dB. It is easily calculated that, for an external reflector of 0 degrees, the phase of the external feedback at the laser facet is 1.7π for the main mode an 0.7π for the side mode. This implies that the external feedback adds up to the reflection of the AR-coated facet, out of phase for the main mode and in phase for the side mode. Thus for an external feedback level of −30 dB, the main mode will see an effective facet reflection of only 3.7% while the side mode will see an effective facet reflection of 6.5%. Although the behaviour of DFB laser diodes with partially reflecting facets is quite complicated and depends on the interference between Bragg reflections and facet reflections, the increased effective facet reflection of the side mode and the reduced effective facet reflection of the main mode may explain the onset of the side mode.

This single mode stability problem can be solved with an isolator in front of the laser. It could however also be solved by controlling the phase of the external reflection, using a phase tunable waveguide in front of the laser. Also here it is remarked that the specific dependence of side mode rejection vs. feedback level depends on the gain suppression coefficient.

For $\alpha = 3$, the behavior is very different. For all reflection phases, there is an onset of coherence collapse, characterized by a broad optical spectrum or a spectrum consisting of multiple lines corresponding with the external cavity modes. Fig. 4 shows the resulting SMSR vs. feedback ratio for reflection phases 0 and 90 degrees. Coherence collapse occurs at feedback levels of around −42 dB and −32 dB for reflection phases of 0 and 90 degrees respectively. Fig. 5 shows a typical spectrum after coherence collapse.

For the case $\alpha = 0$, we investigated the influence of the external cavity length. We found that the onset of a side mode due to external feedback only occurs for sufficiently short external cavities. E.g. we found it also for an external cavity length of 5 mm, but not for an external cavity length of 15mm or more. For longer external cavities (assuming unchanged reflection), there are external cavity resonances close to the original lasing modes for which the external reflection already adds up in phase and which will act as lasing mode. There is then no possibility that the side mode has higher roundtrip gain than the external cavity mode close to the original main mode. For shorter external cavities, such external cavity resonances may not exist [11].

III. Conclusion

We have shown that external reflections can cause a DFB laser to become multimode even if the solitary laser exhibits a stable single mode behavior. This is also the case for QD DFB lasers with zero linewidth enhancement factor. Although such lasers don’t show coherence collapse, care still has to be taken to make sure they remain single mode. The multimodal behavior is also not due to the onset of external cavity modes, but due to the onset of a side mode of the solitary laser (e.g., at one or more nm from the main mode).

The reason is that DFB lasers are very sensitive to the amplitude and phase of the facet reflections. In DFB lasers with one HR-coated facet and one AR-coated facet (reflecting one to several percent, e.g.,), the single mode operation is particularly dependent on the amplitude and phase of the reflection of the AR-coated facet. External feedback can change this reflection amplitude and phase differently for a main and a side mode and in this way alter the single mode stability.

Important to note is that for any external feedback level, there is usually a range of feedback phases for which the DFB laser remains single mode. Inserting an extra phase tunable section in front of the laser might therefore alleviate such problems. For lasers with $\alpha = 0$ the phase of this tunable section could be controlled by feedback loop minimizing the voltage between the contacts of the DFB laser.

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