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Temperature tolerance of a hybrid III-V/Si distributed feedback semiconductor laser with a large quality factor

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ABSTRACT

The sensitivity of a hybrid distributed feedback semiconductor (DFB) laser heterogeneously integrated onto silicon (Si) is extensively characterized in the presence of external optical feedback at different bias and temperature conditions. The unique modal engineering approach of the device allows the light generated in the III-V material to be stored in the low-loss Si region to significantly enhance the quality (Q) factor of the cavity resonator. This design leads to an increased temperature tolerance of the laser without impacting the transmission efficiency even under the most severe feedback conditions. At a temperature of T = 35°C, the laser continuous to unveil optimal performance and exhibits feedback insensitivity when externally modulated at 10 Gbps transmission over a 10 km fiber coil. The study presented here demonstrates the ability of a high-Q laser to achieve floor-free transmission at different operating conditions with a power penalty degradation no greater than 1.5 dB. The prolonged transition to the coherence collapse regime at a much higher reflection level evidenced by this device when compared to its III-V counterparts in addition to its ability to withstand perturbations associated with temperature variations and unintentional back-reflections delivers a step forward towards isolator-free applications. This work suggest that this type of semiconductor lasers can serve as a promising solution for the development of compact and reliable photonic integrated circuits (PICs).

Keywords: Distributed feedback semiconductor, optical feedback, high-Q, high-speed transmission, coherence collapse

1. INTRODUCTION

The fast-paced development of efficient PIC[1] is vital to effectively meet the rapidly increasing bandwidth demand at the data centres and keep-up with the craved hyperconnectivity levels imposed by the inevitable digital transformation. PICs gather all the desirable functionalities of photonic systems, except for optical isolation; therefore, addressing undesired short-cavity reflections remain a critical challenge.[2] These devices continue to draw a great amount of attention from various fields mainly from the telecommunication industry due to the unique features PICs provide to a wide range of applications such as high rate production at a lower cost, size reduction, enhanced performance and increased power efficiency among many others.[3] This field continues to exponentially grow and has evolved in the desired direction exhibiting added benefits to the datacom industry. Recently, it has been demonstrated that the low linewidth enhancement factor in quantum dot lasers greatly enhances the sensitivity to optical feedback.[4] Other accomplishments include semiconductor lasers with an intracavity optical isolator,[5] photonics crystal Fano nanolasers,[6] and parity-time symmetry DFB lasers among many others.[7]

However, despite the progress demonstrated up-to-date, a light source with absolute feedback insensitivity has yet to be reported particularly down to the system level. In this work, we shed insight on a recent demonstration exhibiting a quasi complete reflection insensitivity based on a hybrid III-V on silicon DFB laser with a large

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quality factor (i.e., the so-called Q factor of the cavity). Prior studies on linewidth and phase noise measurements in such a novel hybrid device,[8] have revealed its remarkable robustness against coherent and incoherent feedback. In this paper, we consider a low-noise hybrid laser[9] which is based on the same design concept. The work herein discusses the dynamics and optimized performance of an externally modulated high coherence hybrid DFB laser heterogeneously integrated onto silicon when subject to a variation of external optical feedback at increased temperature values. It aims at analyzing the enhanced feedback insensitivity and temperature tolerance demonstrated by the high-Q device. The ability of this novel device to preserve floor-free transmission at 10 Gbps under optical feedback and at different operating conditions brings encouraging findings and insights towards the understanding of efficient semiconductor lasers as a vital component of integrated photonics technologies.

2. DESCRIPTION OF THE LASER DEVICE

2.1 Structure and Design

Fig. 1(a) displays the cross section of the high-Q laser structure, bonding a silicon photonic layer onto a quantum well (QW) gain material. The geometry is optimized in such a way that the mode is buried into a rib silicon waveguide with a shallow grating of 30 nm deep teeth. The width of the grating is tapered longitudinally to create an effective confining potential which allows a single, bell-shaped longitudinal mode within the stop band of the DFB.[8] It has been demonstrated that this mode has a large Q factor leading to a cavity photon lifetime of $\sim$ 100 ps. In order to harness the low internal loss of the silicon resonator, the loss contributed by the active material has to be mitigated by decreasing the overlap between the optical field and the gain material. The modal gain is decreased as well, but it remains large enough to compensate for losses. The choice of a large silicon (Si) waveguide with width of 2 μm leads to the desired overlap of about 5%. Typically, the Q can reach up to 4×10^5 when the silicon width is increased to 2 microns, which results in a substantial reduction of the threshold current.[10] The mirror losses, more precisely the coupling rate of the cavity to the output is adjusted to ensure mild overcoupling, hence improving differential efficiency without increasing the threshold. The DFB laser is made by different sections. The first section corresponds to the parabolic tapered grating with length L_c and the two other are related to uniform sections at each side with length L_b. The total cavity length $L = 2L_b + L_c$ is fixed to 900 μm.

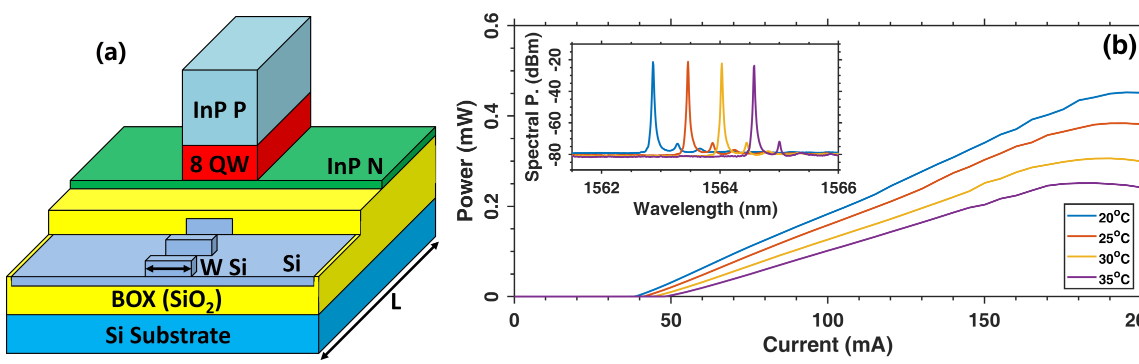

Figure 1. (a) Schematic of the high-Q DFB laser structure; (b) L-I curves of high-Q DFB laser at T = 20°C, 25°C, 30°C, and 35°C; the inset depicts the optical spectra under $3{\times}I_{th}$ at each temperature.

Fig. 1(b) depicts the light-current (L-I) characteristics of the free-running device. These measurements were performed at different temperatures, 20°C, 25°C, 30°C and 35°C. We can clearly see that the thermal variations on the high-Q laser causes not only a shift on the threshold current I_{th} values, which are found at 38, 41, 44 and 47 mA respectively, but also a reduced output power, which is halved at 35°C (0.2 mW) compared to 20°C at 200 mA (0.45 mW). Let us point out that, at 20°C, the flattening of L-I curve at maximal pump current is induced by the accumulating heat, and subsequently, the roll-over is advanced by the increase in operating temperature.

The optical spectrum is captured at $3\times I_{th}$ for all four temperatures and is accordingly shown in the inset of fig. 1(b). At 20°C, the blue spectrum confirms the single mode behavior along with a side-mode suppression ratio (SMSR) $>$ 50 dB and a dominant emission wavelength of 1562.6 nm. In this fabrication, the Q factor is maximized by increasing the device length hence allowing a stronger grating coupling coefficient at the center of the cavity ($\approx$ 200 cm^{-1}) and a large cavity photon lifetime of about 100 ps. On the other hand, while the thermal condition is degraded, although the SMSR is preserved above 50 dB, the dominant emission wavelength shifts concurrently: λ = 1562.6, 1563.5, 1564.2 and 1564.6 nm respectively. Temperature variations affect the bandgap of the semiconductor laser junction and therefore, the peak wavelength of the gain profile. However, for this particular device, thermal variations do not impact the bit error rate (BER) and floor-free transmission is still achievable as demonstrated in Section 3.

2.2 Test-bed

Fig. 2 represents the experimental setup used to investigate the effects of optical feedback under both static and dynamic configurations. The emission from the laser diode (LD) is coupled by a lens-end fiber with anti-reflection (AR) coating. A 90/10 splitter is used to send 90% of the coupled light to the back reflector (BKR) in order to control the feedback amount. On this stage, the feedback ranges approximately from 0 to 3.3% of the emitting power, i.e. the maximal attainable amount of feedback is -14 dB. Here, the feedback strength r_{ext}, defined as the ratio between the reflected power and the free-space emitting power at the front facet of the device, is normalized to the maximal level, hence ranging from 0 to 100%. The 7-meter long external cavity length implies a long-delay feedback scenario, meaning that the effects associated with the phase of the back-reflected field can be neglected. The remaining 10% is split again in a 90/10 manner, where 10% of this coupled light is used for spectral monitoring to insure that no irregularity occurs and the remaining 90% is modulated by a Mach-Zehnder modulator (MZM). A pseudo-random bit sequence (PRBS) of 31 bits BER transmission stress pattern is used with 2 Vpp amplitude to estimate the BER output at 10 Gbps. The modulated signal is then transmitted over a 10 km single mode fiber (SMF) coil before the BER and eye diagram analysis.

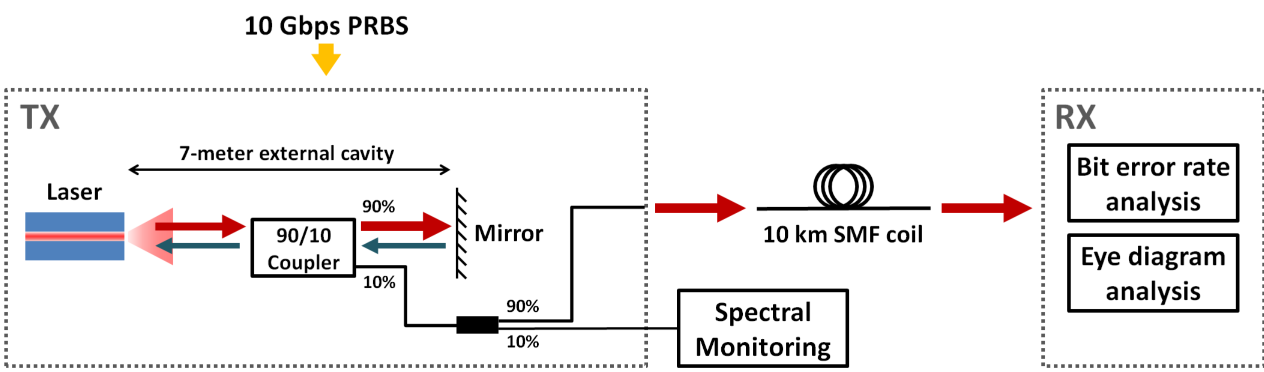

Figure 2. Experimental set-up used for optical feedback investigation.

3. EXPERIMENTAL RESULTS

In what follows, the high-Q DFB laser is first evaluated at room temperature, T = 20°C at three times the threshold followed by characterizations conducted at higher temperature values to determine the effect temperature variations have on its performance parameters. Fig. 3 illustrates the optical and electrical spectra of the device in the free-running case and under 100% optical feedback. The optical spectra displayed in Fig. 3(a) do not exhibit any perturbations up to r_{ext}=100% (i.e., -14 dB), only a slight wavelength red-shift of a few picometers, which is indicative of the enhanced tolerance high-Q lasers have against the detrimental effects arising from parasitic reflections. The electrical spectra of the device are accordingly displayed in Fig. 3(b) where a stable operation can also be observed without any evidence of undamping of the relaxation oscillations often expected from a precursor regime associated with the coherence collapse operation. The enhanced laser stability is in agreement with the very long photon lifetime and large damping factor already reported in.[11]

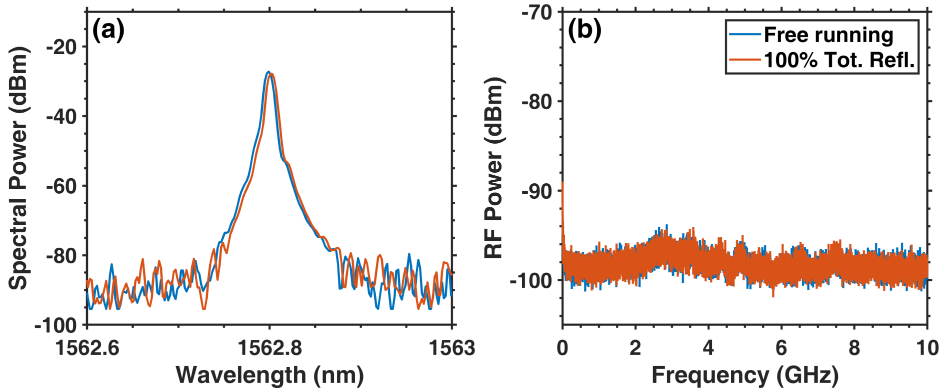

Figure 3. (a) Optical and (b) RF spectra of the high-Q DFB laser biased at $3\times I_{th}$ for the free-running case (blue) and under 100% (i.e., -14 dB) optical feedback (red) at T= 20°C.

In,[10] we compared the optical and radio frequency (RF) spectral evolution of the high-Q device against the conventional QW DFB laser under the same operating conditions to quantitatively assess the strengths and limitations exhibited by these two types of structures. In that study, the QW DFB demonstrated strong and well pronounced periodic oscillations on the route to chaos while the high-Q remained stably operating in both the optical and RF domain. It is well known that any changes in the amplitude phase coupling inside the cavity have a significant impact on the overall performance characteristics of the QW DFB laser and strongly affects its operation.[2] Under a variation of optical feedback strengths, the relaxation oscillations of a conventional QW DFB device become easily excited subsequently leading to the coherence collapse state of the laser's output.[4] In a high-speed communication system, this chaotic oscillation state is known to greatly affects the quality of the data transmission and therefore, it must be avoided through the inclusion of expensive and bulky optical isolators.[12] On the other hand, this study unveils a much higher tolerance offered by high-Q devices when subjected to optical feedback. Indeed, it was recently shown that owing to the large quality factor, a high coherence collapse level was successfully revealed hence transformed into a floor-free transmission at the most stringent optical feedback conditions at room temperature.[10]

Fig. 4 depicts the optical spectral map evolution of the high-Q laser under various operating conditions to diagnose the stability of the device. Each column represents the individual temperatures for the different settings and each row the 5°C incremental values for the different bias current. When increasingly comparing the maps horizontally to 30°C and above, the thermal contribution results in a slightly more pronounced wavelength alteration. On the other hand, if we observed the maps vertically, it is clear that the lasing operation's stability is further enhanced at higher bias current due to the larger damping effect.[13] Overall, the results clearly demonstrate that, despite some minor output wavelength shifts, stable lasing operation persists under any willingly introduced external perturbation within the investigated range, without displaying any oscillations nor rise of noise floor in the RF domain that can be considered as evidence of coherence collapse. Consequently, the RF spectral maps are not presented here since the they remained constant throughout the study. To sum, due to the large quality factor, the stability of the high-Q DFB laser is greatly preserved regardless of the temperature and the bias current evaluated. No coherence collapse regime is reported even under the most stringent conditions namely 100% of optical feedback back to the laser cavity.

Fig. 5 depicts the BER characteristics and the eye diagram of the high-Q DFB laser for different experimental conditions. Fig. 5(a) and 5(b) display four scenarios, before or after transmission over 10 km fiber coil (blue or orange colors resp.) with or without optical feedback (triangle or circle markers resp.). In each figure, the overlapping curves for both sets of measurements demonstrate that the high-Q hybrid laser's performance is not altered by the external feedback nor the temperature variation and that an error-free transmission can easily be achieved close to 10^{-12} and 10^{-10} BER for B2B and transmission operation respectively, implying that the power penalty of ~ 1.5 dB is primarily caused by the fiber dispersion during the transmission. These deductions can then be confirmed by the eye diagrams presented in Fig. 5(c) and 5(d) that corresponds to the rightmost solid orange circles for each temperature respectively, where opened eyes can be clearly observed.

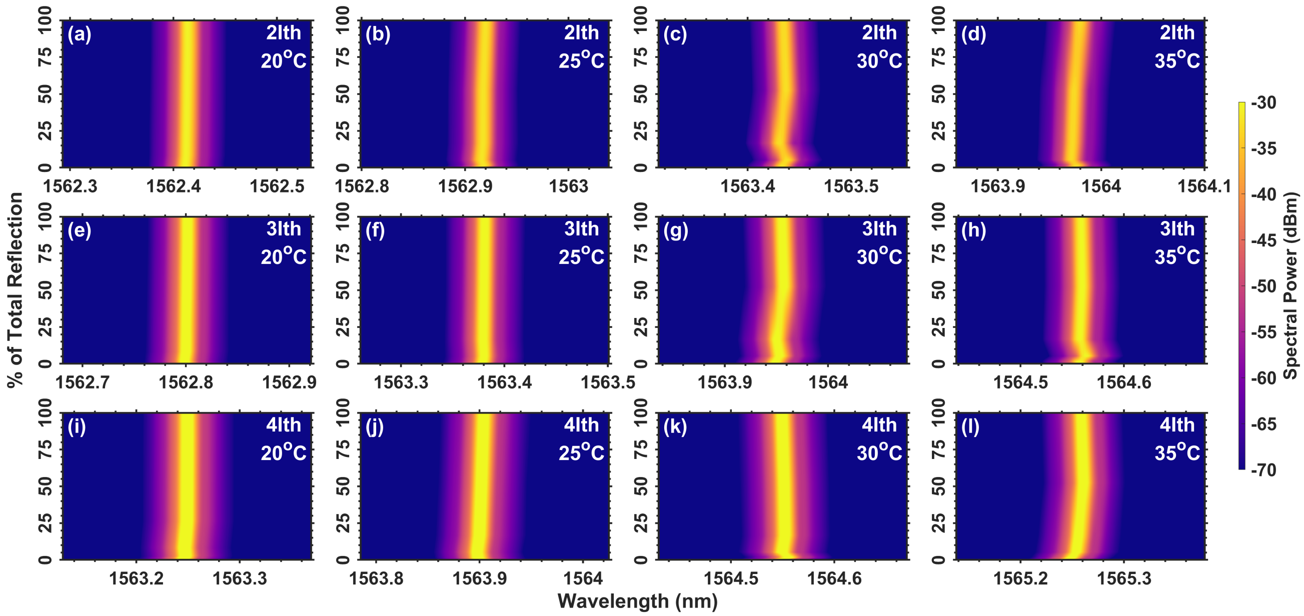

Figure 4. Optical spectral maps of the high-Q laser at T = 20°C, 25°C, 30°C, 35°C under 3 different bias conditions of I = $2\times I_{th}$ ((a),(b),(c),(d)), $3\times I_{th}$ ((e),(f),(g),(h)) and $4\times I_{th}$ ((i),(j),(k),(l)).

The results presented herein indicate that high-Q laser exhibits an enhanced tolerance against optical perturbations. Its prolonged transition to the coherence collapse regime at a much higher reflection level can certainly serve as a tool to potentially achieve error-free transmission without the use of optical isolators.

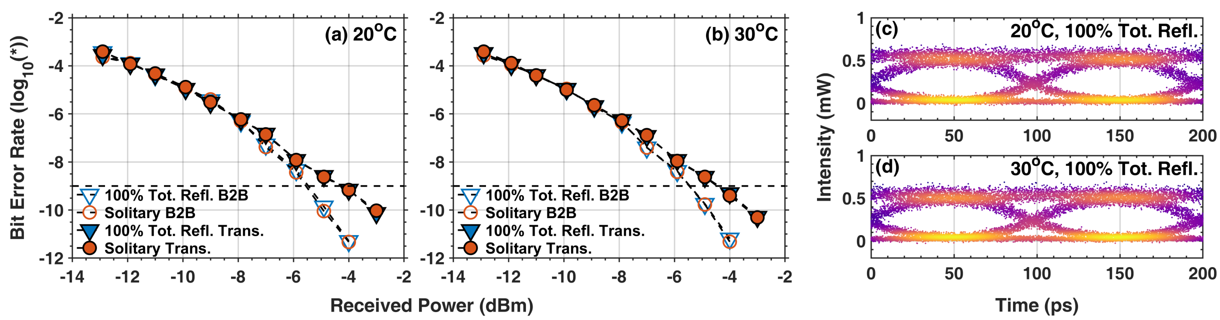

Figure 5. BER characteristics of the high-Q laser at (a) T = 20°C and (b) T = 30°C with (hollow and solid blue triangles) and without (hollow and solid orange circles) feedback; eye diagrams with maximal feedback after transmission over 10 km fiber coil at (c) T = 20°C and (d) T = 30°C.

4. CONCLUSIONS

The high-speed dynamics of a hybrid DFB semiconductor laser heterogeneously integrated onto silicon was experimentally investigated in the presence of external optical feedback and under different temperature conditions. We showed that the high-Q device offers enhanced tolerance against optical perturbations hence leading to a 10 Gbps floor-free transmission with a power penalty not exceeding 1.5 dB. This statement remains perfectly valid for different bias and temperature scenarios. In conclusion, owing to the large quality factor, a high coherence collapse level was efficiently unveiled. Our findings indicate that these novel devices have the vast potential to serve as an alternative for the development of isolator-free applications in future photonics integrated circuits.

5. ACKNOWLEDGMENTS

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