Demonstration of a High-Power and High-Reflection-Tolerance Semiconductor Laser for Co-Packaged Optics

Ning Cheng, Dechao Ban and Xuezhe Zheng
Innolight Technology Research Institute, 168 Shengpu Road, Suzhou, Jiangsu, China
ning.cheng@innolight.com

Abstract: A high-power (>100mW) semiconductor laser is demonstrated with a small far-field divergence of 9.3°×17.6°. Under a −19.8dB back-reflection, this laser exhibits little changes in relative intensity noise and almost no power penalty for 53Gbd/s PAM4 transmission.

1. Introduction

To address future bandwidth and power challenges in data centers, co-package optics provides an advanced solution with heterogeneous integration of electronic and photonic chips on a single packaged substrate. Such an approach brings a paradigm shift from traditional pluggable optics. It has drawn broad interest and intensive studies from the industry due to its potential for better scalability, higher bandwidth, increased port density, reduced power consumption, and lower cost [1]. For example, OIF (Optical Interconnect Forum) has established a Co-Packaging Framework studying the relevant technologies for a 3.2T co-packaged optical module [2]. In this project, ELSFP (External Laser Small Form-Factor Pluggable) defines a future-proofed external laser source for CPO applications. ELSFP module requires semiconductor lasers operating in CW (continuous wave) mode with tens of milliwatts output power. Although high-power lasers have been developed and commercially available, these lasers require isolators for stable operation because they are inherently very sensitive to back reflections [3].

The detrimental effects of back reflection on the operation of semiconductor lasers have been studied since the 1980s. A back reflection as low as −30dB may result in coherence collapse in traditional semiconductor lasers [3, 4]. Furthermore, some lasers became more sensitive to back-reflection at higher output powers [4]. Efforts to improve the back-reflection tolerance of semiconductor lasers have led to different design approaches, such as using a quantum-dot or quantum-dash gain medium, a partial corrugation grating, or internal passive feedback [5-7]. As of today, however, there is no report of semiconductor lasers operating with >100mW output power without an optical isolator. In this paper, we demonstrate a high power (>100mW output) semiconductor laser with good back-reflection tolerance and a small far field angle of 9.3° (vertical) and 17.6° (horizontal). Compared to a conventional high-power DFB laser with uniform grating, the relative intensity noise (RIN) of this laser under back-reflections (e.g. −20dB) is much smaller. With increasing back-reflection, its RIN increases only at low frequencies less than 3GHz. For frequencies higher than 3GHz, the laser shows little changes in its RIN under back-reflection. 53Gbaud/s PAM transmission with the high-power laser operating under −20dB reflection shows almost no power penalty compared to the case without back-reflection.

The paper is organized as follows. Section 2 presents the structure of the high-power semiconductor laser, particularly the design approaches for small far-field angles and back-reflection tolerance. Section 3 shows the testing results of the semiconductor laser, including its light-current-voltage (LIV) curves, optical spectrum, and relative intensity noise under back-reflections. Section 4 demonstrates the application of this laser for co-package optics. 53 Gbaud/s PAM4 transmission experiments reveal almost no power penalty in receiver sensitivity when the laser is subject to back-reflections as high as −19.8dB. Finally, conclusions are given in section 5.

2. High-power semiconductor laser design and fabrication

Figure 1 illustrates the epitaxial structure of the high-power laser. Grown on a 2″ n-type InP wafer, the epitaxial layers include (from the bottom to the top) an n-InP buffer layer, an n-AlInAs bottom cladding layer, an n-AlGaInAs GRIN-SCH (graded index separate confinement) layer, an AlGaInAs MQW layer with three wells (6nm) and four barriers (8nm), a p-AlGaInAs GRIN-SCH layer, a p-AlInAs top cladding layer, an InGaAsP grating layer, and an InGaAs contact layer. Thinner cladding and GRIN-SCH layers are used on the n-side to extend the field more toward the n-type region, resulting in an expanded mode in the vertical direction while keeping the free-carrier absorption small. Furthermore, a high-index passive layer of InGaAsP is embedded in the n-InP buffer layer to pull the vertical field further toward the substrate [8]. After the epitaxial growth, a 2μm ridge waveguide is etched on the top, and metallization is done after passivation. Finally, laser bars with 1000μm chip length are cleaved, and facets are coated for 90% and 1% reflectivity, respectively. To improve the reflection tolerance of the laser, we adopted a partial grating design. The grating length and coupling coefficient are optimized to minimize spatial hole burning at high powers. In addition, the detuning loading effect could also make the laser more immune to back reflections [7].

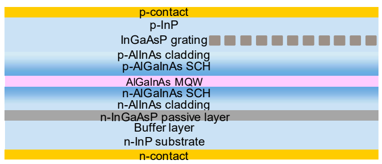

Fig. 1. Epitaxial structure

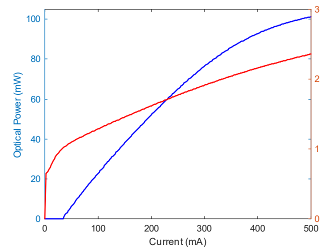

Fig. 2. Light-current-voltage curves

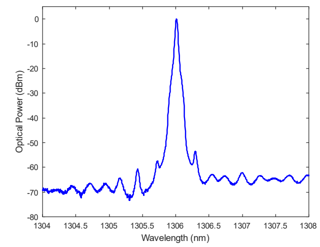

Fig.3. Optical spectrum

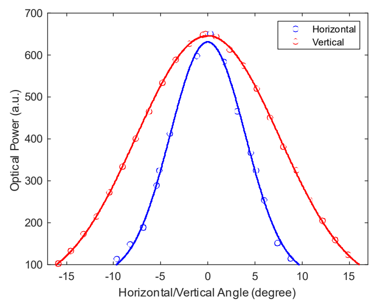

Fig. 4 Vertical and horizontal far field profile

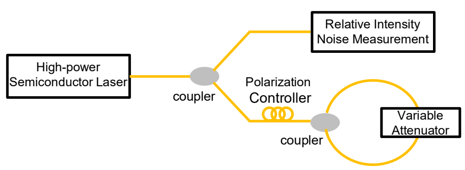

Fig. 5 Experimental setup for RIN measurement

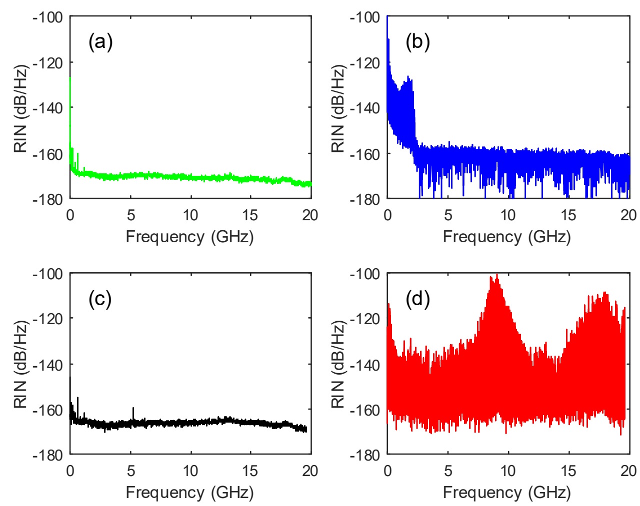

Fig. 6. Relative intensity noise of high-power semiconductor lasers

3. High-power laser characterization

Figure 2 shows the LIV curves of the high-power semiconductor laser, where the blue and red curves represent the light-current and voltage-current relationship, respectively. With a 25°C ambient temperature, the laser has a threshold of 34mA, and its output power reaches 100mW with 480mA injection current. Due to thermal effect, the laser output power starts to roll off around 300mA current. The optical spectrum of the high-power laser under 200mA current injection is given in Figure 3. The laser shows a very good side mode suppression ratio of over 50dB in the current range from 50 to 500mA. Figure 4 presents the horizontal and vertical far-field measurements. The far-field profile of the laser fits well with a Gaussian mode with FWHM (full-width half-maximum) divergence angles of 9.3° in the horizontal and 17.6° in the vertical direction.

To study the behavior of the high-power laser under back-reflections, its RIN under 200mA current injection is characterized by an experimental setup shown in figure 5. In the RIN measurement, the laser is coupled to a directional coupler whose outputs are connected to a fiber loop mirror and a RIN tester, respectively. A variable attenuator in the loop mirror controls the level of the back reflection, and a polarization controller is inserted between the fiber loop mirror and the directional coupler to control the polarization state of the reflected light. During RIN measurement, the polarization of the reflected light is adjusted so that the RIN is worst under a given reflection level. For comparison, the RIN of a conventional high-power DFB laser with uniform grating is also measured using the same setup. Figure 6 shows the RIN measurement results. Without back-reflection, both lasers have very low intensity noise shown in Fig. 6(a) and (c) for high-power lasers with partial grating and uniform grating, respectively. The RIN is below −160 dB/Hz in the frequency range from 10 MHz to 20 GHz for both lasers. However, under −20dB back-reflection, the RIN spectrum shows a dramatic difference between these two lasers. For the high-power DFB laser with uniform grating, the RIN increases rapidly with increasing back-reflection (Fig. 6(d)). Its RIN spectrum shows a peak around 9 GHz, close to its relaxation oscillation frequency. On the other hand, the high-power laser with partial grating (Fig. 6(b)) shows very little change in RIN for frequencies higher than 3GHz although the RIN noise for lower frequencies does increase with increasing back-reflections. Under the same level of back reflection, the peak RIN of this high-power laser with partial grating is 20 dB below that of the high-power DFB laser with uniform grating. Furthermore, as the frequency range for high RIN noise is narrow (< 2.8GHz), the total noise power is low when integrated over the frequency range of interests. Because of its RIN characteristics under back reflection, this high-power laser with partial grating showed little degradation in transmission performance as shown in the following section.

4. 53Gbaud/s PAM4 transmission experiment

To further evaluate the performance of the high-power laser for application in co-packaged optics, 53Gbaud/s transmission using PAM4 intensity modulation is carried out using the high-power laser as the light source. In the experiment, the CW output of the laser is modulated by a high-speed Mach-Zehnder modulator driven by $2^{31}-1$ PRBS sequence from a pattern generator, producing a 53Gbaud rate PAM4 optical signal. After transmitting through a single-mode optical fiber of extended length, the signal is attenuated before being detected by a 35GHz ROSA (receiver optical subassembly). On the transmitter side, the laser is biased at 200mA current and different level of back-reflections (–25.1, –21.8, and –19.8 dB) are generated by a loop mirror and fed back to the laser. A polarization controller adjusts the polarization of the back reflection for the worst bit error rate. The measured eye diagrams and bit error rates for the laser under different levels of back-reflections are shown in figure 7. Under a back reflection less than or equal to –19.8 dB, the eye diagrams show little change and the bit error rate curves almost overlap with the case without back-reflection. The slight variations in bit error rate measurement with and without back-reflection are within the experimental error range, and the receiver sensitivity for KP4 FEC threshold at 2.4×10^{-4} bit error rate is around –8.0 dBm. In comparison, the bit error rate is well-above FEC threshold for the conventional high-power uniform-grating DFB laser under –20 dB back reflection. Clearly, the high-power laser we demonstrated can tolerate the back-reflection level of –21.4 dB as defined in IEEE 802.3bs for a packaged laser. Hence, it is promising for application in isolator-free ELSFP modules for CPOs.

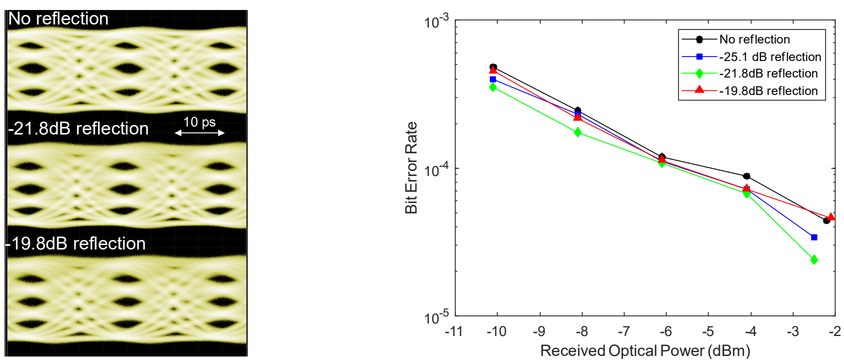

Fig. 7. Eye diagrams (left) and bit error rates (right) of 53 Gbaud/s PAM4 transmission.

5. Conclusions

In summary, a high-power semiconductor laser is developed successfully for isolator-free applications in co-packaged optics. It achieves a high output power of 100mW and small far-field angles of 9.3° (horizontal) and 17.6° (vertical). Under a back-reflection of –19.8 dB, it exhibits little changes in RIN spectrum for frequencies higher than 2.8 GHz. Although the RIN does deteriorate for frequencies lower than 2.8 GHz, little power penalty was observed in a 53 Gbaud/s PAM4 transmission experiment when the laser is under a back reflection as high as –19.8 dB.

6. References

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