Ultra low RIN, low threshold AlGaInAs/InP BH-DFB laser

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This study presents a comparative analysis of AlGaInAs buried heterostructure laser diodes by using dual-channel ridge-waveguides. Different shaped channels, including bowl shaped groove and vertical groove, are explored. Using a vertical groove structure, we achieved an output power of 90 mW at 25°C with a threshold current of only 4 mA. This represents a 3.6-fold increase in output power compared to the BH-DFB structure. At a high temperature of 85°C, the laser maintains a side-mode suppression ratio of over 45 dB at the maximum power point. The laser’s relative intensity noise in the 0-40GHz frequency range is less than -162.8 dB/Hz when operated at 300 mA with the chip butterfly packaged. These findings underscore the robustness, reliability, and high-performance capabilities of the developed DFB laser, highlighting its potential for various practical applications.

1 Introduction
2 With the growing demand for enhanced signal transmission system performance, microwave photonic links are gaining popularity due to their significant bandwidth and low loss. With the growing applications of microwave photonic links in radar[1, 2], electronic warfare[3], and other fields, there is a strong emphasis on achieving the highest possible performance capabilities of the developed DFB laser, thereby enhancing its performance. Lower series resistance delays the saturation of photocurrent characteristics, thereby improving laser output[8]. In addition, the cavity length of the cavity greatly affects its output characteristics. A longer cavity can enhance thermal management by reducing the thermal resistance of the device, thereby increasing the maximum output power[9].
37 depth of quantum wells and a heightened risk of Auger recombination processes[6]. As the pumping current increases, carriers may flow out of the active region, resulting in leakage current and consequently reducing the quantum efficiency of the laser. Auger recombination further reduces radiative recombination, laser efficiency, and increases heat dissipation.
38 Compared to InGaAsP, AlGaInAs exhibits a lower Auger recombination rate due to its larger conduction band offset difference [7], which enhances electron utilization, effectively reduces non-radiative recombination, and improves carrier confinement and injection efficiency. This leads to higher differential gain and enhances device temperature characteristics. Minimizing the series resistance of the laser is crucial for enhancing its performance. Lower series resistance delays the saturation of photocurrent characteristics, thereby improving laser output[8]. In addition, the cavity length of the laser greatly affects its output characteristics. A longer cavity can enhance thermal management by reducing the thermal resistance of the device, thereby increasing the maximum output power[9].
39 In this letter, we present a BH-DFB laser that utilizes AlGaInAs quantum well materials. By integrating additional groove structures, we effectively mitigate lateral current spreading, thereby enhancing current utilization. The laser features a low threshold current, exceptionally low RIN, and a high side mode suppression ratio. We also explain the effects...
of various groove structures on the laser’s series resistance. Additionally, we investigate the impact of chip temperature and cavity length on threshold current and slope efficiency.

Design and experiment

This study entailed the fabrication of an edge-emitting BH-DFB laser designed for operation at C-band wavelengths, specifically around 1550 nm. Figure 1 illustrates the structures of the laser diodes (LDs) employed in this investigation. The epitaxial layer was grown on an n-type InP substrate utilizing metal-organic chemical vapor deposition (MOCVD) technology. Initially, a 0.8-micron-thick n-doped InP buffer layer was grown, followed by the deposition of an active layer comprising multiple quantum well structures and separately restricted heterostructure (SCH). Then, the grating layer is grown. The mesa structure is formed through wet etching. Subsequently, p-InP and n-InP buried layers were grown to establish a current barrier. A layer of SiO2 is grown on top of the wafer as a hard mask. Windows are opened in the silicon dioxide layer using reactive ion etching (RIE), and then wet etching is performed to form two different groove structures: a bowl-shaped groove structure based on isotropic etching and a vertical groove structure based on anisotropic etching. The etching depths of the two groove structures are roughly the same, as shown in Figure 2. After passivation, the SiO2 dielectric layer was regrown and contact windows were etched using RIE. Then, a p-metal composed of Ti/Pt/Au is deposited and annealed to form ohmic contacts. Similarly, Ti/Pt/Au is grown on the thinned backside InP to form the n-side metal. Finally, the chips were cleaved according to different cavity lengths, and anti-reflection (AR) and high-reflection (HR) coatings are grown on the two end faces of each bar. The AR surface exhibited a reflectivity of 0.5%, while the HR surface boasted a reflectivity of 99%. Butterfly packaging was employed, and Relative Intensity Noise (RIN) testing was conducted subsequent to packaging.

Laser cross-sections were characterized using scanning electron microscopy (SEM). The current-voltage (I-V) curve of the ohmic contact interface was measured by a semiconductor parameter measuring instrument (4200-SCS/F+SUSS PM8). The laser output characteristic curve is measured by the laser emitting BH-DFB structure; the dotted line area is the groove structure. During the operation of semiconductor lasers, the connection between the laser and external circuits is primarily achieved through metal/semiconductor contacts. Two fundamental prerequisites for ohmic contacts are low contact resistivity and high thermal stability. In this study, the ohmic contact performance was evaluated using the Ring Transmission Line Model. The semiconductor contact layer employed in this experiment was AlGaAs, while the metal contact layer consisted of Ti/Pt/Au. The outer radius of the ring transmission line model was set at 150 μm, with the minimum circular electrode radius being 60 μm, incremented by 10 μm. The inset in Figure 3 shows a scanning electron microscope (SEM) image of the actual ring transmission line model. After annealing at 425°C for 125 seconds, voltage-current tests were conducted. Figure 3 illustrates the voltage-current test diagram of the ring transmission line model, where ‘r’ denotes the spacing value between the two electrodes. It is evident from the figure that the current-voltage curves across all six sets of electrodes exhibit linearity. Upon calculation, the specific contact resistance is determined to be 4.61E-5 Ω*cm², with a corresponding contact resistance of 0.689 Ω*mm.
In this study, both groove structures have the same top width of 15 μm, the width of the ridges between the grooves is also 15 μm, and the etching depths are approximately the same at 6 μm. However, due to the unique "bowl-shaped" structure, as the etching depth increases, the width of the ridges also increases. This implies that the cross-sectional area of the pn junctions in the buried structure also increases, leading to a decrease in the pn junction interface resistance and an increase in leakage current. We have demonstrated this in our experiments, as shown in the figure below.

The ability of the buried structure to limit lateral diffusion current is provided by the electron potential barrier between the pn junctions within the buried structure, manifested as the "high-resistance region." The injected current, as shown in Figure 4, can be viewed as a parallel connection of three current components due to the unique "narrow stripe" structure of the BH laser active region (red area). As shown in formula 1.

\[ I = I_1 + I_2 + I_3 \]  

Among them, \( I_1 \) represents the actual injected current into the active region; \( I_2 \) represents the leakage current between the buried structure and the active region when designing the BH laser; and \( I_3 \) represents the small amount of current leaking into the buried structure. Ideally, compared to \( I_1 \), \( I_2 \) and \( I_3 \) can be neglected. However, in reality, due to doping elements and process limitations, the leakage currents represented by \( I_2 \) and \( I_3 \) cannot be ignored and have a significant impact on the laser performance. Fortunately, we can control the size of \( I_3 \) by increasing the grooves, thereby reducing leakage current, that is, increasing the proportion of the \( I_1 \) current component in the injected current.

\[ I_m = \frac{R_n}{R_1 + R_2 + R_3} \quad n=1,2,3 \]  

As indicated by formulas (1-2), we can reduce the current component leaking into the buried structure by increasing the resistance \( R_n \) of the buried structure. The resistance of the buried structure mainly comes from the pn junction barrier resistance, while the bulk resistivity of the material itself can be neglected. The barrier resistance of the pn junction is inversely proportional to the cross-sectional area of its interface. By adding groove structures to increase \( R_n \), the principle mainly involves reducing the cross-sectional area of the current flowing through the buried pn junction.

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threshold current of merely 4 mA and the highest output power 90 mW, as depicted in Figure 6. This outcome is attributed to the beneficial effects of longer cavities, which contribute to the reduction of both electrical resistance and thermal resistance within the device, consequently leading to slower power saturation. However, it’s important to note that despite these advantages, longer cavities also result in increased internal losses, which consequently lead to lower slope efficiency. This trade-off between threshold current, output power, and slope efficiency underscores the importance of optimizing cavity length based on specific application requirements.

The Spurious-Free Dynamic Range (SFDR) denotes the power range over which microwave photonic links can transmit signals without distortion. In critical fields such as radar and electronic warfare, achieving a high SFDR in microwave photonic links is paramount. For instance, in anti-radar and electronic warfare, achieving a high SFDR in transmit signals without distortion. In critical fields such as power range over which microwave photonic links can achieve excellent single-mode stability and highlights its robust performance under different temperature conditions.

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The side mode suppression ratio (SMSR) refers to the ratio between the output power of the main mode and that of the secondary mode when the laser is operating. It is an important indicator of the laser’s stability in single-mode operation. A higher side mode suppression ratio indicates that the laser’s single-mode operation is more stable and the output spectrum is purer. According to Figure 7, our 1000 μm long vertical groove laser reaches peak power at a bias current of 400 mA, and the side mode suppression ratio remains above 45 dB in the temperature range of 5°C to 85°C. This indicates excellent single-mode stability and highlights its robust performance under different temperature conditions.

In Figure 8, RIN curves for a 1000 μm long vertical groove laser in a butterfly package are illustrated at 200 mA and 300 mA, with a TEC temperature of 25°C. Remarkably, the RIN for this laser remains below -162.8 dB/Hz within the 0-40 GHz range at 288 a working current of 300 mA.

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In this work, we compare AlGaNAs buried heterostructure (BH) laser diodes using dual-channel ridge-waveguides with different groove shapes: bowl-shaped and vertical. In a vertical groove laser with a cavity length of 1000μm, we have achieved a maximum output power of 90 mW and a threshold current as low as 4 mA. When the laser operated at a bias current of 400 mA, it achieved a side mode suppression ratio greater than 45 dB within a temperature range of 5-85°C. The laser's RIN in the 0-40GHz frequency range is less than -162.8 dB/Hz when operated at 300 mA with the chip butterfly packaged. These findings demonstrate the superior performance of the developed DFB laser in terms of RIN, threshold current, and single-mode stability, highlighting its potential for microwave photonic link applications.

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Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References