InGaAsP/InP Buried-Ridge Waveguide Laser with Improved Lateral Single-Mode Property

Su Hwan Oh, Ki Soo Kim, Oh Kee Kwon, and Kwang Ryong Oh

ABSTRACT—A novel InGaAsP/InP buried-ridge waveguide laser diode structure is proposed and demonstrated for use as a single-mode laser. The lateral mode of the proposed device can be controlled by adjusting the composition and thickness of the InGaAsP layer grown over the active region. Stable single-mode operation without kinks or beam-steering is achieved successfully with lateral and transverse in the junction plane even for the device with the ridge width of 9 μm up to an injection current of 500 mA.

Keywords—Buried-ridge waveguide, single-mode operation.

I. Introduction

Ridge waveguide (RWG) lasers have attracted much attention as low-cost light sources because of their simple fabrication with high process uniformities [1], [2], high wide-temperature-range performance [1], [3], [4], low parasitic capacitance [1], and high reliability [1]-[5]. In order to achieve maximum brightness and fiber coupling efficiency in the desired application, it is necessary for the laser to have excellent beam quality. This requires the lasers to operate in a single lateral mode, which is difficult to maintain at a high output power [6]. In conventional multiple quantum well (MQW) RWG lasers, the lateral mode mainly depends on the width of the ridge and the thickness of the upper cladding layer [7]. Usually, a ridge width of less than 3 μm is required to maintain lateral single-mode operation for the device with an upper cladding layer thickness of 0.1 μm. However, it is difficult to uniformly realize a ridge width of less than 3 μm by using the conventional photolithography process. To overcome this problem of conventional RWG (C-RWG) lasers, we propose a new buried-ridge waveguide (B-RWG) laser, in which lateral single-mode operation can be guaranteed even for ridge widths over 5 μm by inserting an InGaAsP layer into the ridge region. The waveguide structure of the proposed device is different from that of previously reported B-RWG lasers [8]-[10]. It has been reported that B-RWG lasers have been used as high-power 0.98 μm or 1.02 μm wavelength lasers. However, there have been no reports of a high-power 1.56 μm optical-communication laser fabricated using B-RWG to our knowledge. Therefore, we have fabricated a B-RWG laser with a 9 μm ridge width, which is over 2 times larger than that of the C-RWG laser, which has ridge widths of 3 and 4 μm with the maximum condition of lateral single-mode operation. In this letter, we propose the novel B-RWG laser structure for single-mode lasers. The width and thickness of the InGaAsP layer can be controlled by photolithography and an epitaxial growing process, respectively.

II. Design and Fabrication

Figure 1 shows a schematic drawing of the B-RWG laser diode structure. The lateral refractive index difference between the ridges and the outside region can be controlled by the composition and/or thickness of the InGaAsP layer (d_2 layer) in the ridge region. The lateral leakage current is expected to be less than that of the buried-ridge structure because the ridge is surrounded by an n-InP current blocking layer.

This device was fabricated by using two MOCVD growth steps. In the first step, an n-InP buffer layer, a 1.55 μm separate confinement heterostructure (SCH) MQW, a 150 nm-thick

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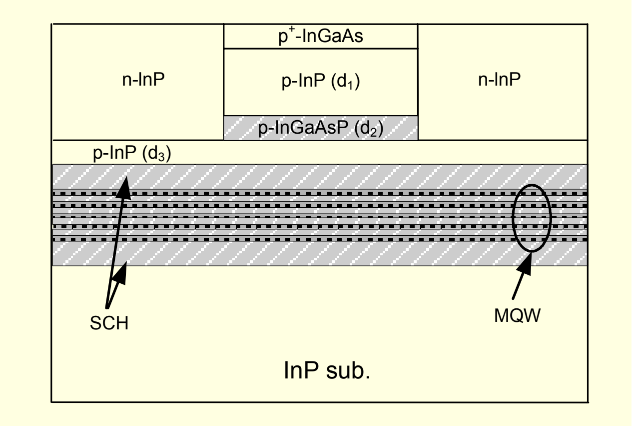

Fig. 1. Schematic cross section of the buried ridge waveguide laser.

p-InP layer (d_3 layer: $N_d = 7\times10^{17}$ cm^{-3}), a 100 nm-thick p-InGaAsP (d_2 layer: λ_g =1.25 μm, $N_d = 7\times10^{17}$ cm^{-3}), a 1.2 μm thick p-InP cladding layer, and a 0.2 μm-thick p^+-InGaAs ($N_d = 5\times10^{18}$ cm^{-3}) ohmic layer were grown in sequence. It is noted here that the combination of d_2 (the thickness of p-InGaAsP layer) and d_3 (that of p-InP layer) is designed to ensure lateral single-mode operation for a given ridge width even with a high injection current by two-dimensional waveguide analysis. If a d_2 of 150 nm is chosen for 9 μm-wide B-RWG lasers, d_3 should be over 900 Å thick to guarantee lateral single-mode operation. In this structure, we adopt a 100 nm-thick d_3 layer. The strained MQW consists of five pairs of a 0.7% compressively strained InGaAsP (λ_g=1.55 μm) well and a 0.35% tensile strained InGaAsP (λ_g=1.25 μm) barrier. The SCH is composed of undoped InGaAsP (λ_g=1.25 μm) layers. A 9 μm-wide SiN$_x$ mask pattern for the ridge region was aligned along the [110] direction using photolithography. Then, the p^+-GaInAs ohmic layer, the p-InP (d_1) layer, and the p-GaInAsP (d_2) layer were wet-etched using selective wet etchant for each layer. The second growth step for current blocking was accomplished by growing one layer of n-InP ($N_a = 2\times10^{18}$ cm^{-3}) using MOCVD growth. The SiN$_x$ mask of the ridge region was removed after MOCVD growth. The Ti/Pt/Au and Cr/Au electrodes were formed on the top and the bottom of the wafer as p-type and n-type ohmic contacts, respectively.

III. Results and Discussion

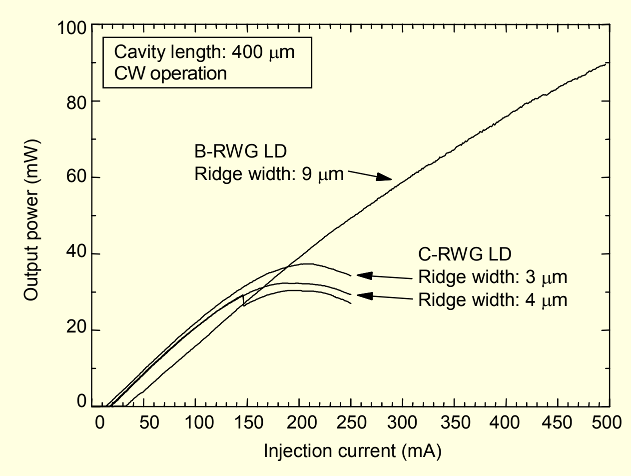

Fig. 2. Light output power characteristics under CW operation for a 400 μm-long cavity with as-cleaved facets.

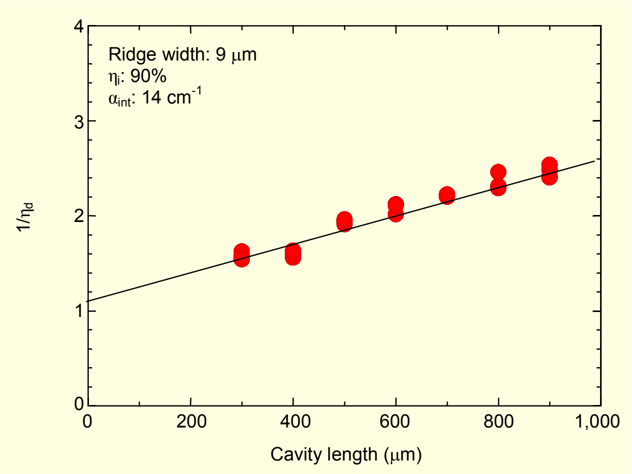

Fig. 3. The internal quantum efficiency and internal loss with respect to cavity length.

Figure 2 shows the output power of B-RWG and C-RWG lasers versus injection current (L-I) under CW operation at 25°C for 400 μm-long cavity lasers with as-cleaved facets. The ridge width of the B-RWG lasers is 9 μm, and those of the C-RWG lasers are 3 μm and 4 μm. We assume that the same layer is active in those lasers. As the injection current increases, the output powers of the C-RWG lasers become saturated around the injection currents of 150 mA and 170 mA, while that of the B-RWG laser still increases linearly. In particular, the 4 μm-wide C-RWG laser has a kink which results from the lateral second-mode generation. We think this second-mode generation can be attributed to the effective refractive index reduction of the ridge by the increased current, and the probability of a kink occurring can increase with an increase in the ridge width. Apparently, the proposed device shows kink-free operation up to 500 mA without any degradation or saturation of output power even for a ridge width of 9 μm. In this device, the average threshold current and slope efficiency were 32 mA and 0.24 W/A, respectively. The maximum output power was 90 mW at a current of 500 mA.

Inverse differential quantum efficiency $1/\eta_d$ versus cavity length L is shown in Fig. 3. By fitting a curve to the measured

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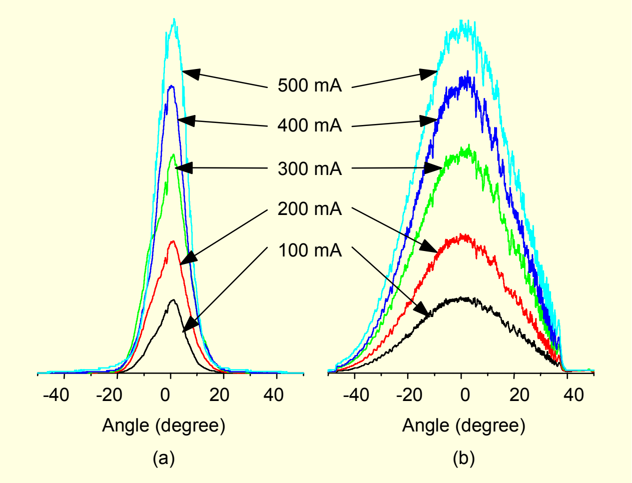

Fig. 4. Far field pattern in the junction: (a) lateral to the junction and (b) transverse to the junction.

data, the internal quantum efficiency and the internal loss were estimated to be 90% and 14 cm^{-1}, respectively.

Figure 4 shows the far field pattern at drive currents from 100 mA to 500 mA in 100 mA increments under CW operation at 25°C for a 400 μm B-RWG laser. A stable fundamental-transverse-mode operation was observed up to 500 mA injection current. From this result, we confirmed stable single-mode operation with lateral and transverse in the junction plane for the device with a ridge width of 9 μm in the B-RWG structure. The beam divergence angles at half maximum are 43° and 15° along the directions lateral and transverse to the junction plane, respectively, at an injection current of 500 mA. The large beam divergence angle of our device in the transverse direction was due to a difference between the ridge width and the active thickness of MQW and SCH structures. The beam divergence in the far-field pattern can be reduced by integrating the spot-size converter [6]. Compared to the C-RWG structure, the B-RWG structure has several advantages such as the kink-free LI property, stable far-field pattern, high power, and no-beam steering, although an additional growing step is required. The proposed device is expected to be a low-cost light source with high fabrication yield and high output power.

IV. Conclusion

We have proposed and demonstrated a 1.56 μm B-RWG laser with a novel waveguide structure which can provide an improved lateral single-mode property. We experimentally confirmed that even with a ridge width of 9 μm, the device could be operated up to a current of 500 mA in a stable single-mode operation without kinking, beam-steering, or saturation of output power.

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