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Semiconductor laser using multimode interference principle

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ABSTRACT

Multimode interference (MMI) structure is introduced in semiconductor laser used in optical communication system to realize higher power and better temperature tolerance. Using beam propagation method (BPM), Multimode interference laser diode (MMI-LD) is designed and fabricated in InGaAsP/InP based material. As a comparison, conventional semiconductor laser using straight single-mode waveguide is also fabricated in the same wafer. With a low injection current (about 230 mA), the output power of the implemented MMI-LD is up to 2.296 mW which is about four times higher than the output power of the conventional semiconductor laser. The implemented MMI-LD exhibits stable output operating at the wavelength of 1.52 μm and better temperature tolerance when the temperature varies from 283.15 K to 293.15 K.

1. Introduction

Semiconductor laser, also known as laser diode (LD), is an ultra-compact laser source compared to all other types of lasers such as solid, gas or ion laser. Conventional semiconductor laser is a straight single-mode waveguide use both ends of the wafer as mirrors to form a cavity, and the gain saturation limits the output power. To increase the power of the semiconductor laser, one has to increase either the laser cavity length or waveguide width. Since recent growth of data traffic in optical transmission system requires smaller size and higher optical power laser diodes, longer cavity length is normally unacceptable. Meanwhile, wider waveguide width commonly comes with high order mode, which is not desired in most of the cases.

In contrast to single-mode waveguide, Multimode Interferometer (MMI) has been an effective way to get high power for laser diode cavities because of its wide pumping area [1–6]. Consequently, many researches of active MMI using in laser diode have been reported in recent years. Superluminescent diode by using active MMI has been realized [7], asymmetric active MMI has been successfully used in laser diode [8,9]. Hamamoto et al. reviewed and summarized the recent progress in active MMI devices comprehensively, most of the designs could achieve high output power with high injection current [10].

In this paper, an MMI structure is introduced in semiconductor laser used in optical communication system successfully which achieves a high power laser with its device length no longer than the conventional semiconductor laser's. We use beam propagation method (BPM) in the device design. Multimode interference laser diode (MMI-LD) is demonstrated in InGaAsP/InP based material. When the injection current is 230 mA, the output power is up to 2.296 mW, which is about four times higher than the output power of the conventional semiconductor laser. The implemented MMI-LD exhibits stable single-mode output operating at the wavelength of 1.52 μm and shows better temperature tolerance.

2. Principle

The principle of straight single-mode waveguide and 1 × 1 MMI coupler [11] are shown in Fig. 1 done by 2-D BPM simulation. Conventional semiconductor laser is a straight single-mode waveguide using both ends of the wafer as mirrors to form a cavity, which has a small area to produce gain and the optical power distribution is concentrated. In this paper, an MMI structure is introduced to enlarge the gain in the semiconductor laser diode. The main part of the proposed MMI-LD is a 1 × 1 MMI coupler with an MMI region which has a width of W_M and length of L_M. The length L_M is given by [11]

$$L_M = \frac{3}{4}L_\pi = \frac{3}{4}\frac{4n_rW_e^2}{3\lambda} = \frac{n_rW_e^2}{\lambda} \tag{1}$$

where L_π is the beat length of the fundamental mode and the first order mode, $W_e = W_M + \left(\frac{\lambda}{\pi}\right)\left(\frac{n_c}{n_r}\right)^{2\sigma}\left(n_r^2 - n_c^2\right)^{-(1/2)}$ is the effective width of the MMI region, where $\sigma = 0$ for TE and $\sigma = 1$ for TM, n_r is the ridge (effective) refractive index and cladding (effective) refractive index n_c. As shown in Fig. 1(b), single mode can be gained

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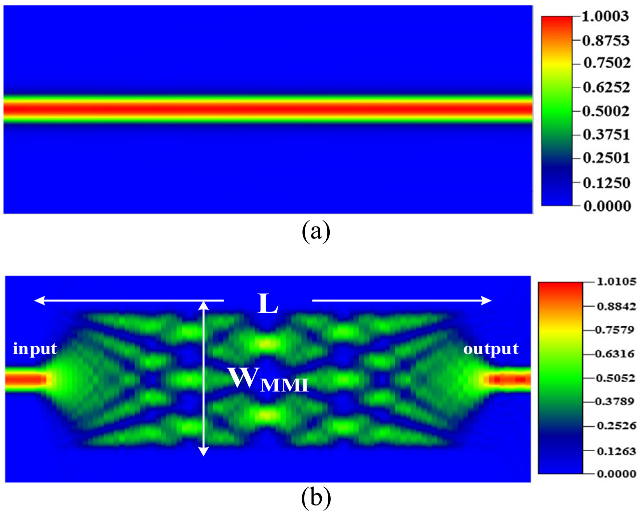

Fig. 1. The principle of (a) single-mode waveguide; (b) 1 × 1 MMI coupler.

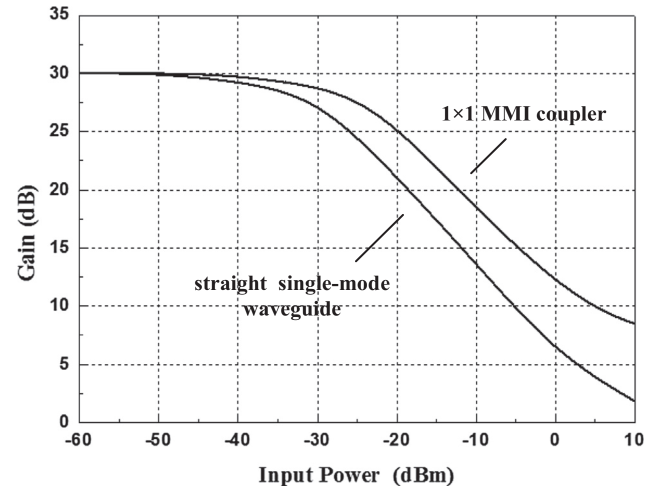

Fig. 2. Gain with input power varies.

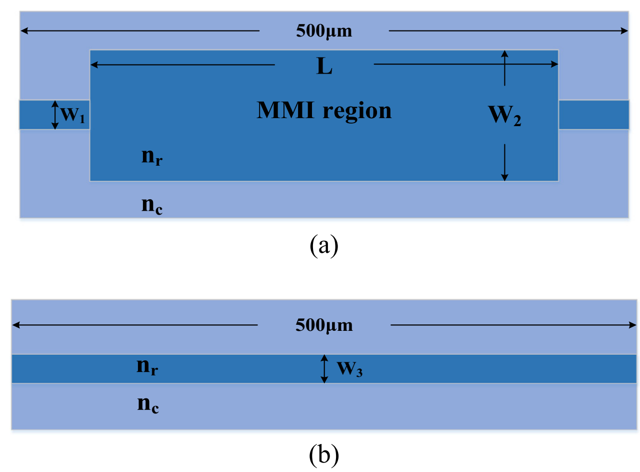

Fig. 3. 2-D index mode of (a) MMI-LD; (b) conventional semiconductor laser.

again after a propagation distance of length L_M. This principle is called "self-imaging". And MMI coupler has a large area to produce gain and the optical power distribution is relatively dispersive when the light is propagated to MMI region.

Then we consider that the light in semiconductor material is ideal traveling wave type and the internal scattering loss is negligible. The gain coefficient g_0 is given by [12]

$$g_0 = A_g\left(\frac{\tau J}{ed} - N_0\right) \tag{2}$$

where A_g is differential gain, τ is the carrier lifetime, J is the current density, e is the electron charge, d is the active layer thickness, N_0 is the transparency carrier concentration. The small-signal gain [13]

$$G_0 = \exp(\Gamma g_0 L) \tag{3}$$

where Γ is the optical confinement factor, L is the active layer length. Then we can get the gain G [13]

$$G = \frac{P_{out}}{P_{in}} = G_0 \exp\left[-(G-1)\frac{P_{in}}{P_{sat}}\right] \tag{4}$$

where P_{out} is output power, P_{in} is input power, and $P_{sat} = P_{out}|_{G=G_0/2}$ is the saturated gain.

For both straight single-mode waveguide and 1 × 1 MMI coupler, we calculate the gain G with a varying input power P_{in} when the small-signal gain G_0 is 30 dB. The computation result is shown in Fig. 2. As the input power rises, the gain firstly stays about G_0 and then starts to decrease. After decreasing linearly, it finally approaches a gain value about 0 dB for high input powers, which is called "gain saturation". This limits the output power of the laser diode. For 1 × 1 MMI coupler, the emergence of the gain saturation is later and falling more slowly. As a result, the MMI-LD will produce a higher output power than the conventional LD under the same input power. The larger MMI width can achieve higher output power, but it also leads to the longer length of the MMI-LD. Therefore the parameters should be chosen properly.

3. Device design

Fig. 3 shows the 2 dimensional index mode of (a) MMI-LD and (b) conventional semiconductor laser. The main part of MMI-LD is a 1 × 1 MMI coupler which consists of an MMI region, input and output waveguides. The MMI region is a multimode waveguide with the width of W_2 = 12.0 μm, the input/output waveguide is single mode waveguide with W_1 = 3 μm. The effective refractive index are n_r = 3.2453, n_c = 3.2027 (calculated using effective refractive index method) and the wavelength is λ = 1.55 μm. Using BPM we calculate the power transmission of the MMI coupler when L varies. The maximum transmission of 0.9892 is gained when L = 354.6 μm. For comparison, conventional semiconductor laser using straight single-mode waveguide with W_3 = 3 μm is also designed in the same wafer. The cavity length of both structures is 500 μm.

The MMI-LD and conventional semiconductor laser are implemented with InGaAsP related material. Fig. 4 shows the 3-D index mode of MMI-LD. The material structure with an etching depth of 1.65 μm is shown in Fig. 5.

4. Experiment and discussion

Fig. 6 shows the scanning electron microscopy (SEM) photo of the MMI-LD with a length of about 500 μm. We also fabricated conventional LD (straight single-mode waveguide) on the same mask as comparison.

The following results are all gained at the temperature of 283.15 K. Fig. 7(a) shows the relation between the injection current I and the output power P_{out}. At the maximum current of 230 mA, the output power of conventional LD is about 0.534 mw while a