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Analysis of Spot Shape Behavior on a Spot-Size Controllable Laser Diode

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Abstract

The influence of the modulator current on the beam shape of a variable spot size laser diode is analysed. The injected carrier distribution in the modulator is calculated taking the carrier diffusion in the active layer into account. Then, the spot shape is calculated, taking the reflective index change caused by injected carrier into account as perturbation. The calculated results are consistent with the experimental data. A 3-μm modulator spacing provided the largest spot size variation and smoothest change in the spot size.

1. Introduction

Recently we proposed a laser diode whose near-field spot size can be changed by varying the electric current used in high-quality laser printers. The laser diode has a spot size variation ratio of 1:2.1[1], and improved printing quality in a laser printer using this laser diode[2] was demonstrated. However, the dependence of the spot size and light output power on the main and modulator current is complicated in that it is difficult to optimize the laser diode design and to precisely control these currents in an actual system. Here, we analyze the dependence of the spot size on the modulator current for various injection stripe spacings.

2. Analysis of carrier distribution

Figure 1 shows a plane and cross-sectional views of the spot-size controllable laser diode. The lateral mode of the laser beam is kept in the fundamental mode by the relatively narrow (5 μm) straight stripe. An electric current is injected from the parallel injection stripes in the modulator and the laser beam is transformed by the refractive index distribution formed by carrier injection. The injected carrier density in the modulator can be calculated by using the Schwarz-Christoffer transform to solve the Poisson equation in the cladding layer, and by solving the diffusion equation in the active layer.[3] In the Schwarz-Christoffer transform, the complex axis z=x+iy is transformed into the complex axis w=u+iv. Here, w is written as

$$w = \frac{1}{4} + \frac{1}{2K(k)} \mathrm{tn}^{-1}\left(E, k\right), \quad (1)$$

$$E = \exp\left[\frac{\pi}{2A}\left(\frac{S}{2} + z\right)\right], \quad (2)$$

$$k^2 = 1 - \exp\left(-\frac{\pi S}{A}\right). \quad (3)$$

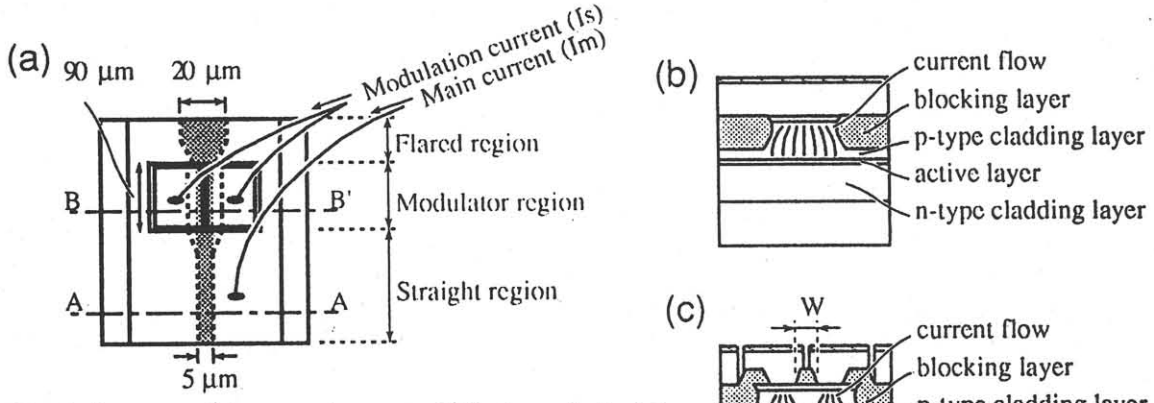

Fig. 1 Structure of the spot-size controllable laser diode: (a) plane view, and cross-sectional views at (b) the straight region, and (c) the modulator region. The modulator region has a single optical guiding stripe with two parallel current injection stripes.

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Here, S is the width of the electrode, A is the distance between the active layer and the electrode, and K(k) is the real part of the elliptic integral of the first kind, while tn^{-1} is the inverse Jacobian elliptic function.

By this transform, the injection stripe of the modulator is projected as the line $v=\tau/2$ which is a periodic function of u. The whole width of the injection stripe is projected into a single period of u. The active layer is projected as the line v=0 which is also a periodic function of u. Here, $x=-\infty$ to ∞ is also projected into a single period of u. If we assume that the electrical potential of the injection stripe is constant, the injected current distribution in the field can be obtained by using the Fourier series of electric potential on the v=o line as follows

$$j(x) = \frac{\pi}{4AK}\left(\left\{1+\exp\left[\left(-\frac{\pi S}{2A}\right)\left(1-\frac{2x}{S}\right)\right]\right\}\left\{1+\exp\left[\left(-\frac{\pi S}{2A}\right)\left(1+\frac{2x}{S}\right)\right]\right\}\right)^{1/2}\left\{2\frac{1}{l} + \frac{1}{\rho}\sum C_{2n}\, 4\pi n \coth\left(2\pi n\frac{K'}{K}\right)\cos\left(4\pi n\, u(x)\right)\right\}, \quad (4)$$

$$C_{2n} = 4\int_{1/4}^{3/4} U(x)\cos(4\pi n u)du. \quad (5)$$

Here, K and K', respectively, are the real part and the imaginary part of the elliptic integral of the first kind. U(x) is the potential formed on the active layer.

The interaction between the left and right electrodes are only considered in the electric potential of the active layer.

The carrier density in the active layer is obtained by solving the diffusion equation for the active layer

$$D\frac{\delta^2 n}{\delta x^2} - f(n) + \frac{j(x)}{ed} = 0 \quad (6)$$

Here, D is the diffusion constant of the carriers in the active layer, d is the thickness of the active layer, and j(x) is the injected current density to the active layer. The relation between the carrier density (n) and the voltage in the active layer U(x), and the relation between n and the carrier recombination rate f(n) can be calculated by using the conventional effective mass theory and density matrix formalism.

Figure 2 shows the calculated carrier densities for various spacings between the parallel injection stripes. The dip in the injected carrier density at the center of the space was about 28% for the 2-μm stripe spacing, but it increased to61% when the stripe spacing was 5 μm.

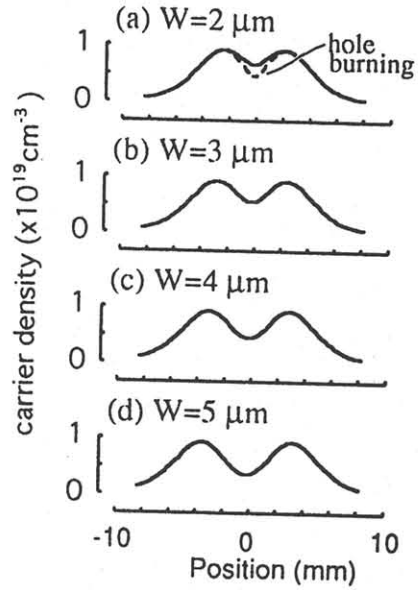

Fig. 2 Injected carrier density distribution in the active layer. The space between the injection stripes (W) was varied from 2 to 5 μm. Injection current for the modulator is about 50 mA.

3. Analysis of spot shape

The refractive index change caused by carrier injection was assumed to be $\Delta n_{in} = 10^{-20}\infty n$. The beam-shape calculation for the waveguide (Fig. 3) was based on the coupling mode theory and included the refractive index change as a perturbation. The outline of the calculation is as follows.

First, we calculated the guided modes of an index guide stripe with a constant refractive index stripe. The stripe widths varying from 4 to 20 μm in 1-μm steps. The fundamental to 10th mode for each stripe was calculated. In relatively narrow stripes, in which mode cut-off occurs below the tenth mode, leaky modes whose electric field falls to zero at the edge of a 30-μm-wide region around the stripe are assumed. The electric field of light (E) in the waveguide can be expressed as a series of guided modes as

$$E = \sum_n A_n e_n, \quad (7)$$

since the guided modes for the same waveguide are orthogonal. The spot deformation caused by the waveguide propagation can be expressed as a divergence of modes that have different propagation constants from each other. At the boundary of two stripes, where the stripe width increases by 1 μm, the mode in former stripe can be expressed as

$$e_{n,m+1} = \sum_k B_{kn}\, e_{k,m}, \quad (8)$$

$$B_{kn} = \left\langle e^{(0)}_{k,m+1} \middle| e^{(0)}_{n,m} \right\rangle \quad (9)$$

Then the mode $e^{(0)}$ can be modified into the mode $e^{(1)}$ to take

into account the perturbation caused by changes in the refractive index due to the injected carriers.

$$e_n^{(1)} = \sum_k C_{nk}\, e_k^{(0)}, \tag{10}$$

$$C_{nk} = \frac{\langle e_k^{(0)} | \mu\Delta\varepsilon\omega^2 | e_n^{(0)} \rangle}{\beta_n^{(1)2} - \beta_k^{(0)2}} \tag{11}$$

$$\beta_n^{(1)2} = \beta_n^{(0)2} + \langle e_n^{(0)} | \mu\Delta\varepsilon\omega \, | e_n^{(0)} \rangle, \tag{12}$$

As the laser beam passes through the straight stripe, it is divided into perturbed modes and each perturbed mode propagates with its own propagation constant. All of the modes are then combined at the far end of the modulator. A similar operation occurs in the flared region, which is assumed to have a step-width stripe with 1-μm intervals.

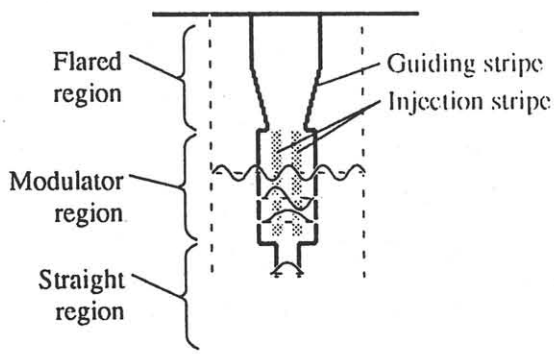

Fig. 3 Calculation model for the spot-size controllable laser diode.

4. Results and comparison with experimental results

Figure 4 shows the calculated dependence of the spot size on the modulator current density for the 2- to 5-μm stripe spacing. The spot size decreased with increasing modulator current density. The calculated spot-size variation ratio (W_{max}/W_{min}) for 0 to 5 kA/cm^{-2} of modulator current was 2, 2.2, 1.9, and 1.5, respectively, for Ws=2, 3, 4, and 5-μm spacing. The spot size variation ratio was largest when Ws=3 μm, which is consistent with the experimental data shown in Fig. 4. The experimental data for Ws=2 μm appears to show a shift in the injected current density from 3 kA/cm^2 to 4 kA/cm^2. This might be caused by hole burning, as was shown in Fig. 2. In the case of Ws=3, 4, and 5 μm, hole burning is suppressed because there are few injected carriers at the stripe center. These results show that smooth variation in the spot size and a large spot size variation ratio can be attained at a modulator spacing of 3 μm.

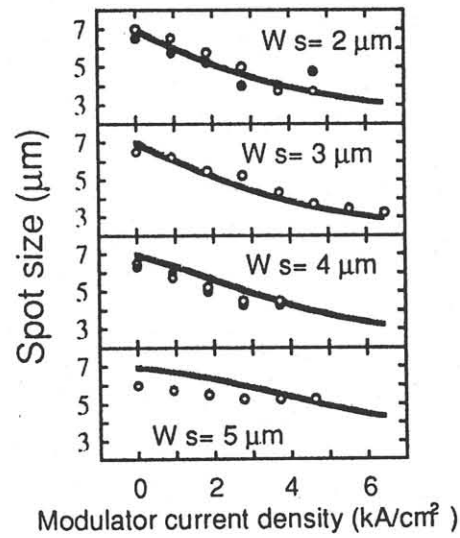

Fig. 4 Calculated and experimental spot-size dependence on the injection-stripe spacing.

5. Conclusion

We analysed the variation in the beam shape of a variable spot size laser diode that has a flared stripe and a twin stripe at the flare base. The injected carrier distribution in the modulator was calculated by using a Schwarz-Christofel transform to solve the Poisson equation in the p-type cladding layer while taking the carrier diffusion in the active layer into account. The spot shapes were calculated by using the coupling mode method and taking the change in the refractive index caused by the injected carrier into account as perturbation. The calculated results were consistent with the experimental data. A that 3-μm-spacing of the modulator was found to be best for achieving large spot size variation and smooth change of spot size.

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(3) G. Lengyel et al. IEEE J. Quant. Elec. QE-18 (1982) 618