TRANSVERSE MODAL BEHAVIOR OF TRANSVERSE JUNCTION STRIPE LASER EXCITED BY SHORT ELECTRICAL PULSE

Kam Y. Lau and Amnon Yariv

California Institute of Technology

Pasadena, California 91125

ABSTRACT

The transverse modal behavior of the transverse junction stripe (TJS) laser excited by short (70 ps) electrical pulse is investigated experimentally and theoretically. It is predicted theoretically and observed experimentally that the transverse mode strongly depends on the excitation pulse amplitude and the dc bias current (which is set below threshold). This dependence is found to be due to transient lateral carrier diffusion at the lasing junction.

Among the many laser structures developed for optical communication, the transverse junction stripe (TJS) laser [1-2] has established itself as an outstanding candidate [3]. In this paper we present results on the transverse mode behavior of TJS lasers under short (70 ps) intense electrical pulse excitation. It was experimentally found that the fundamental transverse mode dominates even under pulse excitation and its position depends on the excitation pulse amplitude and on the bias level. The results are successfully explained by theoretical calculations that include injected carrier diffusion. These results are important in high data rate communication links using single mode fibers, for the transverse mode pattern of the laser significantly affects the coupling between the laser and the fiber.

A schematic diagram of a TJS laser is shown in Figure 1. Confined by the heterostructure in the vertical direction, the carriers are injected across the p^+n homojunction in the active layer, thus creating an inverted population near the junction. The gain profile is provided primarily by the injected holes in the n region.

We shall calculate the time evolution of the optical mode gain after the injection of an intense narrow current pulse. We assume that the laser is biased way below threshold so that very few photons exist in the cavity. When the current pulse is injected across the junction, the carriers initially accumulate at the junction and do not support a mode with positive gain. Only after the carriers diffuse to a certain width will the mode experience net gain, and an optical pulse follows. The transverse mode structure of this optical pulse clearly depends on the amplitude and width of the carrier profile at the moment that the mode gain shoots above threshold. Before this moment, we can neglect the optical field and treat the conventional carrier diffusion problem in a straight forward manner.

The transient carrier density distribution satisfies the following field free diffusion equation:

$$\frac{\partial p}{\partial t} = D\,\frac{\partial^2 p}{\partial x^2} - \frac{p}{\tau} \tag{1}$$

where:

- p = hole density
- D = diffusion constant
- τ = spontaneous lifetime

Suppose that the laser is biased by a dc current and we assume at $t = 0$, a δ-function current pulse of total charge Q is injected across the junction:

$$D\,\frac{\partial p}{\partial x}\Big/_{x=0} = J_o + \sigma\delta(t) \tag{2}$$

where:

- J_o = dc bias
- $\sigma = Q/w\ell$
- w = thickness of the active layer
- ℓ = the length of the laser

The solution for (1) is:

$$p(x,t > 0) = \frac{\sigma}{\sqrt{\pi}d(t)}\,e^{-t/\tau}e^{-x^2/d^2} + P_s(x) \tag{3}$$

where the time dependent width of the gaussian $d(t) = 2\sqrt{Dt}$, P_s is the steady state solution. In using (2) as an initial condition, we have assumed that the source impedance of the drive circuit is infinite, i.e., a current source drive.

The actual source impedance is 50Ω and the diode shunt resistance is less than 5Ω.

We will next apply the solution $p(x,t)$ of (4) to obtain the transient solution of the electromagnetic laser mode. The relative permittivity of the medium can be written as:

CH1616-2/80/0000-0366 $00.75

$$\varepsilon(x) = \varepsilon_r + iG(p(x,t) - P_o) \tag{4}$$

where P_o is the carrier density for transparency, G is the coefficient as defined in (4), which is directly related to the gain coefficient of the laser mode in a straight-forward manner, and ε_r is the square of the refractive index. After suitable approximations, the field equation reads: (5)

$$\frac{d^2E}{dx^2} + \left[\frac{\omega^2}{c^2}(\varepsilon_r + iA - iB + iC) - \beta^2 - \frac{iAx^2\omega^2}{d^2c^2}\right]E = 0$$

where:

$$A = G\sigma/(\sqrt{\pi}d(t))$$

$$B = GP_o$$

$$C = GJ_o\sqrt{\tau/D}$$

where β is the propagation constant of the mode. The mode profile, with the boundary conditions $|E| = 0$ at $x = 0$ and $x = \infty$, are therefore the odd parity Hermite-Gaussians. Experiments show that the lowest order mode $m = 1$ dominates even under pulse excitation. The maxima of this mode occurs at

$$x_m = \sqrt{\frac{2\lambda}{\pi}}\, d^{3/4}\left(\frac{2}{Ad}\right)^{1/4}. \tag{6}$$

and the mode gain is

$$\beta_i \simeq \frac{1}{2\sqrt{\varepsilon_r}}\left[\frac{2\pi}{\lambda}(A - B + C) - \frac{3}{d}\sqrt{\frac{A}{2}}\right] \tag{7}$$

The mode gain can also be expressed as a function of time:

$$\beta_i = \frac{1}{2\sqrt{\varepsilon_r}}\left(\frac{2\pi(G\sigma/\sqrt{\pi})e^{-t/\tau}}{2\lambda(Dt)^{1/2}} - \frac{3(G\sigma/\sqrt{\pi})^{1/2}e^{-t/2\tau}}{4(Dt)^{3/4}} - \frac{2\pi}{\lambda}(B-C)\right) \tag{8}$$

The first two terms are due to the δ-function current pulse, B is due to intrinsic loss and C is the contribution from the bias current. The threshold value of β_i for lasing is $(1/\ell)\,\ell nR$ where ℓ is the length of the laser, R is the amplitude reflectivity.

We have assumed for convenience, in the above calculations that the current pulse is a δ-function. In actual experiments, the current pulse is of both finite width and amplitude. In the following numerical calculations, we shall therefore describe the strength of the δ-function by an equivalent current amplitude such that a current pulse of this current amplitude and of 70 ps duration (the actual value in our experiments) contains the same amount of charge as in the δ-function pulse. The other parameters we used are $\tau = 1$ ns, $G = 6.9 \times 10^{-8}\ \mu m^3$ as calculated from Stern's results, the thickness of the active layer is 0.2 μm, and the cavity length is 250 μm. The carrier density for transparency is taken to be $2.6 \times 10^{18}\ cm^{-3}$. Figure 2(a) shows a plot of

$$\beta_i' = \beta_i - \frac{\pi}{\sqrt{\varepsilon_r}\lambda}(B - C) \quad ,$$

i.e., the contribution to mode gain due to the current pulse for various injection pulse strength. We notice that β_i' diverges to $-\infty$ as $t \to 0$ according to equation 13. This is non-physical and results from our approximation. An exact numerical solution of the wave equation with gaussian profile shows that β_i' actually converges to zero at $t \to 0$ as shown in Figure 2(a). This, as mentioned before, results from the fact that a δ-function gain profile does not support a mode with gain.

From Figure 2(a) we see that the time delay for the mode gain to go above threshold is less for pump pulse of higher amplitude. Since the carrier diffusion distance d and time t are related by $d = 2\sqrt{Dt}$, we can plot β_i' as a function of d, as shown in Figure 2(b). This plot shows that for a given bias level, at the time lasing occurs, d would be smaller for higher pulse current. The peak of the actual optical mode when lasing first occurs is at a position x_m related to d. Figure 3 shows a plot of x_m for different bias levels and various pulse current amplitudes.

The dependence of the transverse mode position on the pulse current amplitude predicted above has been observed experimentally. The laser used was a TJS laser on a semi-insulating substrate with a cw threshold of about 30 mA. The laser was biased with a dc current below threshold, ranging from 5-15mA. It was driven with a step-recovery diode (SRD) which generates 70 ps pulses, of variable amplitude and repetitive at low frequency (250 MHz or 100 MHz). The laser responses to the current pulse with a single sharp optical pulse, the width of which is very possibly below 100 ps--the risetime of the APD used.

Figure 4 shows the transverse mode structure of the optical pulses under different excitation levels. As the peak current of the exciting pulse is increased, the mode shifts closer to the junction. Compared with the mode structure when the laser is operated cw above threshold, the pulsed mode shows a second "bump," which is possibly the second order transverse mode. The measurements at different pulse amplitudes are made at different bias levels, for the laser diode cannot be pulsed too high above threshold without destruction. The amount of mode shift measured are in good agreement with theoretical predictions in Figure 3.

References

[1] H. Namizaki, IEEE Jour. Quant. Elect., QE-11, 427 (1975).

[2] C. P. Lee, S. Margalit, I. Ury and A. Yariv, Appl. Phys. Lett., 32, 410 (1978).

[3] S. Nita, H. Namizaki, S. Takamiya and W. Susaki, IEEE Jour. Quant. Elect., QE-15, 1208 (1979).

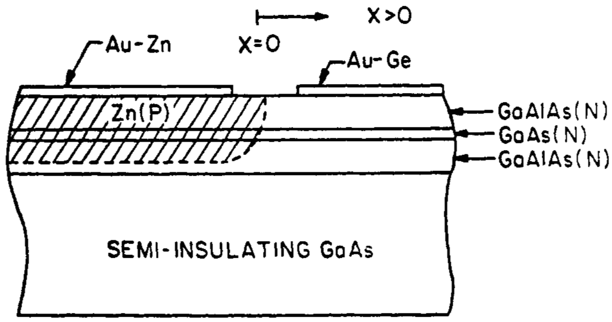

Fig. 1 Schematic diagram of the cross section of a TJS laser.

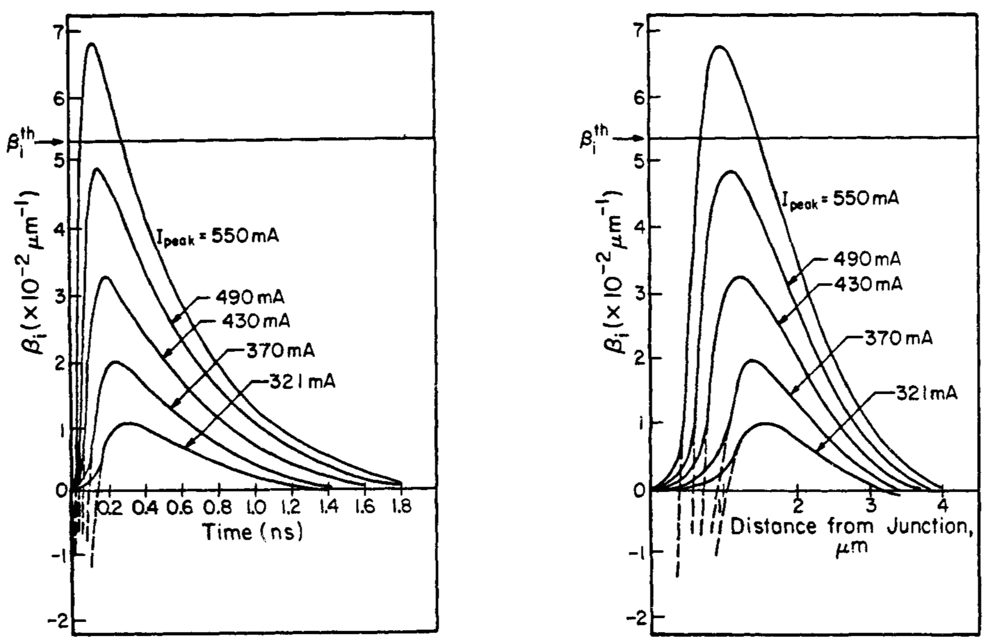

Fig. 2 Plots of mode gain vs (a) time after a current pulse is injected and (b) width of the diffused hole profile in the N side of the junction, for various pump current amplitude. β_i^{th} is the minimum mode gain for lasing when no DC bias is applied.

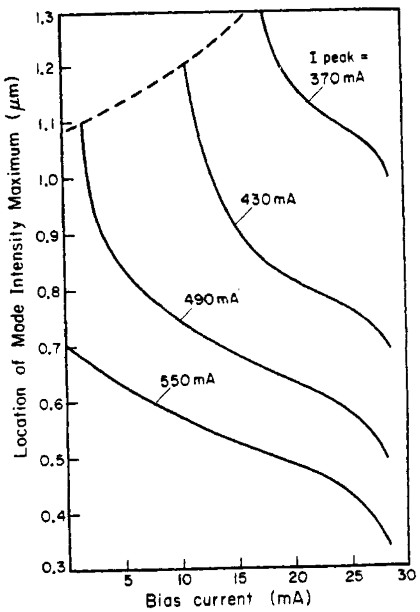

Fig. 3 Plots of positions of the peak of the optical mode at lasing threshold vs DC bias level, for various pump current pulse amplitudes.

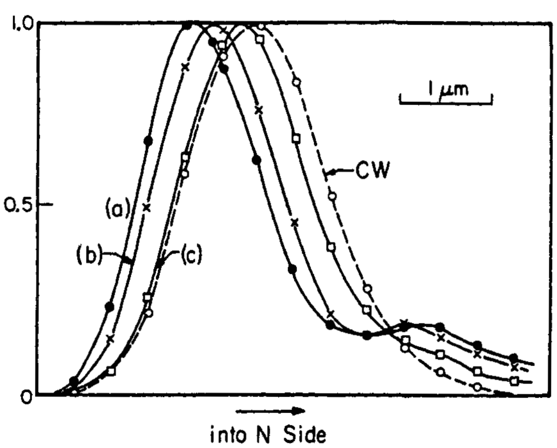

Fig. 4 Measured transverse mode profile with bias and peak pulse current respectively equal to (a) 12 mA,430mA, (b)15.5mA, 350mA, (c)20mA, 205mA. For comparision, the mode profile under cw operation is also shown.

14.4