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SINGLE-TRANSVERSE-MODE BIPOLAR CASCADE LASERS WITH THICK QUANTUM WELLS AND NO OPTICAL CONFINEMENT LAYERS

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ABSTRACT

The use of thick quantum wells with no optical confinement layers allows designing single-transverse-mode bipolar cascade lasers with high external differential quantum efficiencies. By controlling the number of wells the available laser power is maximized.

I. INTRODUCTION

The recycling of carriers by tunnel junctions allows designing bipolar cascade lasers (BCLs) with high external differential quantum efficiencies (DQEs) that increase with increasing the number of active regions, *M*. Thus, providing an additional gain factor which may be utilized in different applications such as direct modulation of optical carriers by analog signals. At the same time the requirement of single-transverse-mode (STM) operation of BCLs sets up an upper bound on *M*, which limits the DQE. This bound is not high (e.g. 2 or 3) [1], mainly due to the non-zero thickness of the optical confinement layers (CLs), which are used for the purpose of maintaining sufficient electron-photon interaction and avoiding large penalty on the threshold current.

In this work the DQE of the STM-BCL is maximized by eliminating the CLs and maximizing *M*. It is shown that this elimination does not sacrifice the optical power confinement, Γ, which also increases by increasing *M*. Thick quantum wells are used to ensure efficient collection of carriers in the absence of CLs.

II. THEORY

The steady state solution of simplified rate equations was used to derive the following expression of the DQE of a BCL,

$$\eta = (M\eta_s)[(\Gamma/M)/(Nt_w d/w)]. \qquad (1)$$

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Here, η_s is the conventional DQE of a single active region, *N* is the number of quantum wells in each active region, t_w is the thickness of each well, *d* is the lateral width of the active regions, and w is the power-equivalent modal spot size. The quantity between brackets represents the deviation of recycling efficiency, $\eta_r(\equiv \eta/\eta_s)$, from linearity with increasing *M*. It equals the ratio between the average optical confinement, Γ/M, to the maximum possible optical confinement, $Nt_w d/w$, of each active region. In a broad-area BCL, $Nt_w d/w \to Nt_w/w_\perp$, where $w_\perp$ is the power-equivalent modal width in the direction normal to the substrate.

An analytical expression of the upper bound on *M* has been derived by invoking the root-mean-square (rms) index approximation and applying the single array-mode condition [2]. This bound is given by,

$$\hat{M} = \left\lfloor \pi/\cos^{-1}\left(\cos(T) - (S/2)\sin(T)\right)\right\rfloor, \qquad (2)$$

where $\lfloor u \rfloor$ denotes the floor of *u*, $T \equiv k_o t\sqrt{\tilde{n}_1^2 - n_2^2}$, and $S \equiv k_o s\sqrt{\tilde{n}_1^2 - n_2^2}$. Here, *t* is the thickness of a single active region, *s* is the separation between successive regions, $k_o(= 2\pi/\lambda_o)$ is the free-space propagation constant, $\tilde{n}_1$ is the rms approximation of the core index, and n_2 is the cladding refractive index. According to (2), $\hat{M}$ increases by decreasing *t*, s, $\tilde{n}_1$, and/or increasing n_2. The index $\tilde{n}_1$ decreases as *N* decreases, which suggests using a single quantum well (SQW) instead of multiple QWs in each active region for the purpose of maximizing $\hat{M}$.

III. CONFINEMENT LAYERS

A planar $Al_xGa_{1-x}As$ design example of a BCL is used to demonstrate the effect of minimizing the thickness t_C of the CLs on η_r and Γ, under the condition, $M = \hat{M}$. Each active region of the specific design consists of a separate-confinement heterostructure (SCH) with a SQW of thickness, $t_w = 20$ nm. This relatively large thickness of the QW is chosen to ensure efficient collection of carriers in the absence of CLs (i.e. as $t_C \to 0$) [3]. The values of *x* are 0.4, 0.2, and 0 in the cladding, barrier, and QW layers. The separation between successive active regions is fixed at a minimum value which is limited by the thickness of the tunnel junctions. This minimum value is chosen to be $s = 100$ nm for 50nm-thick tunnel junctions. The thickness $t_c(\equiv t - t_w)$, decreases by decreasing *t*. It becomes zero when $t = t_w$. Fig.1 shows η_r and the corresponding $\hat{M}$ versus t_C. In the limit as $t_C \to 0$, $\eta_r \to 4.70$ and $\hat{M} \to 6$. Fig.2 compares Γ versus t_C

for this BCL (with $M = \hat{M}$) to that of the corresponding conventional SCH laser with a single active region (*M*=1). While in the latter case Γ reaches a minimum value of 0.02, in the former case it reaches a maximum value of 0.14, as $t_C \to 0$. This fundamental difference between the two cases is mainly due to the corresponding increase in *M* of the BCL as $t_C \to 0$. These results suggest eliminating the conventional CLs and maximizing *M* in the design of BCLs.

IV. STM RIDGE_WAVEGUIDE BCL

The above planar design of BCL (with *M*=6 and no CLs) was used as the vertical structure of a STM ridge-waveguide BCL as in [2], with a cover layer thickness of 1 μm and 0.2 μm in the ridge and slab regions, respectively. The ridge width, $d = 2.9\,\mu$m, was chosen using the effective index method to maximize the lateral modal confinement under STM condition.

As a preliminary step to compute the threshold current density, J_{th}, the gain of a SQW was computed as in [4], with an intraband relaxation time of 50 fs. Because of the relatively large well depth that results from eliminating the CLs, the nonparabolicity of the conduction band was included in these computations through an energy-dependent effective mass, as in [5]. The peak-gain-current relation was used to compute J_{th} and the threshold current I_{th} as a function of the cavity length, L. In these computations, the internal quantum efficiency of a single active region is 0.8, the laser facets are uncoated while the optical propagation loss coefficients in the QW, tunnel, and cladding regions are 20 cm^{-1}, 50 cm^{-1}, and 10 cm^{-1}, respectively. The results show that at $J_{th} = 400$ A/cm^2, $L = 195\,\mu$m, $I_{th} = 2.3$ mA and $\eta = 2.86$. The corresponding $w = 1.7\,\mu$m^2 (with $w_\perp = 0.65\,\mu$m) leads to an available laser power of 60 mW, assuming a catastrophic damage power density of 35 mW/μm^2 outside the laser cavity.

V. TRADEOFF BETWEEN DQE AND AVAILABLE LASER POWER

Unlike η_r which is maximized by minimizing *s* and maximizing *M*, the power equivalent modal width $w_\perp$ (and consequently the available laser power) is maximized by maximizing *s* and minimizing *M* [1,2]. This tradeoff is verified by computing η_r and $w_\perp$ for the planar design of section III (with no CLs) as a function of *M* under minimum and maximum separation *s* between the active regions. As before, the minimum *s* = 100 nm while the maximum *s* is determined from the STM condition [2]. The results of computations in Fig.3 show that by reducing *M* and maximizing *s*, high values of $w_\perp$ are obtained (e.g. $w_\perp$=1.5 μm at *M*=2). However, this minimization of *M* sacrifices the optical power confinement and increases the penalty on the threshold current. In order to estimate the threshold current requirements, both of the threshold current per unit stripe-width $\bar{I}_{th}\left(\equiv I_{th}/d\right)$ and J_{th} were computed as a function of cavity length, *L*, at different *M* and maximum *s*. Fig.4 shows L and $\bar{I}_{th}$ at J_{th}=400 A/cm^2, as a function of *M*. At *M*=3 and maximum separation *s* = 0.45 μm the values of *L*=1.1 mm and $\bar{I}_{th} = 4.4$ mA/μm while $w_{\perp} = 1.1\,\mu$m and η_r = 2.3.

The above planar design (with *M*=3 and no CLs) was used as the vertical structure of a ridge waveguide, as in section 4. The cover layer thickness is chosen to be 1.5 μm and 0.2 μm in the rib and slab regions of this waveguide. The ridge width $d = 3.3\,\mu$m maximizes the lateral modal confinement under STM condition. The corresponding $w = 3.2\,\mu$m^2 (with $w_{\perp} = 1.1\,\mu$m) leads to an available laser power of 112 mW while $I_{th} = 14.5$ mA and η = 1.39.

REFERENCES

[1] T. A. Ramadan, "High-power expanded-core-waveguide edge-emitting bipolar cascade lasers," in Conference on Lasers and Electro-Optics, technical digest (Optical Society of America, 2006), paper JWB9.

[2] T. A. Ramadan, "Expanding the core: A new approach for the design of single-mode waveguides," *IEEE J. Lightw. Technol.* **23**, 3843-3856 (2005).

[3] H. Shichijo, R. M. Kolbas, N. Holonyak, Jr., R. D. Dupuis, and P. D. Dapkus, "Carrier collection in a semiconductor quantum well," *Solid State Commun*. **27**, 1029-1032 (1978).

[4] S. L. Chuang, *Physics of Optoelectronic Devices* (Wiley, 1995), Chap. 9.

[5] R. Nagarajan, T. Kamiya, and A. Kurobe, "Band filling in GaAs/AlGaAs multiquantum well lasers and its effect on the threshold current," *IEEE J. Quantum Electron.* **25**, 1161-1170 (1989).

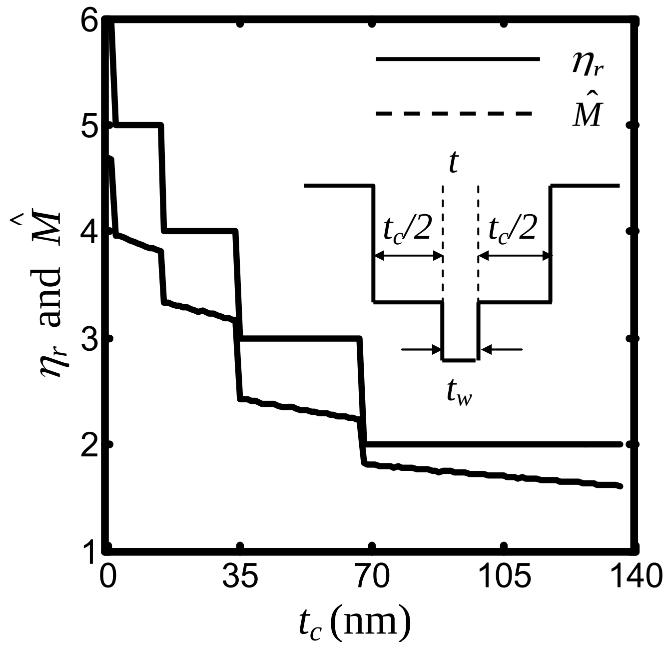

Fig.1. η_r (solid line) and $\hat{M}$ (dashed line) versus t_c. The inset shows t_c , t, and t_w on a schematic of the conduction band of a single active region.

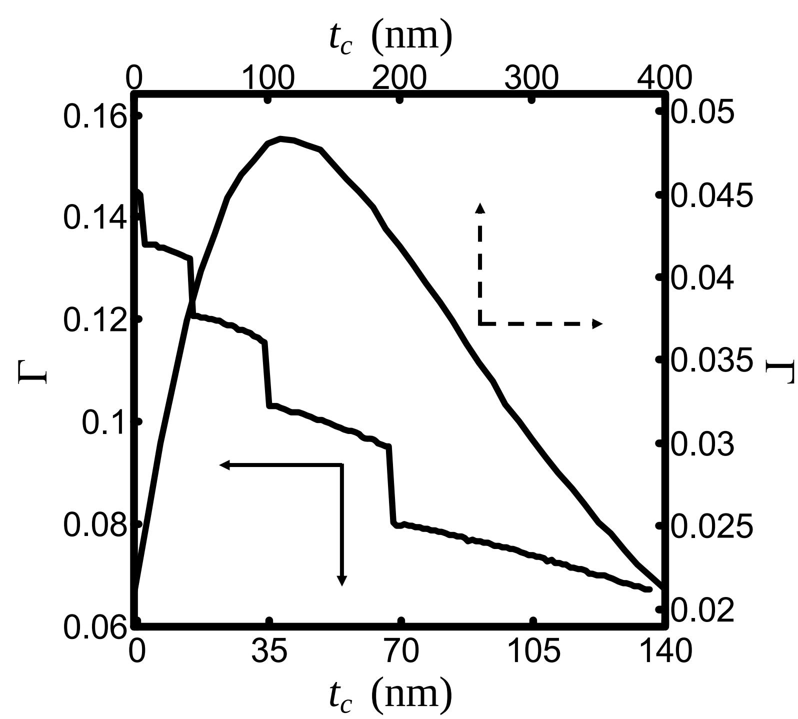

Fig.2. Γ of the BCL with $M = \widehat{M}$ (solid line) and that of the corresponding conventional SCH laser with M=1 (dashed line) versus t_c.

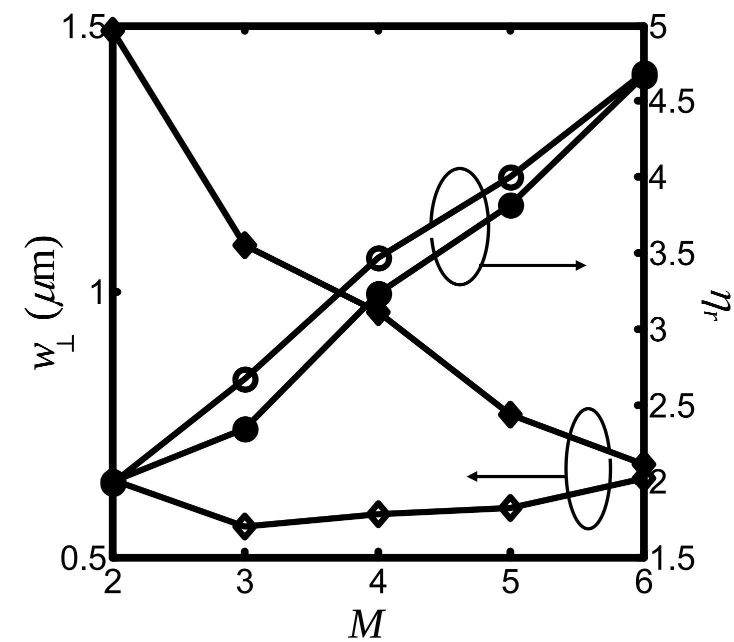

Fig.3. η_r (circles) and $w_\perp$ (diamonds) versus M under maximum (closed) and minimum (open) separation s between the active regions. The dashed lines have no meaning. They connect relevant data points to clarify their dependence on M.

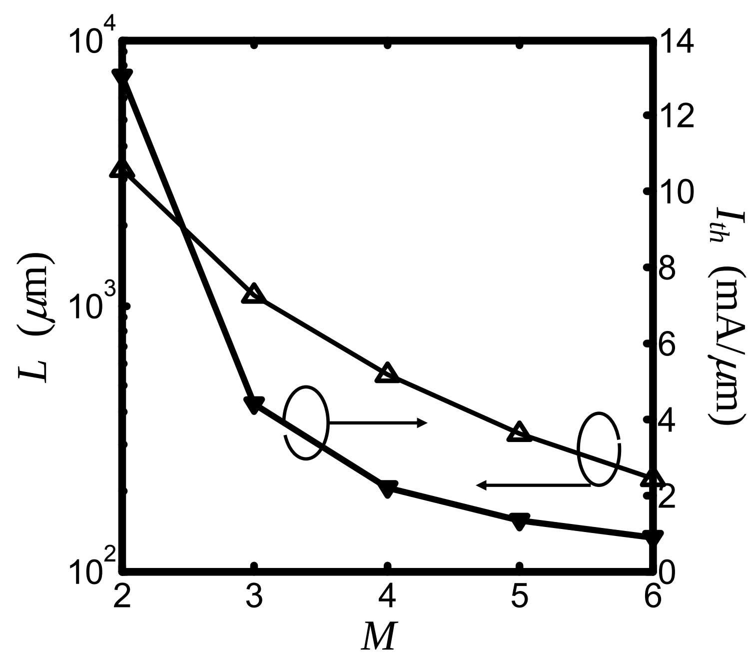

Fig.4. L (up triangles) and $\bar{I}_{th}$ (down triangles) versus M at J_{th}=400 A/cm^2. The dashed lines have no meaning. They connect relevant data points to clarify their dependence on M.