Increasing Output Power of Pulsed Eye Safe Wavelength Range Laser Diodes by Strong Doping of the *n*-Optical Confinement Layer

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***Abstract*—A semi-analytical model for internal optical losses at high power in a 1.5 µm laser diode with strong *n*-doping in the *n*-side of the optical confinement layer is created. The model includes intervalence band absorption by holes supplied by both current flow and two-photon absorption. The resulting losses are shown to be substantially lower than those in a similar, but weakly doped structure. Thus a significant improvement in the output power and efficiency by strong *n*-doping is predicted.**

***Index Terms*— high power lasers, laser efficiency, laser theory, eye safe spectral range, semiconductor lasers**

I. The problem

High -power pulsed diode lasers operating in the eye-safe region of 1400-1700 nm are becoming increasingly important, for applications ranging from EDFA pumping to laser radar technology. However obtaining high output power within this spectral range is a more complex task than for shorter wavelengths of ~ 1 µm, mainly due to higher optical losses at high currents in InGaAsP and AlGaInAs quaternary compound materials used in the eye safe range lasers. An important origin of this effect is accumulation of nonequilibrium carriers nonuniformly distributed in the Optical Confinement Layer (OCL) at high currents (see e.g. [1] and references therein). This has a particularly strong effect on optical losses in the quaternaries, for at least two reasons. Firstly, in these materials the free-hole Intervalence Band Absorption (IVBA) cross-section, which scales the optical losses, is rather high ($2\text{-}6\times10^{-17}$ cm^2 as opposed to $\sim1\times10^{-17}$ cm^2 typical for GaAs/AlGaAs materials at ~1 µm). Crucially, the ratio of the IVBA (free hole) cross section to the free electron absorption cross-section is particularly high ($\sim10^2$) in the eye-safe wavelength quaternary materials. Secondly, the low hole diffusion coefficients typical for quaternaries facilitate accumulation of nonequilibrium electrons and holes (a) in the *p*-OCL – the region between the active layer (AL) and the *p*-cladding layer as in Fig.1 - due to the carrier (current) flow through the *p*-OCL, and (b) in the entire OCL due to the carrier generation by two-photon absorption (TPA). Carrier accumulation due to both current and TPA leads to optical and recombination losses at high power ([1] and references therein). An effective method of counteracting the first, *current-induced*, mechanism of this nonuniform carrier accumulation is the use of a laser design with an asymmetric position of the AL, much closer to the *p*- than to the *n*-cladding, ensuring that the *p*-OCL is thin, in an extreme case almost non-existent. Such designs include one in which the asymmetric AL position is combined with the asymmetry of the refractive index steps at the interfaces of the *n*-OCL with the *n*-cladding (small step) and *p*-OCL with *p*-cladding (large step, Fig.1); see e.g. [2, 3] [4] and references therein) which is termed Extreme Double Asymmetric Structure [4]. Another design with the AL near *p*-cladding is that of the Slab Coupled Optical Waveguide lasers (SCOWLs) and Amplifiers; (see e.g. [5] and references therein), which has been very successful in high-power generation, albeit from relatively narrow stripes to guarantee single transverse mode operation. However even lasers with an asymmetric AL position (at $\lambda\sim1$µm) still exhibit saturation of optical power at high injection level. At least two effects can contribute to this. The first is the current-induced accumulation of electrons and holes in the *n*-OCL (Fig.1) which, although weaker than the effect in the *p*-OCL, may be of some importance if the *n*-OCL is broad (a few µm, as in SCOWLs for example) and the IVBA cross-section is high. The second is the effect of TPA, both direct and indirect due to Free Carrier Absorption (FCA) by TPA-generated carriers in the OCL, most importantly IVBA by TPA-generated holes [1].

II. Analysis and results.

Here, we show that in lasers operating in the eye safe spectral range, the effects of IVBA by nonequilibrium carriers can be substantially weakened by strong *n*-doping of the *n*-OCL. Such doping effectively removes both the current-generated carriers (by changing the dominant mechanism of their transport to the AL from ambipolar carrier diffusion to faster electron drift [6]) and those generated by the TPA (mainly by introducing additional carrier dissipation through recombination). This is partly offset by some carriers being supplied by the doping itself. However, inhomogeneously distributed carriers whose density is reduced by doping are both electrons and holes in equal quantities, whereas *only electrons*, whose absorption cross-section is small, are introduced by *n*-doping, so the net effect is loss reduction. This is an important difference from the case of *p*-doping of *p*-OCL.

The InGaAsP structure, designed to emit at λ≈1.5 µm, is shown in Fig. 1. The bulk InGaAsP active layer, with the composition as in [7], is located just ~0.15 µm (=the thickness of the *p*-OCL) from the *p*-cladding; the *p*-OCL and the adjacent part of the *p*-cladding are assumed to be relatively highly doped (say 5×10^{17} cm^{-3}) which however does not cause strong optical loss due to the small overlap with the field.

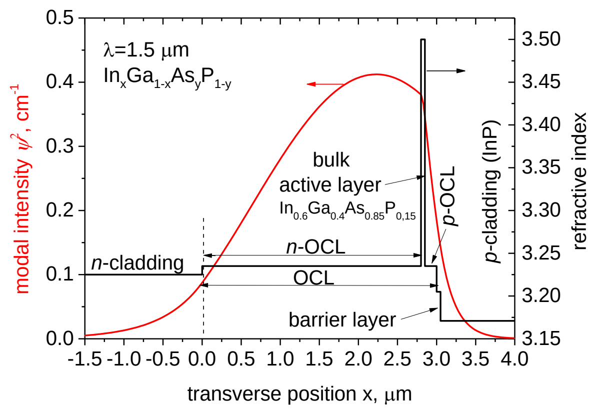

Fig. 1. Schematic of the waveguide structure evaluated and the corresponding intensity distributions in the (fundamental) transverse waveguide mode

Following the previous work [1], we separate the nonequilibrium carrier density profile in the (*n*-)OCL $\Delta N(x)=N_h(x)=N_e(x)-N_D$ (N_e and N_h being electron and hole densities) into three parts, caused by the nonzero time of carrier capture and the finite time of escape (N_b), the injection current flow ($\Delta N_j(x)$), and the TPA ($\Delta N_{TPA}(x)$):

$$\Delta N(x)=N_b+\Delta N_j(x)+\Delta N_{TPA}(x) \tag{1}$$

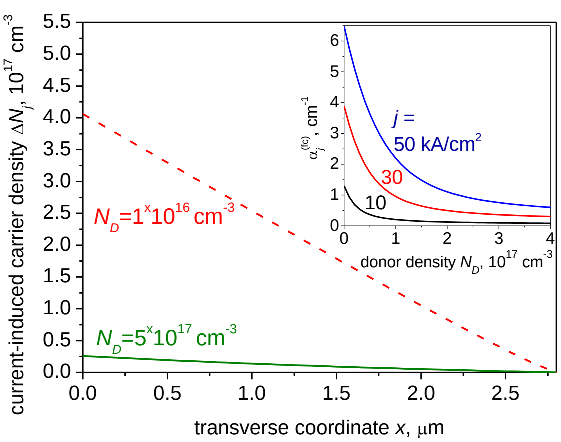

Fig. 2. Transverse profile of the current-induced nonequilibrium carrier density ΔN_j at a given current density (j=50 kA/cm^2) for different *n*-OCL doping levels. Insert: *n*-OCL doping level dependence of the internal absorption due to current-induced nonequilibrium carriers . T= 300 K

A convolution with the mode profile gives the corresponding contributions to the internal loss.

The distribution $\Delta N_j(x)$ can be calculated (Figure 2) for an abitrary doping level using the approach of [6]; the inset shows $\alpha_j^{(FC)}$. As can be seen in the figure, the doping significantly reduces the carrier density and hence the absorption even at highest current densities.

The carrier accumulation due to TPA in the OCL $\Delta N_{TPA}(x)$ is calculated for low doping using the model of [1], and for high doping, using a similar model for minority carrier (hole) diffusion, with linear (assuming $\Delta N_{TPA}(x) << N_D$) recombination included. As in the case of $\alpha_j^{(FC)}$, a pronounced reduction of absorption by doping is seen; the recombination aids the transport in depleting the TPA-induced carrier accumulation and hence reduces the absorption.

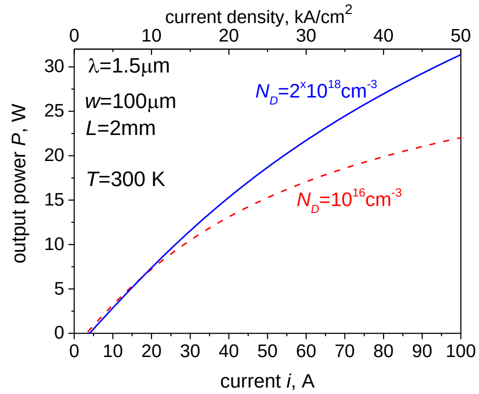

Fig. 3. Calculated light-current curves for low and high *n*-OCL doping

The output power is determined from a self-consistent analysis including the effect of the nonlinear loss mechanisms $\alpha_j^{(FC)}, \alpha_{TPA}^{(FC)}$ on both the output efficiency and effective current-dependent lasing threshold. The direct effect of TPA is also included. The results (Fig. 3) predict a substantial advantage of the highly doped *n*-OCL design. The current work deals with pulsed pumping (T= 300 K) but the design can be expected to be advantageous also for true CW operation.

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