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High Power 1.5µm Pulsed Laser Diode with Asymmetric Waveguide and Active Layer Near *p-*cladding

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*Abstract*— We report first experimental results on a high-power pulsed semiconductor laser operating in the eye-safe spectral range (wavelength around 1.5 µm) with an asymmetric waveguide structure. The laser has a bulk active layer positioned very close to the *p*-cladding in order to eliminate current-induced nonuniform carrier accumulation in the *p*-side of the waveguide and the associated carrier losses. Moderate doping of the *n*-side of the waveguide is used to strongly suppress the nonuniform carrier accumulation within this part of the waveguide. Highly *p*-doped InP *p*-cladding is used for low series resistance. An as-cleaved sample with a stripe width of 90 µm exhibits an output power of about 18 W at a pumping current amplitude of 80 A. Theoretical calculations, validated by comparison to experiment, suggest that the performance of lasers of this type can be improved further by detailed optimization of the waveguide thickness and doping as well as improvement of internal quantum efficiency.

*Index Terms*—Laser radar, optical pulse generation, semiconductor lasers.

# INTRODUCTION

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IGH power broad area pulsed diode lasers operating in the eye-safe spectral range, i.e. within the wavelength range from 1400 to 1700 nm, are becoming increasingly important, for applications including medical instrumentation and range finding / LIDAR systems [1]**.** Typical high power diode laser structures demonstrated to date, within this and other wavelength ranges, use a thin (< 0.1 μm) active region, either bulk or more often consisting of one or several Quantum Wells (QWs). On the other hand, the waveguide designs used differ substantially. Using lasers with ultra-narrow, single transverse mode symmetric waveguide structures ([2], [3], see also [4], [5]), output power values as high as ≈16 W at wavelengths of 1500-1600 nm have been obtained, at pump currents of 80 A, from samples with a length of 2 mm and a stripe width of 95 µm [2]. The advantage of such structures is that they effectively combat the nonlinear optical losses at high currents. At room temperature, these losses are mainly caused by current-induced spatially nonuniform accumulation of carriers in the optical confinement layer (OCL) [6]. Since each point in the OCL, except the near vicinity of the active layer, must remain electrically neutral (*detailed quasineutrality* principle), this involves simultaneous accumulation of *holes* and electrons. The presence of holes is particularly detrimentalin InGaAsP system materials used in the eye-safe spectral region devices since the free hole absorption cross section *σh* in these materials is almost two orders of magnitude higher than the free electron absorption cross-section *σe*  [7]–[9]. By having the active layer positioned quite close to the *p*-cladding, the ultranarrow waveguide design almost eliminates the carrier accumulation effect and the associated losses at high currents. The penalty is that in such waveguides, it is difficult to avoid high built-in optical losses caused by the substantial (almost 50%) penetration of the optical field into the *p*-cladding, where a large free hole density is present even at low currents. It is possible to reduce (but not eliminate) this effect by tailoring the doping in the claddings [3]–[5], which however leads to an increase in the series resistance and can also substantially increase the rate of leakage of electrons from the active layer into the *p*-claddings [10]–[12]. Alternative designs (mostly used at shorter wavelengths) use large optical cavity (LOC) separate confinement symmetric (or nearly symmetric) waveguide structures. Such a structure uses a waveguide, or Optical Confinement Layer (OCL), with a typical thickness over 1 µm, incorporating a thin active layer, most often near the middle [13]. The advantages and disadvantages of these structures are in complete contrast to those of the ultranarrow waveguide ones. Indeed, the broad symmetric waveguides allow the built-in losses to be decreased, by minimizing the waveguide mode overlap with the highly doped *p-*cladding layer. On the other hand, at high currents, they do suffer from the strong absorption due to current-induced spatially nonuniform accumulation of carriers (both electrons and holes) in the (relatively broad) part of the OCL between the active layer and the *p*-cladding. We have earlier investigated this effect in detail [6], specifically for InGaAsP-based lasers operating at λ≈1.5µm, and showed that it could lead to strong power limitations in these lasers. It has been shown also that these nonlinear losses can be decreased radically by reducing the distance between the active layer and the *p*-cladding. One implementation of such a strongly asymmetric active layer position which at the same time achieves reliable single-mode operation with a good far-field profile is a double-asymmetric structure. In this case, not just the position of the active layer, but also the refractive index steps at the waveguide-cladding interfaces are asymmetric, with the refractive index step between the OCL and the *n*-cladding being much smaller than that between the OCL and the *p*-cladding [6]. Structures with a broadened asymmetric waveguide and with an active region located very near to the *p*-cladding were implemented in AlGaAs/GaAs and AlGaAs/GaAs/InGaAs lasers operating at λ <~1µm [14]–[18] in both gain switched [14] and steady state [15]–[18] regimes. Structures of this type (termed by the authors Extreme Double [15], [17], or Triple-[18] Asymmetry Structures, or Asymmetric Decoupled Confinement Heterostructure [16]) showed increased radiation power and reduced series and thermal resistances compared to a typical structure with the active layer near the middle of the OCL.



Fig. 1. Schematic of the InGaAsP/InP laser structure and the waveguide mode intensity distribution.

 The reduction in optical losses when the active region is located near the *p*-cladding can be expected to be much more important in the eye safe InGaAsP lasers [6], in which the hole diffusion coefficient is much smaller than in typical AlGaAs based lasers, and the hole absorption cross section, much larger.

 In the current paper we demonstrate experimentally that, in agreement with theoretical predictions, a broad asymmetric laser structure with an active layer very near the *p-*cladding allows for very high output power in the pulsed regime.

 The design of the asymmetric single-mode InGaAsP waveguide structure with the active layer located near the *p*-cladding is shown in Fig.1.

 The device was designed to lase at a wavelength of λ≈1.5µm. The structure belongs to the class of *broadened* asymmetric waveguide (BAW) structures [19], in which most of the mode energy is localized in the OCL as opposed to the *n*-cladding. Experiments have shown that in AlGaAs lasers, similar structures allow for stable fundamental mode emission [14], [15]. The current structure is similar to the one previously analysed theoretically [20], but with some relatively slight differences. Firstly, the current structure, unlike the one simulated in [20], has no barrier layer at the OCL-*p*-cladding interface. This is possible because of the strong doping of the *p*-cladding, which in turn is made possible by its small overlap with the mode, as discussed above. Note also that, as mentioned above, this uniformly highly doped *p*-cladding gives also the added advantage over the graded-doping structures of [3,5] by ensuring lower series resistance, and also helps prevent electron leakage from the OCL to the *p*-cladding. Secondly, the current structure has a somewhat narrower OCL than the one studied in [20] (1.8µm instead of 2.8µm) and so, to maintain the mode localization in the OCL, has a larger refractive index step at the OCL-*n*-cladding interface. The narrower OCL translates into a far field somewhat broader than that predicted for the structure of [20], with a full width at half maximum of 24° instead of 17°.

The current waveguide design retains the main advantages of the structures studied previously [6], [20], with the weak penetration of the mode into the *p*-cladding ensuring low built-in optical losses, while the very thin *p-*side of the OCL virtually removes the main source of hole accumulation in the OCL at high currents, eliminating the associated losses. To minimize the remaining high-current losses due to accumulation of holes in the *n*-side of the OCL, the latter was *n*-doped, following the approach proposed in [20], though to a lower level of 1017 cm-3 ; the reason for this will be explained in more detail below.

# Experimental and simulations

The semiconductor structure was grown by metalorganic vapor phase epitaxy (MOVPE) method**.** Wafer processing was started by etching 90 µm wide current confining ridge waveguides (RWG) with reactive ion etching using CH4/H2 plasma. The mask for dry etching (SiN) was patterned using photolithography and the average depth of the waveguide defining grooves was 1160 nm from the surface of the semiconductor. Waveguide etching was followed by deposition of insulator (SiO2). SiO2 was removed by wet etching and photolithography from top to ridge to open 80 µm wide stripe through witch current can be injected to the *p-*contact layer. The *p-*side was metallized with a Ti/Pt/Au layer stack to form ohmic contact on top of the waveguide. Thesubstrate was thinned down to ~110 µm thickness by lapping with an AlOx abrasive, and backside of substrate was metallized with a Ni/Au/Ge/Au layer stack that was subsequently annealed at 370 °C, and cleaved and scribed into chips.

The chips with a cavity of 2mm were mounted *p-*side up on ceramic substrate for characterization. The laser diode was driven with current pulses generated by an Avtech AVOZ-A3-B laser diode driver. The output power values were obtained by dividing the measured average output power (Thorlabs S132C Germanium photodiode sensor) by the pulsing frequency (100 Hz) and optical pulse width (~60ns). The results obtained are shown in Fig. 2 (dots), for the sample with the injection efficiency (as defined in [21]) among the highest in the batch. Measurements of the optical spectra of the laser diode output showed that the maxima of the spectra shifted to shorter wavelengths by about 4 nm over a current range from 7 to 80 A, with the spectral width increasing from 7 to 16 nm. The fast axis far-field full-width at half-maximum at low currents (23°) was close to the theoretical prediction (24°) and increased to about 31° at a current pulse amplitude of 79 A, the highest current reached in experiments. Establishing the reasons for this broadening is reserved for further studies.



Fig.2. Experimental and simulated output power, and simulated internal losses. Two-photon absorption coefficient *β2,OCL*=6×10-8 cm/W [23]

As usual with high-power lasers, the output power curve in Fig. 2 is nearly linear at low currents and shows some saturation tendency at currents high above threshold (at *i* > 30 A). The total overall power achieved (≈18 W at 80 A from a laser with a stripe width of 90 μm) compares favorably with published results [2], [4], [5].

To explain these features, we have simulated the performance of the laser based on the approach outlined in [20]. The resulting data is shown in Fig. 2 alongside the measured points (the solid curve). Very good agreement is obtained by setting the injection efficiency (the only fitting parameter we have, having fixed the parameters of the semiconductor material) to *ηi*=0.73 which is similar to that reported in some earlier work on high-power 1.5 μm lasers [22]. Since in the short (2mm), as-cleaved cavity laser studied, the effects of longitudinal spatial hole burning on output power are known to be weak, we used a lumped model describing the increase in the internal losses and the associated decrease in the output efficiency with current via a transcendental equation:

  (1)

Here, *ηi* is the injection efficiency, is the output light photon energy, *e* is the elementary charge, and the output loss  was calculated assuming facet reflectances *R=*0.3. The electron leakage into the highly doped (1.5×1018cm-3) *p*-cladding was estimated to be negligible. The increase in the effective threshold current value *ith*(*i*) with current was taken into account as in [20], but did not affect the results much, as the output curve saturation happens at *i>>ith*, and the increase in *ith*(*i*) was not substantial. As expected, the main saturation mechanism was the decrease in the output efficiency  due to the increase in the internal loss . The latter is shown in Fig.2 as a dashed curve and was calculated as [20]**:**

 (2)

The built- in losses  were calculated as sum of free hole absorption in the moderately doped *p*-OCL and highly doped *p*-cladding, plus the waveguide imperfection loss of 0.5 cm-1. The loss  due to current-induced carrier accumulation in the OCL (in the current design with active layer located very near the *p*-cladding, this means mainly in the *n*-OCL) was calculated as in [20] using the analytical expressions for spatial current-induced carrier distribution determined by the current and the doping level [24]. The direct effect of two-photon absorption (TPA) and the free-carrier absorption losses due to the carriers generated by TPA were also evaluated as in [20], the latter using the analytical expression for the distribution of the TPA-generated carriers in the low-doping limit [19]. Finally, the free-carrier loss in the active layer  was determined from the active layer carrier density, found using the gain-carrier density dependence similar to that used in [20].

Calculated dependences of optical loss components on injection current are shown in Fig. 3. The figure shows that the free carrier losses in the active layer make a substantial contribution to the total loss, because of the use of the relatively thick bulk AL; however the increase in the carrier density in the AL, and hence of , with current is moderate. The main increase in the internal losses with current then comes from the TPA-related contributions and . Due to the thinner *n-*OCL in the current structure, the value of  as opposed to in [20] was sufficient to all but eliminate the losses , lowering them down to under 0.5 cm-1 at *i=*80 A. This has a noticeable effect on the simulated output: in a reference structure, identical to the current one except for a low , the simulated was as high as 2.5 cm-1 at 80 A (curve 5’) and the output power, correspondingly lower than in the current structure (dash-dotted curve in Fig. 2).

For eye safe LIDAR applications, spectral control of the laser output may also need to be implemented, which can be achieved by including a Bragg reflector in the laser cavity without compromising the output power [25].

We note finally that the catastrophic optical damage (COD) threshold in 1.5µm InP based lasers is known to be higher than in GaAs/AlGaAs devices. The latter, under pulsed pumping analysed here, show no COD at power densities at least several times higher than those achieved here. Therefore the COD is not a concern for our structure and operating regime.



Fig. 3. Calculated internal loss components: (1), (2), (3), (4), (5,5’). Parameters as in Figure 2 (1-5) and with  (reference structure, 5’)

In summary, we have shown experimentally that a laser with an asymmetric waveguide design and a bulk active layer located near the *p*-OCL, operating in the eye-safe wavelength range in the pulsed regime, is comparable, or even somewhat superior, in performance compared to a laser with a Quantum Well active layer and a narrow symmetric waveguide design. The result is in agreement with calculations; improvement in performance is expected after further optimization of the structure.

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