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Beam divergence and COD issues in double barrier separate confinement heterostructure laser diodes

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Abstract. The double barrier separate confinement heterostructure (DBSCH) design aimed at reduction of vertical beam divergence and increase of catastrophic optical damage (COD) level for high power laser diodes (LDs) operation is presented. Insertion of thin, wide-gap barrier layers at the interfaces between waveguide and cladding layers of SCH gives an additional degree of freedom in design making possible more precise shaping of the optical field distribution in the laser cavity. By comparison with the large optical cavity (LOC) heterostructure design it has been shown that the low beam divergence emission of DBSCH LDs can be attributed to the soft-profiled field distribution inside the cavity. This 'soft mode profile' seems to determine narrow laser beam emission rather than the field distribution width itself.

The potential problem with the soft-profiled but relatively narrow (at half-maximum) mode distribution is a lower COD level. Widening of the mode profile by the heterostructure design corrections can increase it, but care must be taken to avoid excessive decrease of confinement factor (Γ). As a result it is shown that DBSCH design is possible, where the low beam divergence and high COD level is achieved simultaneously.

Wide stripe gain-guided LDs based on GaAsP/AlGaAs DBSCH SQW structures have been manufactured according to the design above. Gaussian-shaped narrow directional characteristics are in relatively good agreement with modelling predictions. Vertical beam divergences are 13–15° and 17–18° FWHM for design versions experimentally investigated. Threshold current densities of the order of 350–270 Acm^{-2} and slope efficiencies of 0.95 and 1.15 W/A have been recorded for these two versions, respectively. Optical power at the level of 1 W has been achieved. The version with lower beam divergence proves to be more durable. Higher optical power levels are to be obtained after heterostructure doping optimisation.

Key words: high power, laser diodes, heterostructure, beam divergence, COD, quantum efficiency, threshold current.

1. Introduction

Low beam quality is one of the more troublesome drawbacks of laser diodes (LDs) in most of their applications. In comparison to other kinds of lasers, it has been said for instance that LD's (and arrays) 'produce a beam that does not appear to come from a laser at all' [1]. The reasons are:

- small size of LD's emission slot – of the order of emitted wavelength in the direction perpendicular to junction plane, what causes high beam divergence in this direction and very high optical power density at the emitting surface;
- different guiding mechanisms in both directions – in the junction plane and perpendicular to junction plane in many LD constructions and an astigmatism connected with it;
- susceptibility of active layer material constants to optical power density and temperature in a LD resonator (that means susceptibility to a LD drive level), what, including gain saturation, leads to self-focusing effects;
- technology dependent micro-nonuniformities in the active region superimposed on mentioned above self-focusing effects in the junction plane.

The narrow emission slot (high optical power density) and nonuniformities in the junction plane are most often responsible for low threshold of a laser facets catastrophic optical damage (COD), which is another limiting factor for applications.

Practically all applications would benefit from improved beam quality. In the 800 nm wavelength range they are mainly optical pumping systems, industrial (material processing) and medical applications. For optical pumping systems and material processing the issue of perfect beam focusing is essential. In all these applications an efficient fibre coupling is also of interest. All of that needs high beam quality.

The beam quality is defined using the M^2 parameter that is a measure of an actual beam profile deviation from the 'ideal' Gaussian profile. A product of the actual beam waist (ω – measured at the LD mirror – in the near field (NF)) times the beam divergence (θ – angle in the far field (FF)) is

$$\omega\theta = M^2\lambda/\pi, \qquad (1)$$

where both ω and θ are measured at $1/e^2$ level. $M^2 = 1$ means the ideal Gaussian beam case and the sharpest pos-

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sible focusing. For practical, disturbed or non-Gaussian beams higher $\omega\theta$ products can be achieved which means weaker focussing and is interpreted as increased M^2 value. In planar technology that is common for wide-stripe high power LDs, the technological processes determining the beam quality in both directions can be easily discerned. Therefore the M^2 parameter is usually evaluated separately in these directions.

In the direction perpendicular to the junction plane the width and optical field distribution at the emission slot are determined by the heterostructure design and epitaxial growth. It usually assures tight optical confinement and the (transverse) fundamental mode bonded inside the cavity. As a result, the emitted beam is usually Gaussian-like in typical constructions, with relatively low M^2 value (in the range $1 \div 4$ [2,3]), but the 'vertical' beam divergence can be high (30°–50°). This is troublesome in applications because of optical loss and quite complicated correction optics required.

In the junction plane, in the wide-stripe LD design the gain guiding is usually the main waveguiding mechanism. It is accompanied by carrier-induced index antiguiding and another guiding and anti-guiding effects that are sensitive to carrier and local temperature distributions, depending on a device drive level. The resulting lateral beam profile is irregular – multimode, multifilamentary and unstable as a function of a drive current. This leads to M^2 value in junction plane of the order of 100 and more [2], what means that a precise focusing is impossible despite relatively low beam divergence (10° or less [4]).

Possibility of the beam quality improvement by modifications of the LD design is the subject of this work. The direction perpendicular to junction plane is addressed here because high vertical beam divergence is a serious drawback in most of applications of high power LDs. Various concepts of heterostructure design aiming at the beam divergence reduction and the laser mirror COD level increase have been presented so far [5–16]. Here, the double barrier separate confinement heterostructure (DBSCH) design [16–18] is proposed as a most promising solution for high-power LDs. Insertion of thin, wide-gap barrier layers at the interfaces between waveguide and cladding layers of a conventional separate confinement heterostructure (SCH) causes a local guiding/antiguiding competition allowing for the optical confinement control, thereby increase of a light spot size at the laser facet and the beam divergence decrease. Simultaneously this can cause COD threshold increase. The design considerations are contained in Section 2. The commercial "Photon Design" 1D Waveguide Solver and the Far-Field Calculator have been used for calculations of field intensity distributions and directional characteristics. In Section 3 some preliminary high power operation characteristics of low vertical beam divergence DBSCH LDs are presented.

2. Vertical beam divergence reduction and COD level increase by laser heterostructure modification – theoretical considerations

One of the objectives of high power LDs design is to increase the COD level. In discrete (single stripe) LDs, the common way to attain this is to decrease the optical power density at the laser facet by the light spot enlargement. Various solutions leading to this effect have been described, such as widening of the waveguide layers in the large optical cavity (LOC) version of conventional SCH [5–10], using asymmetric waveguides [9–12,19] including a 'trapping' layer concept [12], inserting additional layers to modify waveguiding properties of symmetrical SCH [13–18] or inserting additional layers in a form of vertically integrated array [20]. In typical symmetric LOC solution the optical field distribution in the cavity is Gaussian-like, resulting in the FF distribution of the same shape. The asymmetrical positioning of quantum well inside the LOC [9,10] practically does not affect the optical distribution symmetry, the only effect being an improvement of higher order modes threshold discrimination. In the asymmetric heterostructure design (including trapping layer) the field distribution is asymmetric – not Gaussian-like [11,12]. Also in SCH heterostructures modified by inserting additional layers (DBSCH) the symmetric optical field intensity distributions can be far from Gaussian [15,16,18].

It can be noticed that the solutions above lead either to increase COD level or to decrease the vertical beam divergence. It is difficult to achieve both these goals simultaneously. Symmetric and asymmetric LOC and the 'trapping layer' solutions usually lead to increased COD level while the beam divergences remain relatively high, of the order of 25–30° FWHM [8,9,11,12,19] or are not specified [6]. In the DBSCH design the vertical beam divergence reduction is mainly addressed, resulting in really low 13°–15° FWHM [13–16,18] while maintaining good threshold and efficiency parameters. High power operation issues of DBSCH LDs are however hardly ever discussed [13,21]. This 'specialization' can be attributed to differences in the shape of transverse optical field distributions inside various cavities. In the wide LOC waveguide the field distribution is accordingly wide but rather tightly confined within the waveguide layers [6,9,10,12]. In the DBSCH concept shown in Fig. 1a, the additional degree of freedom in design is introduced by the presence of barriers that enables separate control of carrier and optical confinements. A local guiding/antiguiding competition at the barrier interfaces [16] allows for the tailoring of the optical field distribution. The designed local antiguiding dominance causes a weakening of the optical confinement and leads to formation of wide evanescent 'wings' of the distribution penetrating the cladding layers (Fig. 1b). The wings formation means the light spot enlargement and in consequence the emitted vertical beam divergence

($\Theta_\perp$) reduction and COD level increase. Extent of these effects depend on an optical intensity level at which the evanescent wings start to depart from the central cosine-like core bonded in the waveguide (within the barriers – Fig. 1b). This in turn depend on heterostructure design details. Calculated fundamental mode distributions for three different DBSCH SQW design versions are seen in Fig. 1b. All versions are intended for $\lambda = 810$ nm range and contain identical tensile-strained GaAsP QW of thickness $d_{QW} = 15$ nm. The versions are named A, C and D in the sequence of increasing mode effective width.

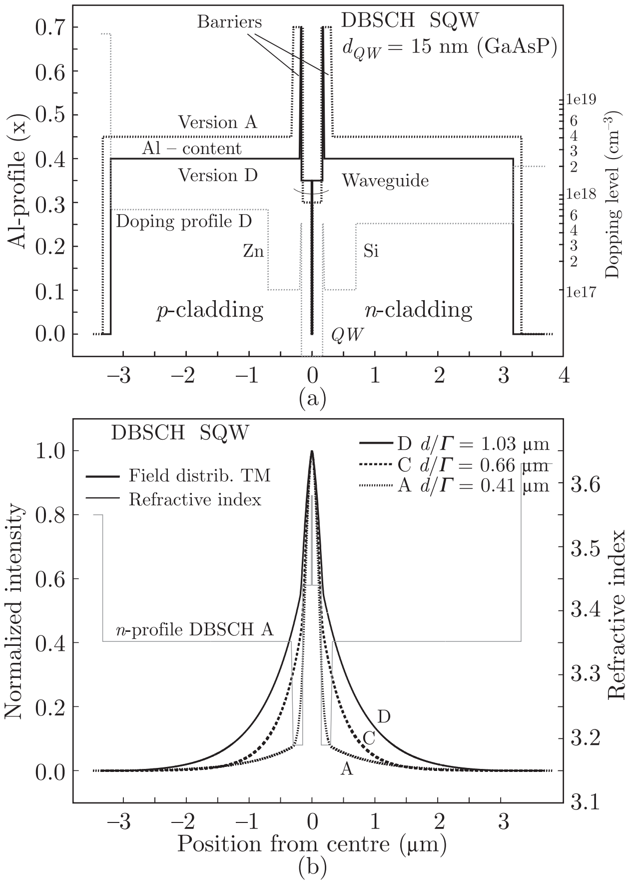

Fig. 1. The DBSCH SQW laser heterostructure design for 800 nm wavelength range. Al-content (x) and doping (Zn, Si) profiles for the design versions A and D. For the picture clarity the x-profile for C-version is not shown (but see text). Doping levels are similar for all versions. Thin, high-x barriers inserted between waveguide and cladding layers and relatively low x-values in wider claddings are the main differences of this structure in comparison to conventional SCH (a). Calculated optical field intensity distributions in heterostructure waveguides (assumed identical with NF profiles). Thick lines – fundamental TM_0 mode distributions for the design versions A, C, D – in a sequence of increasing values of d/Γ (effective waveguide thickness). Thin line – refractive index profile for the version A only (for clarity) (b)

The wide-gap barrier thicknesses of A, C and D versions are tb = 150, 30, 20 nm, the wide-gap-to-waveguide gradient layers are 30, 30, 10 nm thick, the waveguide thicknesses and compositions are $t_w = 140$, 130, 160 nm and $x_w = 0.3$, 0.35, 0.35, respectively. Other parameters, common for all versions are inserted in Fig. 1. It is important that relatively low x-values claddings (0.4, 0.45) are designed. The fundamental TM_0 (dominant due to GaAsP QW tensile strain) modes are characterized by confinement factors $\Gamma_{TM} = 0.0369$, 0.0227, 0.0146 and resulting effective waveguide thicknesses $d/\Gamma = 0.41$, 0.66 and 1.03 µm for A, C and D versions, respectively. The d/Γ can be interpreted therefore as a quantitative representation of the effective mode width for given DBSCH design. Calculated simultaneously Γ_{TE} values are distinctly higher: 0.0496, 0.030 and 0.0193, respectively.

For all these versions the calculated beam divergences $\Gamma_\perp$ fall in relatively narrow range of 12°–15° FWHM despite notable differences in NF profiles. The field distributions in waveguides are irregular in the sense that they differ from Gaussian profile. This is shown in Fig. 2, where mode profiles of high d/Γ versions (C, D) and their least square fits to Gaussian profiles are compared. Refractive index (n) profiles are shown in the 'background'. Oscillatory curves at the bottom of the graph (fit error) show the mode profiles deviations from their Gaussian approximations. For these two design versions the irregularities determined in such a way look similar. D profile seems to be somewhat more 'smooth' however, which is indicated by lower deviation (negative) maxima at the wide-gap barriers positions. The main difference between C and D is however in the mode profile effective widths, what can be controlled by the barriers and waveguide design details (described above).

In comparison to earlier mentioned LOC heterostructures, the DBSCH high d/Γ versions show intrinsic difference in waveguiding properties.

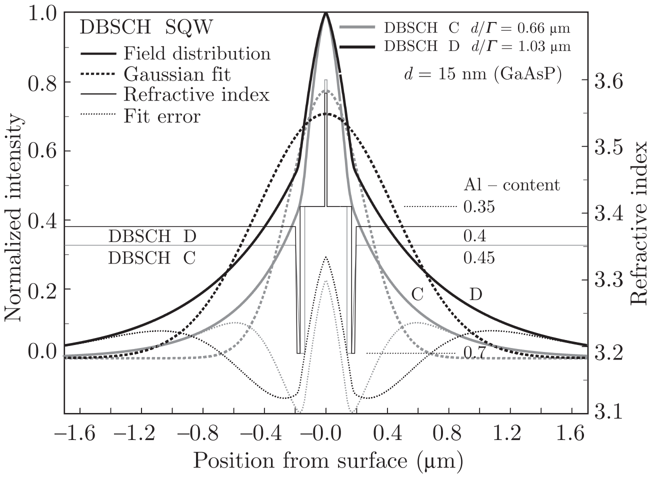

Fig. 2. Mode profile irregularities of the high d/Γ versions (C, D) of DBSCH laser diodes. Thick solid lines – TM_0 mode distributions (as in Fig. 1b). Broken lines – the least square Gaussian approximations. Thin broken lines – mode profile deviations from their Gaussian approximation (fit error). Thin lines – refractive index profiles for versions C, D

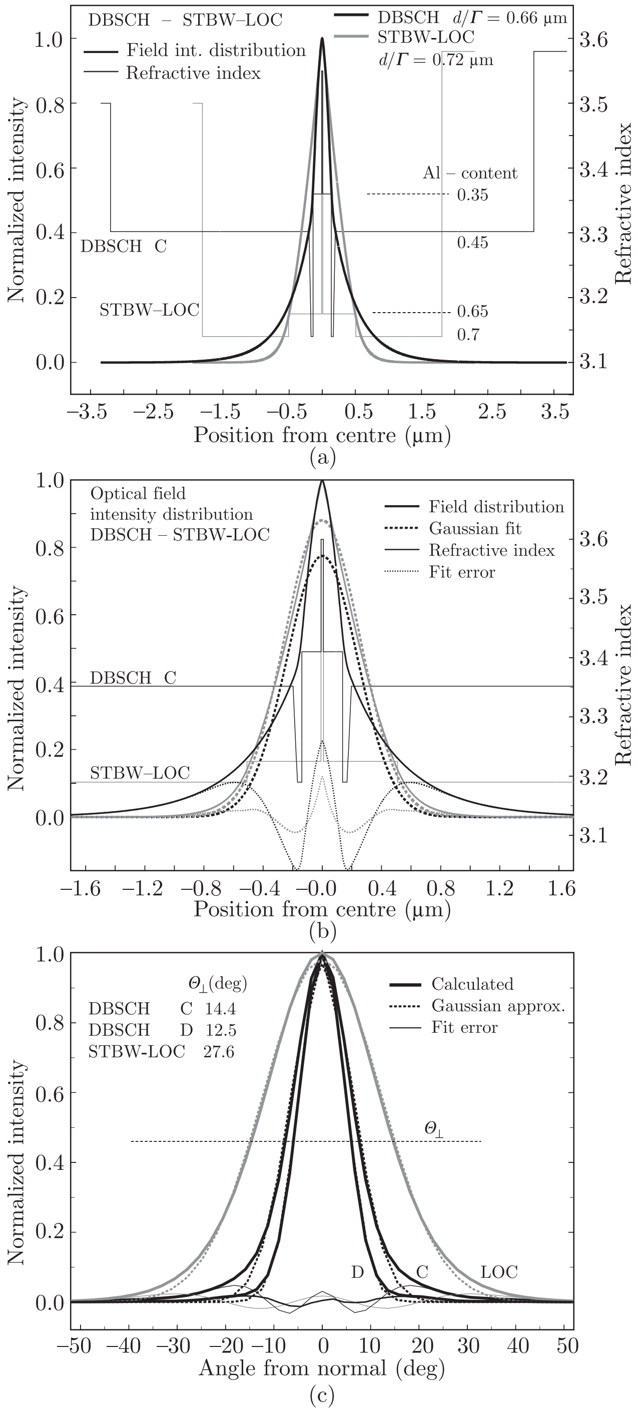

Fig. 3. Comparison of calculated vertical TM_0 field intensity distributions in waveguides of STBW-LOC and DBSCH SQW (version C) LDs. Refractive index profiles and Al-contents data are also given. The calculated field distribution in STBW-LOC is based on published heterostructure data [8]. Effective waveguide thickness $d/\Gamma = 0.72$ µm calculated here is slightly different from the figure of 0.8 µm given by authors (a,b). Calculated laser emission FF characteristics corresponding with the field intensity distributions shown in Figs. a, b, and similarly for DBSCH version D. Here the calculated beam divergence FWHM ($\Theta_\perp = 27.6°$) for STBW-LOC is similar to the experimental result of 27° given by authors (c). This enhances credibility of the present comparison

This is explained in Figs. 3a–c. In Figure 3a refractive index profiles and calculated TM_0 mode profiles for LOC and DBSCH laser heterostructures of similar d/Γ values are compared. The LOC structure shown is based on the published data [8] on the STBW-LOC (step index broadened waveguide LOC) design proposed by FBH Institute (Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin), while the DBSCH is that of the version C. Both are SQW GaAsP/(AlGa)As structures designed for 800 nm wavelength range, containing tensile-strained QW of similar thickness (LOC – 17 nm and DBSCH – 15 nm). Design details are shown in Fig. 3a – the main differences are the Al-content levels higher in STBW-LOC than in DBSCH [18] and greater overall thickness of DBSCH. Thicker cladding layers in DBSCH are introduced to prevent the mode evanescent wings to reach GaAs regions of high absorption.

In Figure 3b the central part of Fig. 3a is shown. Mode profile details are visible, least squares Gaussian fits and the mode profiles deviations from their Gaussian approximations are enclosed. The mode profiles are different despite similar d/Γ values. The LOC mode tightly confined to the waveguide clearly closer approximates Gaussian profile – it is wide at half-maximum, with steep slopes. Wide evanescent wings of the DBSCH mode make the mode 'soft-profiled'. This mode remains however narrow at half-maximum due to the tight confinement of the central cosine-like 'core'. It can be widened by the barriers and waveguide design corrections resulting e.g. in passing from C to D version (Fig. 2).

Different mode profiles lead to different directional (FF) characteristics shown in Fig. 3c for STBW-LOC and DBSCH versions C and D. For all these distributions the profile deviations from their Gaussian approximations are of similar magnitude and relatively small. Then the M^2 figures are expected to be similar for both heterostructure concepts. The calculated beam divergences of DBSCH LDs ($\Theta_\perp = 14.4°$ and $12.5°$ FWHM for C and D, respectively) are however definitely lower than those of STBW-LOC LDs ($\Theta_\perp = 27.6°$ FWHM), despite similar d/Γ parameters.

Narrow beam emission of DBSCH LDs can be attributed to the soft-profiled optical field distribution in the cavity due to the evanescent wings penetrating cladding layers. This 'soft profile' looks to influence the narrow FF emission more than an overall (e.g. at half maximum) distribution width.

On the other hand, small mode width at half-maximum indicates that COD level can be relatively low because of a high local field intensity. Widening the mode profile can increase COD level as mentioned before, within the limit of an excessive Γ decrease (and increase of a threshold current density J_{th}). There is therefore a room for optimisation leading to low $\Theta_\perp$ and high COD level simultaneously, which is presented in Fig. 4. Optical field intensity distributions for STBW-LOC and DBSCH (versions C and D) LDs shown in Figs. 2 and 3 are recalculated here in such a way that their integrals over heterostructures (in vertical direction) are normalised. For normalised (unit) optical power guided in TM_0 mode of each of waveguides under consideration the field distribution peak is proportional to the local intensity maximum, indicating the COD risk. It is seen from Fig. 4, that similar COD levels for STBW-LOC and C-version-DBSCH can be expected, while lower peak intensity for D-version-DBSCH indicates higher durability (higher COD level). Simultaneously D-version is that of the lowest beam divergence and highest J_{th}. For DBSCH version A the COD level would be the lowest.

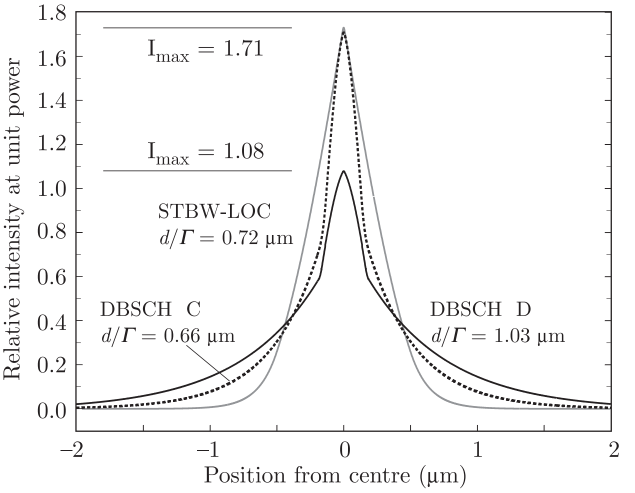

Fig. 4. Calculated TM_0 field intensity profiles in STBW-LOC and DBSCH (versions C and D) LD cavities after the normalization leading to unit optical power guided in each cavity. Therefore maxima of individual cavity field profiles represent local field intensity peaks corresponding with COD threshold. The higher local peak (for constant optical power flux) the higher COD risk

It can be noticed that, for normalised guided power, the ratio of TM_0 intensity peaks of considered waveguide versions are in good agreement with their Γ ratio (Fig. 4). This means that scaling via d/Γ can be useful method of COD level evaluation [5], even when various heterostructure designs are involved.

Scaling $\Theta_\perp$ via d/Γ parameter proves to be unreliable, at least in the case of non-Gaussian mode profiles in the cavity and when various heterostructure constructions are considered. It can be helpful however for comparison of heterostructures of the same type of design, especially those with Gaussian profile [8–10,22].

3. Toward narrow vertical beam divergence high power DBSCH SQW laser diodes – experimental

DBSCH SQW heterostructures, versions A, C and D have been grown by low pressure MOVPE. LDs made from these heterostructures are wide-stripe gain-guided devices with active stripes 100 μm wide defined by 160 keV He$^+$ implantation. Because of thick p-cladding layer (3 μm – Fig. 1) the implantation front is far from the active layer. LDs of cavity length of $L = 1$ mm have been formed by cleaving followed by LR/HR (AlN/AlN-Si) dielectric mirror coating without any special facet passivation procedure. Laser chips were indium soldered p-side down on Cu heat sinks.

The heterostructures have been grown according to the design data given in Section 2 and in Fig. 1. Standard material characterizations (PL, SIMS) have been used to verify an agreement of the design with the performance. The most serious detected disagreement was too high p (carbon) doping. This can negatively influence internal (nonsaturable) cavity loss (α).

CW characteristics of LDs made from the C and D heterostructure versions are shown in Fig. 5 (vertical FF patterns taken with the corrected CCD camera [4]) and in Fig. 6 (P-I-U curves). Only fundamental transverse mode with no trace of higher modes has been observed in all devices. Gaussian-shaped FF characteristics with low beam divergences have been recorded in quite good agreement with calculations (shown in Fig. 3c). Beam divergences of the D-version LDs ($\Theta_\perp = 13$–15° FWHM) are closer to the theoretically predicted $\Theta_\perp$ of 12.5° then those of the C-version (17– 18°) to their theoretically predicted $\Theta_\perp$ of 14.4°. A possible explanation is that the modelling is more exact for more smooth (more Gaussian-like) optical field distribution of the D compared to C-version (see Fig. 2). Another cause of disagreement can be (vertical) thermal index guiding, not included in modelling, but maybe not negligible in comparison to actual weak heterostructure index guiding.

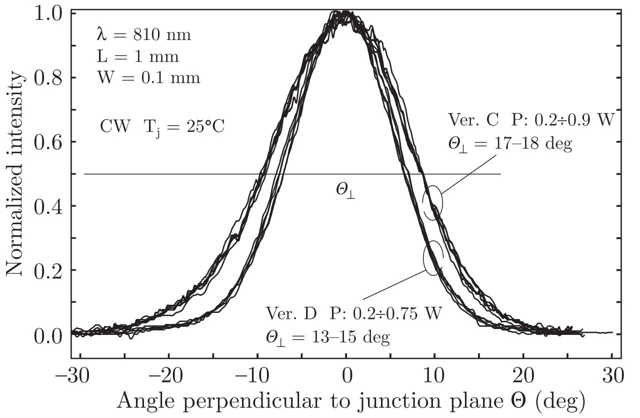

Fig. 5. Vertical FF CW characteristics of DBSCH SQW LDs made from the heterostructure versions C and D

Measured threshold currents (I_{th}) were 270–300 mA and 300–350 mA for C and D version LDs, respectively, which for present laser chip geometry gives the same numerical values of the threshold current density (J_{th}) in units of Acm^{-2}. Measured slope efficiencies (η) were 1.15 and 0.95 W/A for C and D version (Fig. 6). Higher threshold current of D-version LD is the result of its higher d/Γ value. Lower efficiency is however a shortcoming caused probably by high free carrier absorption due to excessive C-doping of p-claddings. Such interpretation can be justified by comparison with P-I characteristics of C-version LD. In this version the field distributions evanescent wings penetrating into p-claddings are shorter due to lower d/Γ, resulting in lower free carrier absorption and satisfactory slope efficiency $\eta = 1.15$ W/A. Similar η value should be possible for D-version LDs with optimised heterostructure growth. Because of higher d/Γ parameter (then higher COD level) this will lead to obtaining high power LDs of very low beam divergence. Lower series resistance of the D-version LD compared to C-version device seen in the I–V characteristics of Fig. 6 can be attributed to direct-gap claddings (x = 0.4).

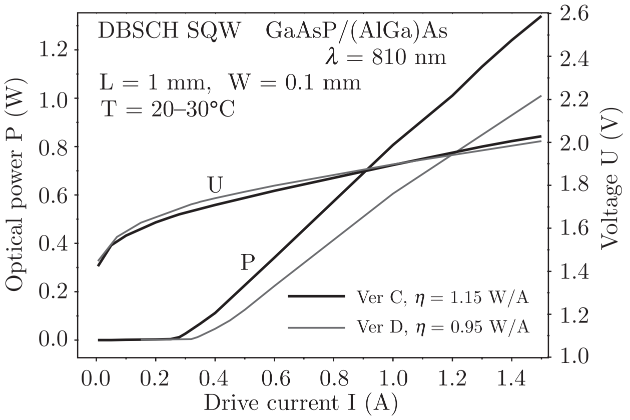

Fig. 6. L-I-V CW characteristics of wide stripe gain-guided LDs made from DBCSH SQW heterostructures, versions C, D

LDs made from the A-version heterostructure feature with slightly lower threshold current and even higher beam divergence of about 22°. They rather resemble conventional SQW SCH devices. High disagreement of the beam divergence compared to that theoretically expected is caused by tight confinement of the most of optical field (Fig. 1) and highly irregular field distribution leading to inexact calculations. For high power LD construction the D seems to be the version of choice because of low beam divergence and increased durability.

4. Conclusions

Double barrier separate confinement heterostructure (DBSCH) has been proposed as a modification of conventional SCH aimed at laser diode vertical beam divergence reduction and COD level increase for high power applications. Insertion of thin, wide-gap barrier layers at the interfaces between waveguide and cladding layers of SCH causes a local guiding/antiguiding competition allowing for the optical confinement control. This additional degree of freedom in design makes possible more precise shaping of the optical field distribution in the laser cavity. By comparison with high power LOC design it has been shown that low beam divergence of DBSCH LDs can be attributed to the soft-profiled optical field distribution in the cavity due to the evanescent wings, penetrating cladding layers. It seems that this 'soft profile' is the determining factor for narrow FF emission rather than the distribution width itself.

On the other hand, for the soft-profiled but narrow (at half-maximum) mode distribution COD level can be relatively low because of high local field intensity. The COD level increase by widening the mode profile is possible way, but care must be taken to avoid excessive confinement factor (Γ) reduction. It has been concluded that careful DBSCH design optimisation can lead to obtaining LDs with the low beam divergence and high COD level simultaneously.

Wide stripe gain-guided LDs based on GaAsP/AlGaAs DBSCH SQW structures have been manufactured according to the design described above. Experimental Gaussian-shaped FF characteristics of low beam divergences are in relatively good agreement with former modelling. Vertical beam divergences are 13°–15° and 17°–18° FWHM (depending on the LD drive current) for two heterostructure design versions investigated. Threshold current densities of the order of 350–270 Acm^{-2} and slope efficiencies of 0.95 and 1.15 W/A have been recorded for these versions, respectively. The design version with lower beam divergence proves to be more durable. Low slope efficiency of LDs of this version caused by non-optimised heterostructure doping prevents however really high power operation, which requires an improvement of growth conditions.

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