Invited paper

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High power diode lasers: topics relevant to optical pumping

B. MROZIEWICZ[*]

Institute of Electron Technology, 32/34 Lotników Ave., 02-668 Warsaw, Poland

Features of diode lasers pertinent to their application in pumps for solid state lasers and erbium-doped fibre amplifiers (EDFAs) are reviewed. Among them the factors restricting diode laser brightness and output power are discussed more in detail. Design and some properties of heterostructures used in fabrication of laser pumps for solid state lasers and EDFAs are described. Al-free lasers proved to be more resistant to the catastrophic optical mirror damage and are discussed more thoroughly. Broad area lasers, 1-D bars and 2-D arrays are surveyed and some remarks relevant to EDFA application are made. The paper is concluded with discussion of diode laser designs capable to provide the output beam of a better optical quality. In this context ROW and ARROW arrays as well as MOPA and MFA-MOPA structures are shortly described.

Keywords: diode lasers, high power, optical pumps.

1. Introduction

Diode lasers are ubiquitous and already became indispensable in a host of applications. This surge in the role played by these devices has been evoked by joint progress in fabrication technology and theoretical assessment of the mechanisms by which they operate. The driving forces behind this process have been mainly optical fibre communications and storage data devices. However, as device output power has scaled up, diode lasers have begun to penetrate other application areas and soon turned out very competitive as optical pumps for solid state lasers (SSLs). This success they owe to a very high electro-optical efficiency, and inherent ability to provide emission in a very narrow spectral line at the wavelength required by the absorption properties of the pumped media. The wavelength tuning and narrow spectrum saves the pumped object from enormous thermal loads typical for flash-lamp pumping which translates into much higher overall pumping efficiency. The relevant figures for this parameter are 1–5% and over 20% for flash-lamps and diode lasers, respectively. In result, diode-pumped lasers have typical operational lifetimes of 10 000 hours CW or 10^9 shots – about 100 times longer than for flash-lamps. Moreover, diode lasers offer the ultimate in compact packing, are maintenance free, and operate at low driving voltage, while recent technologies provide less expensive and more efficient means to manufacture them.

Similar arguments in favour of diode lasers can be quoted when they serve as erbium-doped fibre amplifier (EDFA) pumps with the difference, however, that in this application diode lasers have so far no counterparts. Apart of high reliability and long operational lifetime, the output power and efficiency of the EDFA pumps are even more important than in the case of DPSSL. Light wave telecommunication systems started with 16 channels, while today, the state of the art are 80 channels or more. Each increase in the number of channels requires at least a proportional increase in the optical power of the system. In addition, EDFA must incorporate gain flattening for more wavelengths and dispersion compensation for higher speeds, both of which drain signal power. Transition to higher speed 10 Gbps technologies and ultimately 40 Gbps deployments also require more power to be delivered to the signal.

Semiconductors suitable for fabrication of diode laser pumps are multi-component compounds of the composition selected by the required wavelength [1]. Basic semiconductors that can make the active region in a diode laser capable of emission adjusted in wavelength to the energy levels created by various dopants in a solid state laser host are listed in Fig.1. Since, as a rule, quantum well (QW) struc-

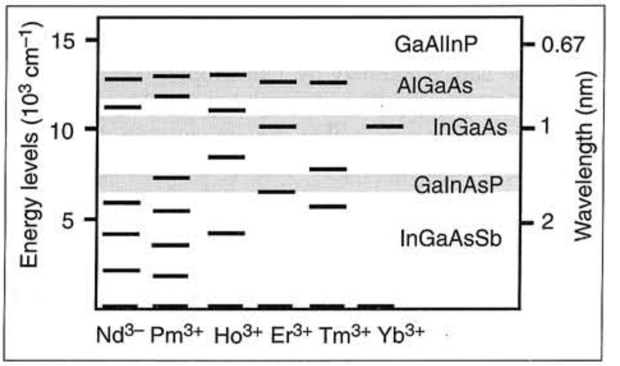

Fig. 1. Ionic energy levels involved in solid state diode pumped lasers and wavelength bands emitted by semiconductors appropriate for fabrication of suitable diode lasers.

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[*] e-mail: bomro@ite.waw.pl

tures are used, the required wavelength can be achieved by choosing appropriately composition of the active region, width of the quantum well or wells, and the waveguide configuration. Controlled lattice misfit introduced in the course of the laser structure growth may strain the QW region. The final goal is to lower laser threshold current and improve its temperature properties [2,3]. It has also been found that QW lasers exhibit higher resistance to degradation caused by dark line defects (DLDs) [4,5].

As it is shown in Fig. 1, the most important wavelength bands concentrate around the 808 nm, 980 nm, and 1480 nm wavelengths for SSL and EDFA pumps, respectively. The 980 nm diode lasers are less noisy than their 1480 nm counterparts [6] and have an opportunity to supplant the latter, in particular, in the under the sea telecommunication market.

In view of the reasoning above, the present paper will be restricted to laser pumps operating at the wavelengths of 808 nm and 980 nm.

Output power, brightness and operating lifetime will be considered in the first place as the most important for the pump performance. The output power of a diode laser may be defined in two ways. For continuous wave (CW) laser's power has its traditional definition of energy flow. The second definition applies to lasers operated in a fast-pulsed quasi-continuous (q-CW) mode. Here peak power refers to the maximum power level attained. Equally essential is the ability to focus the laser output to a small spot. This feature can be characterised by brightness defined as the luminous flux per unit solid angle per unit area of the output surface.

Operational lifetime is important for technical and economical reasons alike. For a given diode laser this parameter has an inverse non-linear dependence on the output power. A major challenge for diode laser manufacturers is, therefore, to extend the laser operational lifetime without sacrificing its power and brightness level.

2. Factors restricting brightness and output power of diode lasers

Maximum brightness of a laser source is defined by admissible density of the optical flux transmitted through the output mirror and is limited by catastrophic optical mirror damage (COMD) [7]. This damage is caused by local melting of the laser mirror within the active layer due to high absorption of laser light at nonradiative recombination centres. The damage is further extended from the surface into the active region in form of crystalline phase change, which is highly nonradiative [8]. Because of small volume of the material involved in the COMD process it proceeds in time shorter than 1 μs [9]. For this reason operation with pulses longer than 1 μs is considered as q-CW one.

The COMD power density is different for various semiconductors and depends on the laser wavelength, treatments applied to its mirrors and configuration of the diode laser waveguide as well as all the factors affecting temperature of the active region. By way of example, uncoated InGaAsP/GaAs lasers emitting at 808 nm exhibited COMD thresholds 10 MW/cm^2 [10] while for similar AlGaAs/GaAs lasers this parameter did not exceed 4 MW/cm^2 [11]. Coating of the mirrors with dielectric films, typically performed to assure proper reflectivity of the rear and front mirrors, strongly affects the COMD process. For AlGaAs/GaAs heterostructures emitting at 808 nm the improvement may be as high as 4 to 5 times [12]. Analogue improvement for InGaAs/InGaAsP heterostructures emitting at 980 nm is only by a factor of 2 or less and COMD values for coated mirrors amounted to 15 MW/cm^2 [13]. The less pronounced effect of coating in this case is possibly a result of the lower surface recombination velocity of the InGaAsP confinement layer versus analogue AlGaAs layers. Higher resistance of InGaAsP to oxidation due to the lack of Al in the compound may also play some role. Most probably it is the composition of the active layer that mainly counts with regard to the COMD power density while material of the confining layers is in this respect rather irrelevant [13]. In any case, figures quoted as the COMD power density for a particular design of the laser must be considered in relation to the laser geometry, total conversion efficiency and other factors that decide about temperature of the laser mirror within the optical cavity. The best evidence supporting this conclusion is that the record high COMD power density value of 19 MW/cm^2 was obtained for InGaAs/AlGaAs lasers with the mirrors coated to provide reflectivity 5% and 95% [14], while similar lasers, but made of GaAs/AlGaAs heterostructures and emitting at 870 nm, exhibited the record high COMD power density of 27 MW/cm^2 [15]. The latter related to the output power of 11.3 W CW from a diode laser with 100 μm stripe and corresponded to the brightness of 24 MW/cm^{2}sr.

Mirror coatings are always beneficial both from the point of the COMD power density and of the laser reliability and operational lifetime. Because of this reason many other coatings like sulphur and SiO_2 [16], ZrO_2 [17] or Si_3N_4 [18] films have been tried to passivate the mirror and modify the reflectance.

Another method to increase COMD power density exploits the concept of diminishing absorption at the mirrors by local enlargement of the bandgap. Although not accepted in practice due to technological difficulties, this method proved to be working in laser structures with non-absorbing mirrors (NAM) [19]. Very good results were also obtained with NAMs formed by coating the mirror with a ZnSe layer [20]. Recently, a laser with current injection window delineated by a SiN_x layer has been proposed [21]. The notion was to suppress current injection near the facets and thus to reduce the non-radiative recombination. Devices with such a window operated at high injection current and output power up to 150°C and showed no failure observed for analogue devices but without the window.

Restrictions of the diode laser output power arise from the heat produced in the device. This heat comes from the losses of the energy supplied to the laser that are caused by non-radiative recombination and series resistance of the laser. A measure of these losses is differential quantum efficiency and electro-optical efficiency. In modern laser designs based on QW heterostructures, these parameters can reach values as high as 91% [22] and 59% [13], respectively. Despite this extraordinary performance, the thermal management is an important factor for high power diode lasers because the expected operational lifetime and output wavelength are closely related to the temperature of the laser active region. Lifetime is greatly affected by the laser operating temperature because any increase in this temperature speeds up the propagation process of DLDs that are the main cause of the diode laser degradation [23,24]. Sophisticated cooling systems are therefore used to draw away the heat produced in the laser [25,26].

3. Design considerations and performance of the SSL diode pumps

3.1. Heterostructures

One of the major problems encountered in technology of the 808 nm AlGaAs/GaAs lasers is evoked by specific difficulty in attaining emission of this wavelength from sparate-confinement heterostructure (SCH) heterostructures with single GaAs QWs, $Al_xGa_{1-x}As$ barriers and $Al_yGa_{1-y}As$ cladding layers. Detailed modelling shows that the 808 nm wavelength is generated when the GaAs quantum well comprises 15 Ga and 15 As monolayers which translates into the QW width of 4.245 nm. The emission wavelength from such a structure is very sensitive to this dimension and to the laser operating temperature. The difficulties are easier to overcome when using multiple quantum well (MQW) structures with appropriately chosen thickness of the QWs and barriers (see Fig. 2). The problem of precise growth of very thin QWs in MQW structures is still left open since the width of the quantum wells in the MQW structure practically remains unchanged. Now, the MQW design features evident advantages over single quantum well (SQW) with regard to output power and temperature dependence of the threshold current. Multiplication of the number of QWs leads to effective volume enlargement of the electrically active region and the available output power is also adequately multiplied. Although this happens at the expense of increase in the threshold current, since more QWs have to be filled, it turns out that this increase is less than proportional to the number of QWs. Temperature dependence of threshold current has been found weaker for MQW than for SQW structures and if expressed in terms of the parameter T_o, values T_o = 128 K and 278 K have been calculated for the particular SQW and MQW structures, respectively (Fig. 3). The major advantage of the MQW structures is, however, a thicker waveguide and therefore lower power density at the mirrors. This allows for safer work with respect to COMD although a thicker waveguide means also a smaller confinement factor and in consequence a larger threshold current density.

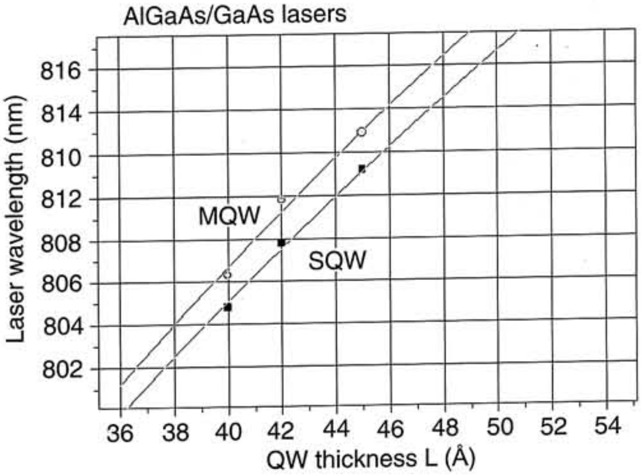

Fig. 2. Calculated wavelength of the light generated in SQW and MQW heterostructures vs. thickness of the quantum wells.

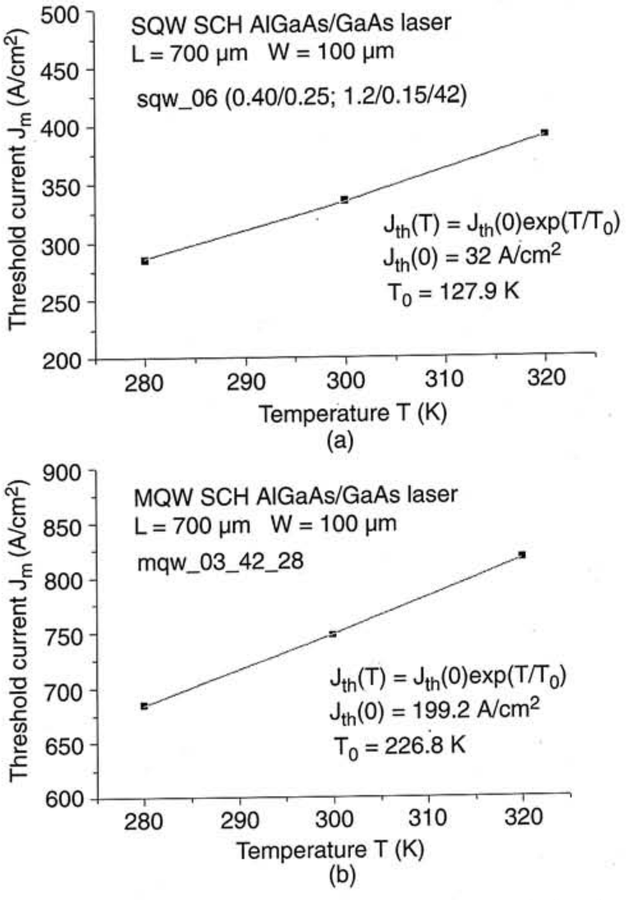

Fig. 3. Temperature dependence of threshold current calculated for SQW (a) and MQW (b) diode lasers.

Some more complicated approach is to extend the optical field in a laser by building into the waveguide additional barriers that modify its properties. Schematic cross-section of a laser with such barriers, so-called "double-barrier" (DB MQW) [27,28], is displayed in Fig. 4. Its main feature is presence of additional AlGaAs barriers with high Al content (60%) and of rather high thickness (30–50 nm) that are located in the waveguide symmetrically on both sides of the active layer [Fig. 3(c)]. The barriers contribute to widening of the mode profile and therefore reduce the power density at the mirror preserving relatively high confinement factor [29]. Although the DB MQW lasers show in result a relatively high resistance to COMD, their major drawback is a significant sensitivity of the threshold current and other parameters to any changes in the composition and thickness of the waveguide layers. Another disadvantage of the weaker waveguide formed in these lasers is their tendency to excite higher order transverse modes.

The obvious solution to the problems caused by the minute dimension of the GaAs quantum wells in the 808 nm lasers would be to add some aluminium to the GaAs QW layer and thus to enlarge its bandgap. Wider QWs could be then made while keeping the emission wavelength constant. However, aluminium present in the active region might be detrimental to the laser lifetime due to generation process of DLDs [30,31]. Since indium is known to inhibit this effect [32] it is usually added to the active layer that becomes then a quaternary alloy InGaAlAs [33,34]. In result we end up, however, with a quaternary compound difficult to grow with precisely enough controlled composition to obtain the desired wavelength. To avoid this difficulty a ternary compound GaAsP – less critical in this respect has been applied with the satisfactory results [35].

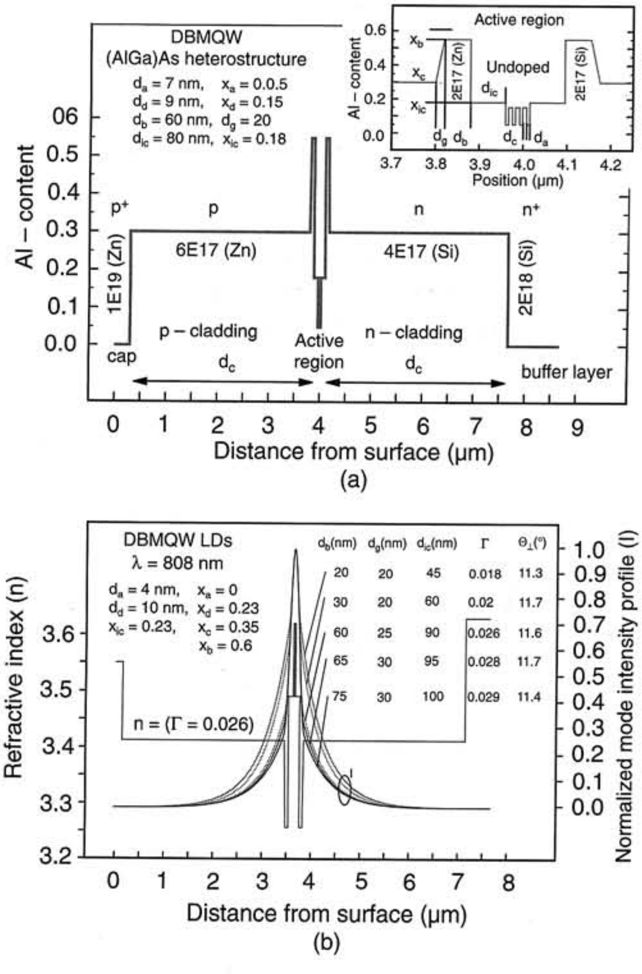

Fig. 4. Double-barrier (DB) MQW AlGaAs heterostructure lasers: (a) aluminium content profile as a function of the distance measured from the top, the inset shows details of the structure; (b) calculated fundamental transverse mode intensity profiles for two DB MQW structures with different heights of the additional barriers and a MQW structure of the same configuration but without the additional barriers (after Ref. 27).

3.2. Al-free lasers

In quest of a method that would allow to avoid the risk of failure brought forth by the Al containing layers, a concept of Al-free lasers has been conceived which has opened a new chapter in technology of high power semiconductor lasers. In these lasers the (AlGaAs)/GaAs heterostructures are replaced by (InGa)(AsP)/GaAs layers (see Fig. 5) grown most frequently by MO CVD process [36,37]. Absence of Al has eliminated, or at least diminished, degradation processs in the laser active region that is caused by generation of DLDs or dark spots [38,39]. Considering higher COMD thresholds observed for these lasers (see Section 2) it is obvious that they should show much higher resistance to rapid degradation. It is not certain, however, if the absence of Al gives definite advantage with respect to slow degradation. The uncertainty results from the methods applied to estimate this reliability, which are generally based on accelerated burn-out followed by calculation of lifetime through extrapolation. Nevertheless, it has been observed that InGaAsP/GaAs lasers with no protective coatings, that emitted in the 808 nm wavelength range the output power of 1 W CW at the ambient temperature elevated to 60°C, did not show any degradation for 30 000 hours. Similar behaviour was observed for InGaP/InGaAsP/GaAs lasers that emitted at 940 and 980 nm [10]. Other advantages of Al-free lasers like lower series electrical resistance and higher thermal conductivity [40] make them in many ways superior to classical AlGaAs/GaAs

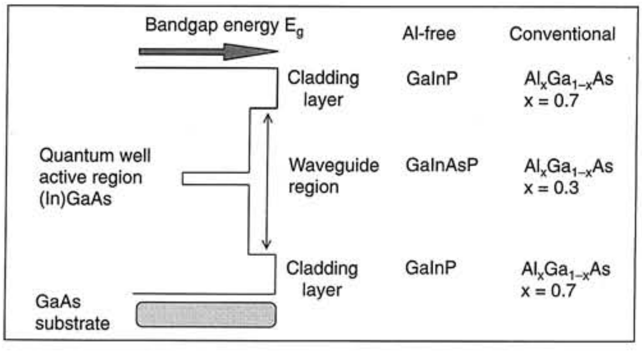

Fig. 5. Schematics of the Al-free lasers compared to conventional AlGaAs lasers.

counterparts in particular when 808 nm wavelength range is considered. Their merits are perhaps less eminent in the case of longer wavelength lasers, since there QWs can be made of pure GaAs. The record high CW power achieved so far from discrete 100 μm wide stripe InGaAs/InGaAsP/GaAs lasers emitting at 970 nm exceeded 10 W [40].

It would be unfair not to mention, however, that despite the above arguments the classical AlGaAs lasers have still adherents who recall their good experience with these lasers and underline simplicity of the structure and technology [41].

3.3. Broad area lasers and 1-D bars

The most obvious way to magnify the output power of a laser is to extend its active region along the heterostructure plane. That is leading to broad contact lasers with the active stripe usually 50 μm to 120 μm wide. The output power from a GaAs/AlGaAs SQW laser with a 150 μm wide contact and emitting at 808 nm was 2.9 W CW at the differential quantum efficiency of about 70% [42]. This power level can be significantly increased by arranging the larger number of diode lasers periodically spaced in 1-D arrays called bars [43] as depicted schematically in Fig. 6. The individual diodes in a bar may have the contact stripe 100 μm to 50 μm wide and be located on 100 μm to 300 μm centres. But to avoid filamentary action [44] or amplified spontaneous emission (ASE) [45] and eventually lateral transverse lasing, the laser bars very often comprise a number of optically and electrically separated groups of narrow stripe lasers [46]. Grooving the substrate or proton bombardment may provide the separation. Each group may consist, for example, of twenty 5 μm-wide stripe lasers with a total CW output of 1 W. Particular design depends on the compromise between thermal load and required brightness limited by COMD. For higher powers the laser bar may comprise as many as 200 lasers in a CW device [47]. The length of the bars is limited by their heat dissipation, with a typical 1 cm long bar producing nowadays up to 50 W CW [48]. The major design goal with these devices is to maximise the output power and brightness without compromising the lifetime inherent in the bars themselves.

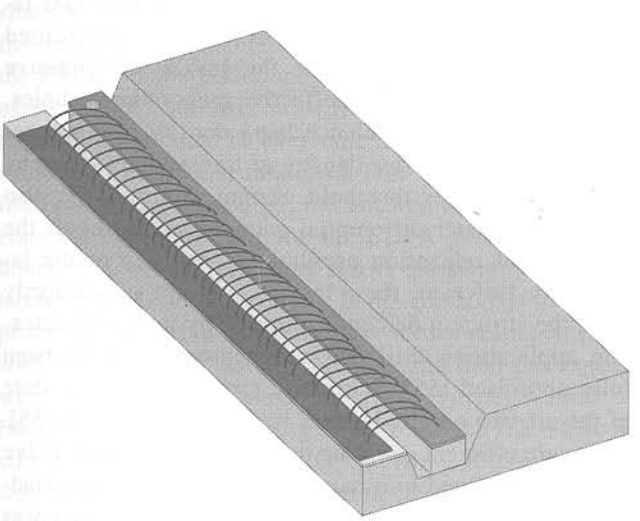

Fig. 6. A sketch of a diode laser bar soldered p-type side down to a copper sink and shown from the top. The n-type side of the bar is connected with a metallised insulator slab by bonded wires. The wires have been replaced in today designs by a metallic band soldered both to the diode bar and the insulator.

The fundamental problem one faces when designing broad area or multi-diode lasers is to conduct away the heat generated in the device. For that purpose they are usually first soldered to a heat spreader in form of a slab made of pure copper, copper alloys or highly conductive ceramics like aluminium nitride (AlN) and berylium oxide (BeO). Diamond heat spreaders are also used. Choosing a high-quality diamond material, with a measured thermal conductivity of 1800 W/mK at 36°C and optimised dimensions of the heat spreader, the overall thermal resistance could be reduced down to 0.34 K/W [49]. As high as 120 W/cm CW output power was obtained at room temperature from a diode laser bar mounted on a diamond heat sink [50]. The importance of this material is growing further because polycrystalline diamond films can be produced relatively cheaply by chemical vapour deposition [51]. One of the factors that must also be considered is the mechanical strain introduced to a bar due to differences in the thermal expansion coefficients of the semiconductor, soldering alloy and the material of the heat spreader. Ceramic and diamond heat spreaders have a great advantage in this respect.

Heat spreaders are as a rule fixed to heat sinks that may be cooled by enforced airflow or thermoelectric coolers but the most efficient are those based on liquid cooling. Very good results have been achieved with microchannel heat sinks [25,26], in particular, when used with a diamond heat spreader in a configuration shown in Fig. 7 [49].

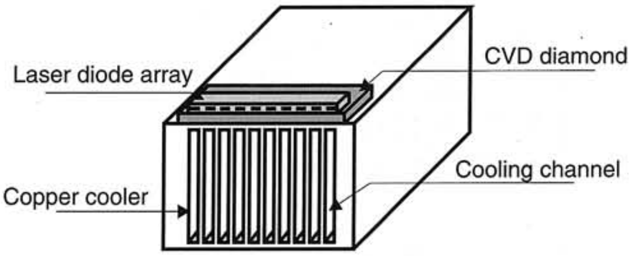

Fig. 7. Cooling system consisting of a diamond spreader soldered to a copper heat sink with channels provided for cooling water.

3.4. Two-dimensional arrays

To achieve still higher powers, bars are stacked into two-dimensional arrays. This is conceptually a straightforward approach but technically the 2-D arrays add some difficulties to provide uniform heat conduction away from the central part. The duty cycle and average power output of such stacks is entirely dependent on their thermal design. In one common approach to cooling, termed "back-plane cooling" or "direct cooling", each diode bar has its own integral heat exchanger [43]. Bar spacings range from 0.5 to 2.0 mm allowing a peak power density of 300–1500 W/cm^2

with higher power densities and closer spacing corresponding to lower duty cycles, ranging from 3% to 20%. In the case of CW operation, efficient cooling has been the major design issue in multi-bar modules. One of the practical solutions is "minichannel" cooling technology [52] in which individual bars are separated by copper cooling plates approximately 1 mm thick through which the cooling water flows [Fig. 8(a)]. The space inside these hollow plates is partitioned into flow channels by thin cooling fins separated by a few hundred microns thereby maximising the metal surface in contact with the cooling water. Using this approach the bars can be closely stacked with 1.8 mm bar-to-bar pitch, yet with a temperature diferential of only 0.3°C/W. This design has allowed stacks of 1 cm bars to be operated at 50 W CW per bar with lifetimes still measured in the 5000–10000 hour range. For example, a 2×10 array can produce 1 kW from a total emitting surface of only 4 cm^2 [52].

Another approach so-called "indirect cooling" is soldering each bar in the array to a common heat sink [53] [Fig. 8(b)]. For a q-CW operation up to 16 bars have been stacked on top of a single water-cooled heat sink [52]. This approach allows the bars to be operated at 100 W peak power per laser, with duty cycles up to 2% pulse duration of 1 ms or less. This type of 16-bar stack delivers a peak output power of 1.6 kW, it has a typical operating lifetime of more than 10^9 pulses [52].

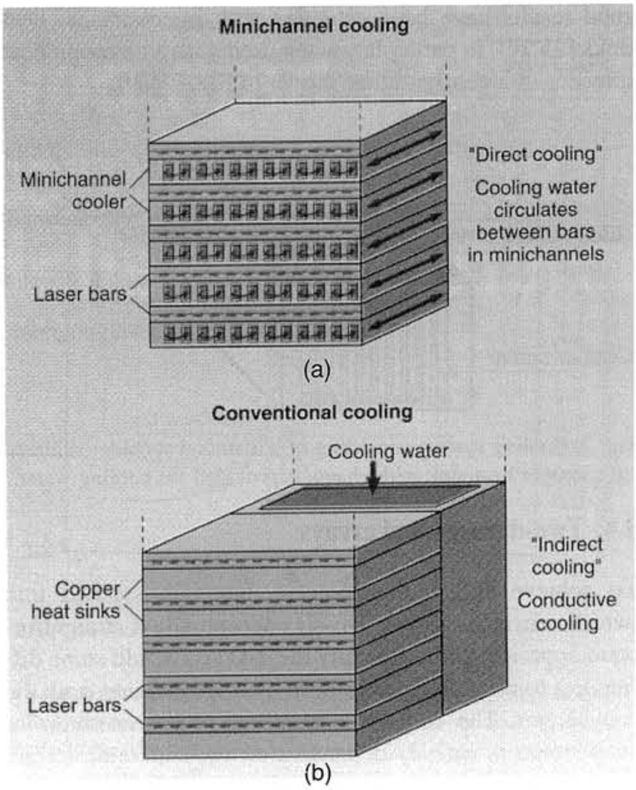

Fig. 8. Two-dimensional arrays of diode laser bars: (a) "back--plane" or "direct" cooling, (b) "indirect cooling" by a common heat-sink (after Ref. 52).

Alternatively, the bars can be embedded in grooves made in a heat sink. Technique involves formation of the grooves in highly heat conductive dielectrics BeO, AlN, cBN , silicon or even diamond [48]. The grooved substrate is then selectively metallised, and individual laser bars are placed in the grooves. Next, the bars are soldered in place forming a monolithic laser with a thermal resistance substantially lower than in the case of "stack" assemblies.

Depending on the application, the packaging density of the laser bars can be varied between 1 and 40 bars per square centimetre. Laser arrays are typically fabricated in 1cm^2 modules that are easily stackable into larger two-dimensional pumping assemblies. When using material of average quality and packaging densities of 40 bars/cm^2, a 20 bar stack may be operating at flux densities of 2.1 kW/cm^2 with a typical electro-optical efficiency exceeding 42% [48]. Such stack would have FWHM of 3 nm at 100 µs, shifting to 3.3 nm at 300 µs pulses. With various manufacturers pushing the standard laser bar from 50 W/cm to 100 W/cm the peak optical flux density may rise to 4 kW/cm^2.

4. Diode laser pumps for EDFAs

Laser diodes used as pumps for EDFAs must satisfy particularly severe requirements due to the crucial role that they play in the light wave communications systems. Apart from the desired 980-nm wavelength and narrow line they must exhibit high brightness, high CW output power and exceptionally long operational lifetime. The 980-nm wavelength emission can be obtained from InGaAs/GaAs strained QW SCH lasers. Strained QWs with interfaces free of misfit dislocations can be grown successfully, as long as the thickness is less than some composition dependent critical value. According to theory, the performance of strained InGaAs/AlGaAs QW lasers should be improved over that of unstrained GaAs/AlGaAs lasers because the biaxial compressive strain reduces the in-plane effective mass of heavy holes. This decrease in the valence band density of states results in a lower carrier density at transparency, thereby lowering the laser threshold current. Similarly, it also leads to a greater differential gain, which increases the fundamental relaxation oscillation frequency of the lasers [54]. However, these lasers could not satisfactorily fulfil the stringent demands imposed by telecommunication applications until fabrication processes have been fully optimised [55]. Schematic cross-section of a state of the art 980 nm diode laser is depicted in Fig. 9 [56]. To secure efficient coupling to an EDFA, the laser active region is confined to a narrow stripe buried in the cladding layers. This particular planar type diode laser was fabricated by a two-step growth with a combination of gas-source molecular beam epitaxy (GS-MBE) and metal-organic vapour phase epitaxy (MOVPE) [56]. Diode lasers of that type featured a threshold current of 20.5 mA and slope efficiency of 0.86 W/A. The device

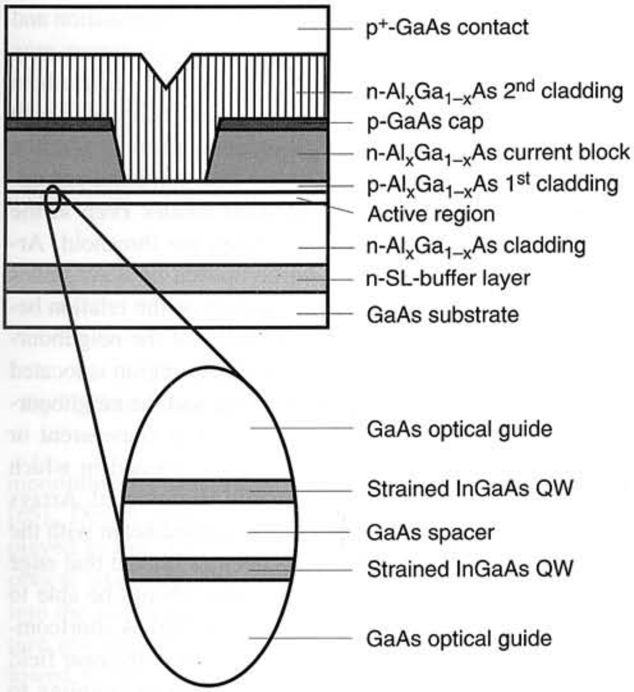

Fig. 9. Schematic cross-section of a strained QW SCH 980 nm laser (after Ref. 56]. Inset shows details of the laser heterostructure.

launched a kink free power of over 300 mW into an output beam with FWHM equal to 28° and 6° to 8° in the directions perpendicular and parallel to the junction, respectively. A stable fundamental transverse mode was maintained up to this power level.

A problem that plagued the 980-nm diodes was not long enough operational lifetime of these devices. Reports regarding the mechanism of their failure have indicated that the degradation was mainly related to the COMD since the presence of indium in the active region protected these diodes from formation of DLDs. As in the case of the 808 nm diode lasers one of the solutions might be to explore the Al-free structures. However, it was found that the difficulties could be overcome if the laser mirror were subjected to a special treatment. One of the most advertised procedure, termed E2, has allowed to extend the operational lifetime of the 980 nm EDFA pumps to 2×10^6 hours [57]. Recently, a new mirror passivation method termed I-3 was developed [56]. In this method a three-step process is applied in which the laser mirror is first cleaned with low energy (< 35 eV) Ar$^+$ ions and then passivated with 2-nm thick amorphous Si layer. The passivation is followed by standard coating of the front and rear mirrors with AR (Al$_2$O$_3$) and HR (AlO$_x$/Si) films, respectively. It was found that the I-3 passivated devices showed no sudden failure over 3000 h, even when operated at 250 mW CW output power. This was in a sharp contrast to conventionally coated diodes of the same configuration which suffered sudden failure after 250 hours of operation at 150 mW output power [56].

5. High power diode lasers with improved optical quality of the beam

All broad contact lasers emit multi-lobe beams comprising many uncontrolled transverse lateral modes. Such profiles are a direct consequence of the cross-section dimensions of the optical cavity which is thin enough to operate in a single perpendicular transverse mode but too wide to prohibit filamentary action and excitation of higher order lateral modes [58]. Moreover, spatial and time coherence of the waves emitted from such source is obviously rather low. In effect, the intensity distribution in the beam is non-uniform and its cross-section is elliptical with FWHM around 50° and 10° in direction perpendicular and parallel to the hetrostructure planes, respectively. Similar beam parameters are observed for diode bars since individual diodes, of which they consist, are not optically coupled. Such feature may not be prohibitive, however, for most of the SSL pump systems that in general may be classified as side-pumped and end-pumped. Geometry of diode laser bars is particularly well suited for side pumped configuration. If necessary, an optical system consisting of two sets of cylinder lenses may be used to focus the beam of each individual diode (Fig.11). In the end-pumped devices, a rel-

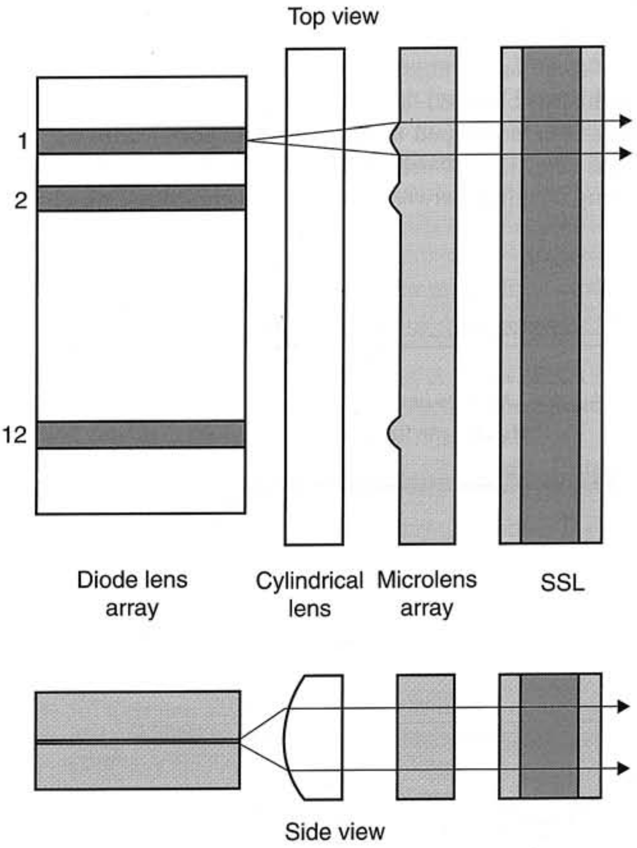

Fig. 10. Schematic diagram of an optical system used for collimating optical beam emitted by a laser bar. It consists typically of two sets of cylinder lenses designed to allow for concentration of the highly asymmetric (in cross-section) diode laser beam.

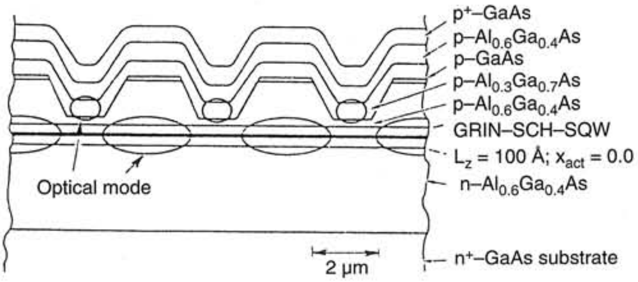

Fig. 11. Schematic cross-section of an antiguided resonant optical waveguide (ROW) array (after Ref. 59).

atively small diode array is located at one end of the solid-state laser rod, and the pumping beams are aligned with the lasing axis. No optical system may be required if the diode laser pump is close enough to the pumped object. Otherwise various optical systems are used to collimate such beams. As a rule they are composed of two sets of cylinder lenses, like the one shown in Fig. 11. Optical fibres with high NA are also used to collect and transmit the optical power generated in the laser [43].

In specific optical applications, optical quality of the beam as described above may be insufficient. Then optical coupling between the individual diodes in the bar would have to be secured. One of the ways to attain such coupling is to build monolithic arrays composed of many narrow-stripe lasers phase coupled through the leaky modes. Such arrays, termed "resonant optical waveguide" (ROW), have been developed in form of a number of different designs (Fig. 12) [59–61]. As it was found, the arrays with a strong coupling between the nearest neighbours, which are called "series" exhibit weak inter-modal discrimination and thus low coherence. Conditions for higher coherence may be more favourable in arrays with parallel coupling where each of the waveguide elements in the array is coupled with all the rest. Systems with parallel coupling show in addition uniform intensity distribution in the near field and are unyielding to excitation of higher order modes even at the drive currents that significantly exceed the threshold. Arrays under consideration can be composed of waveguides coupled in phase or antiphase depending on the relation between the width and the refractive index of the neighbouring stripes. In particular, if the optical gain region is located under the stripe to which the waves leak and the neighbouring stripe with a higher refractive index is transparent or lossy, then a resonance structure will be formed in which supermodes of the resonant cavity will be favoured. Arrays with such coupling emit a diffraction limited beam with the power reaching 1.5 W [62]. It has been estimated that edge emitting arrays with antiguides as above should be able to deliver up to 5 W of coherent CW power [59]. A shortcoming of the ROW arrays is that the light spot in the near field is laterally extended and this hinders efficient coupling to an optical fibre. This problem has been alleviated in antiresonant structures with a reflecting optical waveguide. Arrays of that type are termed "antiresonant reflecting optical waveguide" (ARROW) (Fig. 13). They make feasible generation of a stable, diffraction limited, beam with the output power of 600 mW and 42% of this power contained in the main on-axis mode. Calculations and preliminary experiments have shown that optimised ARROW structures can generate up to 90% of the power in this mode [63]. ARROW designs are unfortunately difficult for practical implementation because they are operational only if made of heterostructures with very strictly controlled optical parameters. Moreover, the ARROW structures suffer from the COMD enhanced by the small output aperture. Although 300 mW of output power has been obtained for a laser with 6 μm wide core [63] only NAM technology would really enable reliable operation at this power level. To summarise this point, we may conclude that fabrication of the lasers based on the concept that output beam is a synthesis of modes generated in the laterally elongated optical cavity is confronted with numerous difficulties. The way to overcome them is to combine a low power oscillator with a coupled optical amplifier. This idea has been materialised in a device called "master oscillator power amplifier" (MOPA) in which an optical signal was generated by a DBR laser, preamplified in a gain section and extracted trough diffraction gratings separated by consecutive amplifiers [64]. MOPAs were able to generate in a pulse regime (5 s, 1 kHz) peak power of 4.5 W with the efficiency of 50%. However, because of the phase coupling between the beams emitted by consecutive gratings, the intensity distribution in the far field was actually similar to that observed for ROW arrays.

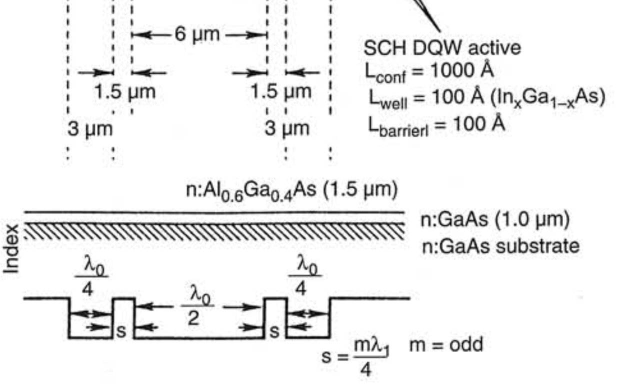

Fig. 12. Schematic cross-section of an anti-resonant reflecting optical waveguide (ARROW) array and the profile of the refractive index (after Ref. 63).

Problems that arise with phase coupling have been finally eliminated in a new class of laser devices called

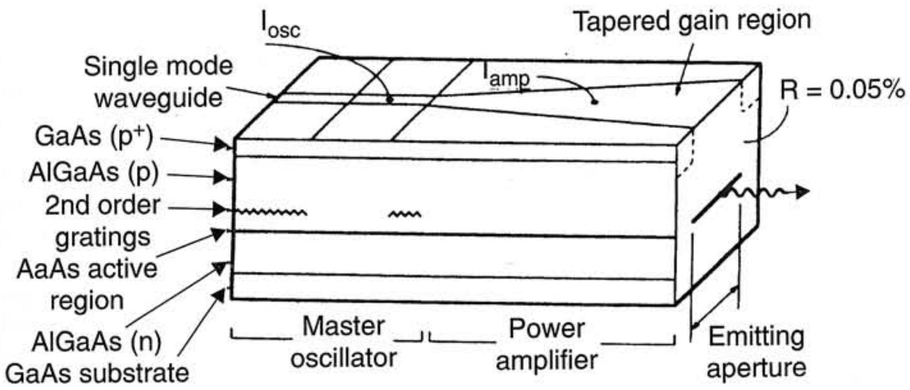

Fig. 13. Schematic diagram of the MFA-MOPA laser. The device consists of a DBR laser and a "flared" optical amplifier (after Ref. 66).

monolithically integrated flared amplifier (MFA-MOPA) [65]. Design principle of a MFA MOPA device is displayed in Fig. 13 [66]. It consisted of a DBR laser and an optical amplifier. The output of the DBR laser was injected into the flared power amplifier with 4-µm wide input aperture and an index guided region. The DBR output was allowed to freely diffract along the length of the amplifier that in the device being described was 2-mm long and its output aperture was 250 µm wide. An antireflection coating was deposited on the output aperture of the MFA-MOPA and had reflectivity of approximately 0.1%. The far field pattern of the output beam was of the kind typical for a single spatial mode generation with FWHM = 0.21° and the M^2 close to 1.5. The spectral characteristic featured a single longitudinal mode and replicated spectrum of the DBR oscillator. The output power at the driving current of 3.5 A exceeded 2 W CW in a single diffraction limited beam and that resulted in a wall-plug efficiency of η_o = 29%. Total output power plotted versus driving current was linear above 200 mW and exhibited differential efficiency η = 50%. The output power could be therefore controlled by variations of the driving current either of the amplifier or the oscillator. The MFA MOPA lasers still remain subject of research and recently output power of 2.4 W CW in a high quality beam ($M^2 < 2$) has been achieved from a single device [67].

6. Conclusions

Progress in epitaxial growth of III–V heterostructures set the stage for fabrication of diode lasers with parameters adequate for pumping SSLs and EDFAs. Particularly encouraging is very high wall-plug efficiency exhibited by diode lasers and availability of the high power emission in a spectrally narrow line of the required wavelength. Integration of discrete diode lasers into 1-D bars and then stacking them into efficiently cooled 2-D arrays brought about optical pumps of very high power. Application of the collimating optical systems enables to deliver high intensity beams to the pumped objects. Due to the crude design based on stacking diode laser bars into 2-D arrays the output beam of the current typical high power arrays is of poor optical quality both in terms of spatial beam profile and the FWHM spectral width. Monolithic arrays consisting of optically coupled lasers generate light beam of much better optical quality but so far the output power from these devices is orders of magnitude lower than that available from the bar stacks.

Although a lot has been achieved, there is still room for further improvements in the performance of high power diode lasers. This trend will continue to produce lasers that are more economical, compact, and reliable.

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