Pump Diode Lasers vs1.2

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1. Introduction

The basis of optical fiber amplifiers is the pump diode laser, their optical power supply. The availability of cheap and reliable pump diode lasers enabled optical amplifiers, in the form of erbium doped fiber amplifiers (EDFA), to conquer the long distance communication market [1].

Pump diode lasers are also enablers of fiber lasers (FL) [2] for material processing, ytterbium/erbium co-doped fiber amplifiers (YEDFA) for TV and fiber to the home (FTTH) distribution, and, more recently, direct diodes (DD) for printing and material processing. Pump lasers are also serving as versatile optical power supplies for active optics.

Nonlinear processes require high power diode lasers, like pump diode lasers, but with severe additional specific requirements on the amplitude and phase noise. High power laser diodes are enabling fiber amplifiers based on the Raman effect [3] as well as visible light generation in periodically poled lithium niobate (PPLN) waveguides and crystals [4].

1.1. Optical Power Supply

Pump diode lasers, being optical power supplies, have to perform with respect to transferred power efficiency and reliability. Thus, the pump diode has to be matched to the etendue (E) and absorption spectrum of the optical load, has to minimize the (parasitic) resistance to the electrical power supply, and has to allow for efficient removal of the dissipated heat. In order to model, design for redundancy, and to meet the required low failure rate in the field, an exact understanding of the reliability is essential.

Pump diode lasers serve many different markets and are based on a variety of technologies. Here we concentrate on fiber coupled pump lasers in the 9xxnm (900nm to 1100nm) and the 14xxnm (1400-1500nm) band. We also include fiber coupled 14xxnm high power diode lasers for Raman amplification and 9xxnm high power diode lasers for consumer application.

There is a huge literature, even within this limited scope, of fiber coupled devices in the two wavelength bands. We concentrate on referring to the origin of innovations and progress in the last few years, quoting articles, as well as patents.

1.2. Telecom Optical Amplifiers

Until five years ago, the development of high power pump and diode lasers was mainly driven by the demands of the telecommunication industry. Since the last review in this series of books [5], investments from the telecom industry have been dramatically reduced. The limited resources have been concentrated on scaling down fabs (while not losing the recipe) and on device cost reduction rather than performance improvement. Consequently, progress has slowed down; the field of pumps diode has matured. Section 2 is dedicated to 980nm pump laser diodes and section 3 to 1480nm pump lasers and 14xxnm high power diode lasers.

1.3. Power Photonics

Even before telecom applications, pump diode lasers have been used for DPSSLs (diode pumped solid state lasers), mostly for 808nm pumping of Nd-YAG 1060nm rod lasers. 808nm pumps diode for low power densities and low cost were developed to compete against the established pump technology (tungsten lamp) and to adapt to the system characteristics (high pump photon defect heating, non-hermetic, large etendue pump input).

With the demonstration of a diffraction limited fiber laser exceeding 100W [6], based on "all fiber" telecom technology, the ground was prepared for converging telecom and industrial pump technologies. This technology, often called "Power Photonics" is all fiber based, all solid state, highly efficient, reliable and completely free of open surfaces. The development has been spectacular, as demonstrated with the commercial availability in summer 2007 of a continuous-wave (cw) 3kW diffraction limited fiber laser, all fiber based, and powered up with multimode pigtailed pumps. This progress is driven by *push* from telecom technology, looking to find new markets, and by *pull* from the industrial side and technology programs (BRIOLAS) [7], SHEDS and ADHELS [8]).

In section 4 we review the status of multimode (MM) pigtailed pumps, as they are used for cladding pumping fiber lasers, YEDFAs and for direct diode applications. Section 5 is dedicated to the topic of increasing radiance by combining diode lasers, and section 6 is a short review on pump VCSELs.

2. Single Mode Fiber 980nm Pumps

Today, C and L band EDFAs are preferably pumped at 980nm, resulting in lower noise figure, lower overall power consumption [9], and providing ample power since the availability of reliable high power, Peltier cooled 980nm pump modules.

Undersea intercontinental links, based on dense wavelength division multiplexing (DWDM), impose the most demanding requirements on single mode fiber 980nm pump diodes. For the undersea application highly efficient and reliable pump modules operating over a wide temperature range (without Peltier temperature stabilization) had to be developed.

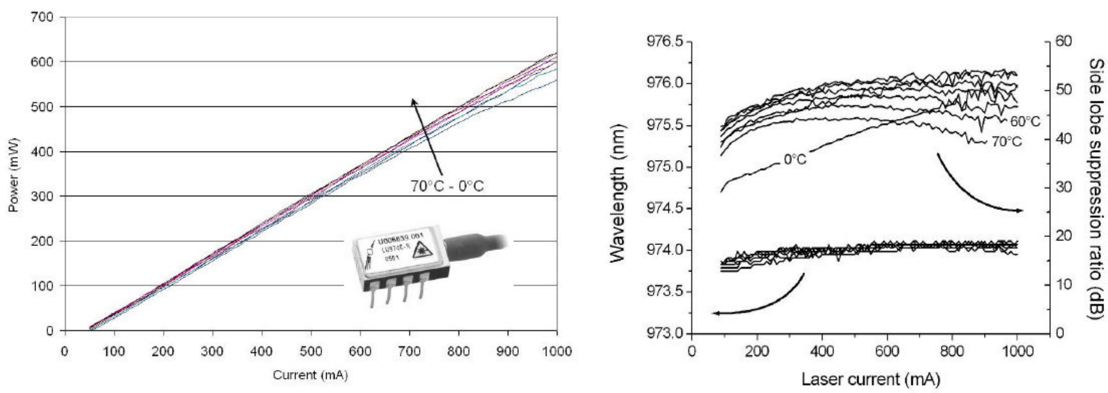

Figure 1: Performance of an uncooled 980nm MiniDIL for undersea systems (courtesy Bookham)

2.1. Materials for 980nm Pump Diodes

Initially, 980nm diode lasers for EDFAs were not available and DWDM systems were using 1480nm pumps. No lattice matched material on GaAs or InP substrate with the corresponding bandgap is available. In the early eighties, strain was considered to lead to unreliable devices. Still, work was done on strained InGaAs quantum wells (QW) on GaAs substrate to investigate the possibility of threshold reduction through strain induced changes in the density of states. It was soon discovered that adding indium improved the stability of GaAs [10], [11], [12], [13]. Today, the benefits of strained InGaAs QW for high power diodes from 900 to 1100nm (often categorized as "9xxnm range"), fabricated by either MOVPE or MBE, are well understood. In addition, different technologies have been developed to suppress the catastrophic degradation mode at the facets.

The impressive performance of pump diode lasers is based on the gain characteristics resulting from the steep density of states of the strained InGaAs QWs [14], [15], and the low optical confinement factor in a low loss large optical cavity (LOC). An active layer with quantum dots (QD) should have an even steeper density of states and thus improve the performance. After twenty years of work on QD fabrication technology, one is still searching for a technology to produce InGaAs QD with the required uniformity. Unfortunately, due to inhomogeneous broadening, no improved device performance with respect to high power lasers can be observed [16], [17].

The power conversion efficiency of a pump diode laser depends on many factors and can be improved by a clever design, but it is ultimately limited by material parameters such as the ratio of mobility and free carrier absorption of holes in the p-type waveguide and, in addition, by the thermal resistance of the p-type waveguide and of the cladding. In order to look for the best material system, InGaAsP on GaAs substrate was investigated, and 980nm pump diodes were fabricated with excellent characteristics [18], [19]. The InGaAsP system is also less reactive to oxygen. Surface passivation is eased (but still necessary), and overgrown structures [20] can be produced. Detailed investigations [21] have shown that the AlGaAs material system is superior with respect to mobility and thermal resistance in p-type waveguide and cladding (free carrier absorption limits are not known yet).

2.2 Optical Beam

Pump modules have either a single mode (SM) (HI 1060, HI 980) or polarization maintaining (PM) (Panda PM 980 family) fiber pigtail with a numerical aperture (NA) between 0.12 and 0.2. No optical isolator is required; it is possible to couple directly into the fiber. A large variety of lensed fiber tips [22], [23], [24] is available to match various single mode laser beams to a single mode fiber. However, it is much more cost effective to design the diode laser beam for coupling into a simple wedged shaped fiber as developed more than 30 years ago [25], [26]and refined later [27], [28], [29]. The diode laser fundamental mode needs to be designed to have the same slow axis NA (or, equivalently, mode field diameter) as the fiber. Beam aspect ratio or fast axis NA is of no concern, as the wedged shaped fiber tip can adapt for fast axis divergence.

2.2.1 Narrow Stripe Technology

To match the slow axis NA of the diode to the NA of the fiber a weak lateral waveguide is necessary. The required index difference, given by the well known approximation $\Delta n = NA^2/(2*n)$, is small: $\Delta n = 2*10^{-3}$ and $\Delta n = 5*10^{-3}$ for fiber NAs of 0.12 and 0.2, respectively. Such weak waveguides can be fabricated in various technologies: impurity disordered [30], [31], buried stripe [32], [33], ridge waveguide [34], and more recently by slab-coupled waveguide [35], [36] and, possibly, ARROW [37].

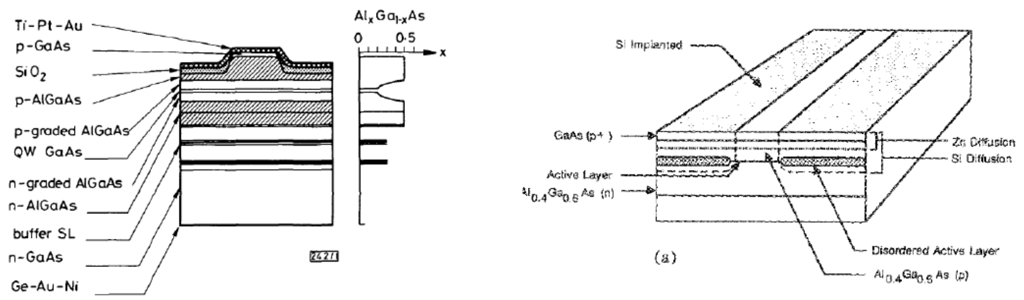

Figure 2: Cross section of a ridge waveguide [34] and a silicon implanted impurity disordered waveguide [31] laser diode on GaAs substrate

Any deviation from the fundamental mode results in severe coupling issues into the fiber, known as kinks. It is common practice to suppress lasing of higher order modes by increasing their threshold gain. This is achieved most easily by introducing mode selective losses [38], [39], [40], [41].

In the early 90's, pump diode manufacturers were baffled by kinks based on systematic beam steering (therefore sometimes called: shift kink) which appeared periodically with pump current. It was soon discovered that high power fundamental mode operation of weak waveguides is limited by resonant coherent coupling of the fundamental mode into the first order mode [42]. The modes of the passive waveguide are orthogonal and, without any asymmetric element, no coupling occurs. In practical diodes slight asymmetries at the front mirror (e.g. angular misalignment, mirror coating, heating) are a likely source for coupling. Power reflected from the Fiber Bragg grating (FBG) in the pigtail also adds asymmetry (as the fiber is not perfectly aligned). The shift kink cannot be suppressed by the standard method of increasing the losses of the higher order mode as the power is resonantly coupled from the lasing fundamental mode to the first order mode (the first order mode can still be below threshold). Kink power level is controlled by controlling the beat length of the two modes, either by an individual adjustment of the cavity length [43], or, by controlling the difference of propagation constants of the two modes by exactly controlling the ridge process [44], and by eliminating asymmetries as much as possible. Today's pump diodes display reduced shift kink issues, most likely due to long cavities, low front mirror reflectivities and low waveguide asymmetries.

2.2.2 Modefilters

Broad area (BA) diode lasers with mode filters, to enforce fundamental mode operation, were thoroughly investigated. Best known are the master-oscillator power-amplifier (MOPA), alpha distributed feedback lasers (DFB) laser, multi mode interference (MMI) waveguide and taper laser [45], [46], [47], [48], [49], [50], [51]. These structures are not in use for telecommunication, as they have not been able to meet the stringent requirement for power conversion efficiency, reliability and ease of coupling. For special applications, the taper laser, preferably in an external grating feedback configuration, generating up to 3W of nearly diffraction limited power, has found industrial application [50].

2.3 Output Power Scaling

It has been possible to increase the pump diode roll-over power by more than an order of magnitude, (Figure 3.) This was achieved by making the laser cavity longer, thus improving the cooling of the pump diode while scaling the other diode parameters appropriately.

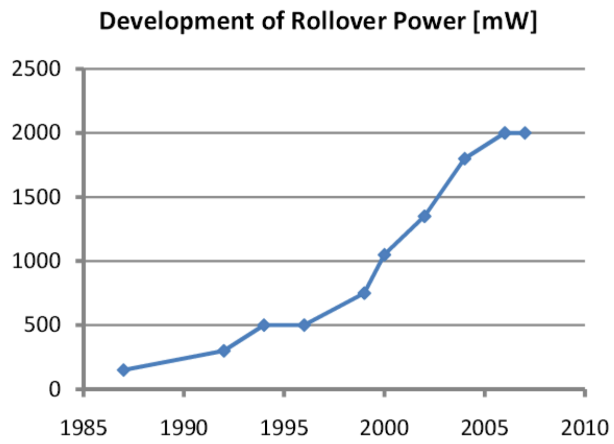

Figure 3: Development of roll-over power of 980nm single lateral mode pump diodes (cw, junction up, at room temperature)

2.3.1 Length Scaling of Laser Diode

Four key figures of a pump diode are: 1. Number of carriers in the quantum well (which is given by the required roundtrip gain G,), 2. External quantum efficiency η, 3. Photon lifetime in the cavity τ_{ph}, 4. Asymmetry of the laser cavity given by the ratio of power behind the front and back mirrors Pr.

For a back mirror reflectivity equal to 1 the four key figures, as function of the laser parameters, optical confinement factor Γ, optical loss α and front mirror reflectivity R, are:

$$G = \left(\alpha + \frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right) / \Gamma \,, \qquad \eta = \left(\frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right) \Big/ \left(\alpha + \frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right)$$

$$\tau_{ph} = 1 \Big/ \left(v_{gr} * \left(\alpha + \frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right)\right), \qquad Pr = (1+R)/(2 * \sqrt{R})$$

Ideally, the laser parameters (Γ, α and R) are adapted to keep all four key figures (G, η, τ_{ph} and Pr) constant, while increasing at the same time the cavity length to improve the thermally limited roll-over power. This is not possible. Thus, gain G and external efficiency η are kept fixed, while, photon lifetime OR power ratio, are adapted, depending on the approach. For obvious reasons the two cases are called “constant photon lifetime scaling” and “constant power ratio scaling”.

For the constant photon lifetime scaling we obtain the following scaling rules:

$$\Gamma(L) = \Gamma(L_0), \qquad \alpha(L) = \alpha(L_0)$$

$$R(L) = R(L_0)^{\frac{L}{L_0}}$$

This method was used in the initial phase of increasing power; one can just cleave longer cavities from the same material and reduce the front mirror reflectivity exponentially, according to the exponential scaling rule, and still maintain efficiency. The power ratio becomes also exponentially larger with increasing cavity length. Due to this increased power ratio, longitudinal spatial hole burning is observed. Hole burning can be reduced by the introduction of a slightly flared adiabatic waveguide [52], [53]. Driving this scaling method too far (i.e. mirror reflectivity well below 1%) causes amplified spontaneous emission (ASE) and external fiber Bragg grating frequency stabilization issues.

Thus, for long cavities, constant power ratio scaling is favored with the following scaling rules:

$$R(L) = R(L_0)$$

$$\Gamma(L) = \frac{L_0}{L} * \Gamma(L_0), \quad \alpha(L) = \frac{L_0}{L} * \alpha(L_0)$$

As a consequence of keeping the power ratio constant, the mirror reflectivity is also constant; therefore this method is often called constant mirror reflectivity scaling. Requirements on confinement and optical losses are demanding. Both have to be reduced linearly with increased cavity length. The constant mirror reflectivity scaling has the advantage of making, to zeroth order, average optical power in the QW, pump current density, heat generation density, and ASE and spectral stability, independent on length. A careful design of the vertical epitaxial structure to reduce the waveguide loss α and confinement Γ is necessary for long cavities.

2.3.2 Vertical Epitaxial Structure

The optical confinement Γ can be decreased by expanding the beam and by asymmetric placement of the QW in the waveguide [54], [55]. The waveguide loss α can be decreased by reducing the various contributions, such as scattering and leaking losses of the passive waveguide. Free carrier absorption is reduced by reducing the carriers within the optical mode field, by careful choice of the material composition and fabrication details. Waveguides with losses α<1cm^{-1} are routinely fabricated and it is not known yet what the physical and engineering limits are. This is an important topic since the maximum power that one obtains from a longer pump laser (i.e. constant power ratio scaling) is ultimately limited by the abilities to scale the losses α in the waveguide. (Losses by the QW are scaled by the simultaneous scaling of the optical confinement). The waveguide loss α has to be reduced, while keeping the joule heating (series resistivity), the heat removal (thermal conductivity) and temperature sensitivity (T_0) under control. In addition, single lateral mode emission has to be ensured. 2W of roll over power have been achieved using such scaling rules(Figure 4).

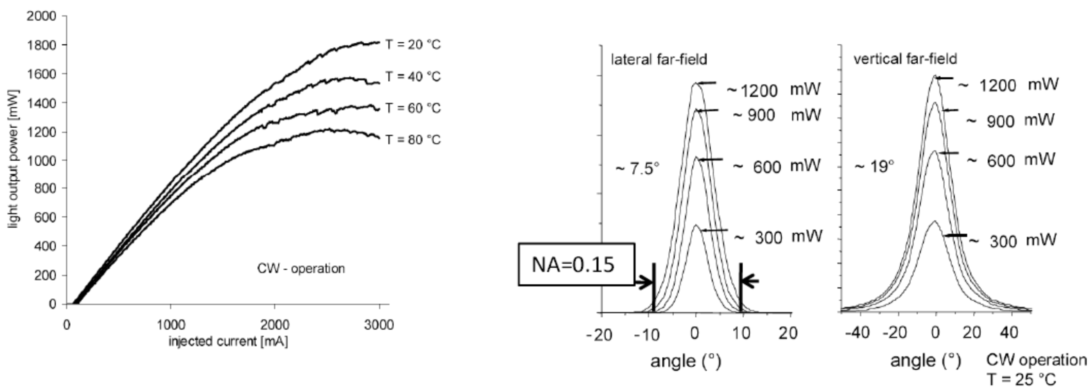

Figure 4: Light output versus injected current of ridge waveguide laser at various heatsink temperatures and farfields at various power levels [56]

Challenges for length scaling BA pumps are very similar. In recent years, much progress has been made towards optimizing the vertical structure, documented mainly within the SHEDS (Super High Efficiency Diode Source) program [8]. Of the many different vertical waveguide structures [57], [58], [59], [60] the asymmetric LOC which expand the beam to a divergence below 30deg (FWHM), as shown in Figure 5 is favored. To reduce leaky losses for the fundamental mode, such LOC structures have an NA high enough to guide a few modes. By placement of the QW and by introducing mode selective losses, only the fundamental mode is brought above threshold gain.

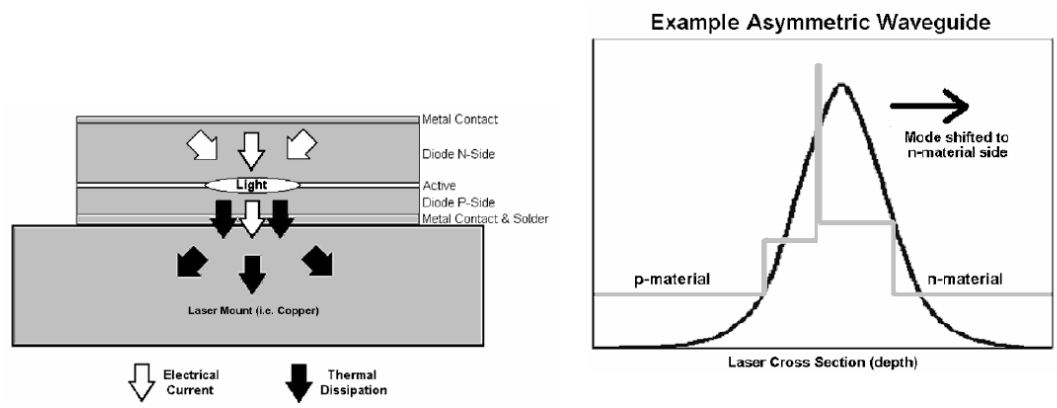

Figure 5: Cross section of "junction-down" mounted BA diode laser and example of asymmetric LOC waveguide [21]

For 1480nm pumps, due to different material parameters and growth challenges, optical trap waveguides [61] have shown excellent performance.

2.4 Spectral Stability

The emission spectrum of the solitary Fabry Perot 980nm laser diodes is not stabilized well and, early on, displayed complex behavior for some (e.g. impurity disordered) waveguide structures [62]. The spectrum of the index guided ridge waveguide laser diodes is very stable with the usual average shift with changing temperature (0.3nm/K), but mode jumps are observed, due to a modulated loss spectrum. This substructure is believed to be due to radiation from the leaky waveguide into the substrate made possible by the GaAs substrate, which is transparent and has a higher index of refraction than the waveguide [63].

Early on, it was realized [64], [65] that, by placing a weak FBG into the pigtail, the spectrum of the Fabry Perot laser could be stabilized effectively. The temperature drift of the spectrum can thus be reduced to 7pm/K, nearly two orders of magnitude lower than temperature drifts of the solitary Fabry Perot laser. Initial shortcomings were noise, cost and reliability concerns due to the complexity the FBG stabilized pump package. However, the gain flatness requirement of DWDM EDFAs required pump sources with a very stable emission spectrum and thus these issues had to be and were solved [66], [67], [68].

Polarization mode effects in the pigtail under FBG stabilization have to be controlled, either by a strict rule for fiber lay in the EDFA module [69], or, much more repeatable, by using a polarization maintaining fiber pigtail. In order to reduce mode hopping noise, FBG stabilized pumps are designed to operate in coherence collapse. Unfortunately, laser diodes can have the tendency to switch from time to time from coherence collapse into a coherent state, thus causing amplitude noise [70], [71], [72], [73], [74]. This switching noise can be effectively suppressed by a dither or a double FBG [75] beyond a critical distance.

A FBG stabilized diode laser can also be designed to have a coherence length of a few centimeters and low noise. This is a useful source for generating visible light by frequency doubling in PPLN waveguides [76].

2.5 Packaging

The basis of a modern 980nm pump package is a monolithic planar Al N substrate which acts as the optical bench. The laser chip is soldered p-side up directly to the metalized Al N substrate, and the fiber, tipped with a low cost wedge lens, is attached in front of the chip on the AlN substrate.

The platform is placed in the MiniDIL housing and hermetically sealed. Package induced failure (PIF) mode is suppressed, by filling the package with a mixture of 20% oxygen and 80% nitrogen, as it was used by some manufacturers in the eighties for short wave lasers and later on applied to 980nm pumps [77], [78]. PIF is based on a photo-thermal decomposition of trace hydrocarbons in the atmosphere on a surface with a high optical power density. Under oxygen it is being *burned-off* faster than deposited [79]. Obviously, this phenomenon is not restricted to the laser diode, but manifests itself on any surface in the laser beam. The presence of oxygen in a hermetic package, however, favors the long term evolution of humidity, as a by-product of the burning of the hydrocarbon traces and hydrogen. A long term humidity concentration below 5000ppm (dew point at 0 °C), has to be ensured by carefully cleaning the package of organic contamination, desiccation and de-hydrogenation processes. Otherwise a humidity getter has to be included inside the package [80].

The stability of this platform is outstanding as is evident from the results obtained in stress testing of an earlier generation (Figure 6) and ensures operation at 400mW from the fiber pigtail in the very demanding undersea application.

It is standard practice to increase the output power by cooling the pump laser diode through a Peltier heat pump [81]. The chip can be stabilized at different temperatures (standard is to stabilize at 25°C), trading off power dissipation and maximum available optical power [66].

Pump powers in excess of 1Watt from a single mode fiber have been demonstrated already a few years ago [82], [83], [84]and products in the 700mW range, corresponding to 70MW/(cm^2sr), with outstanding reliability, are commercially available.

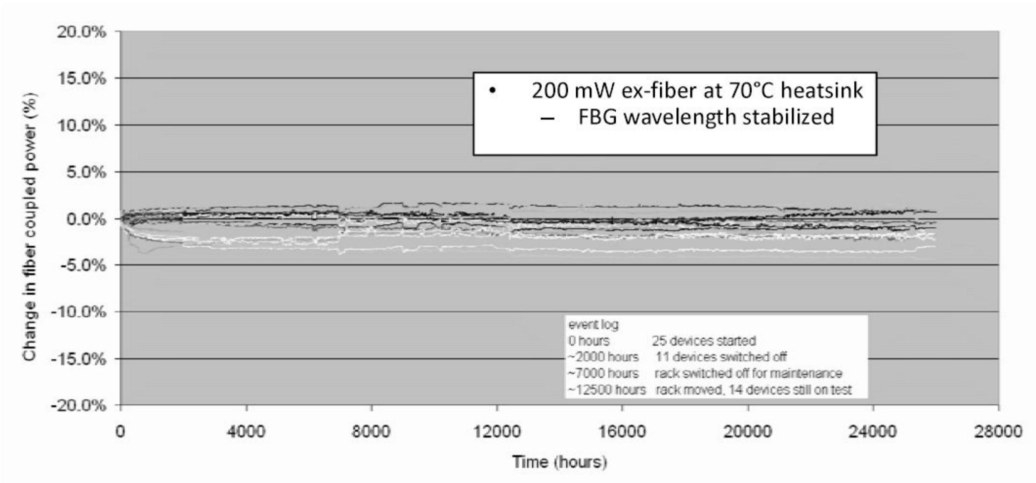

Figure 6: Stability of 25 uncooled FBG stabilized 980nm pump diode MiniDIL over 3 years of high temperature and maximum power operation, courtesy Bookham

2.6 Reliability

Today's reliable high power 980 pump diodes for the demanding telecom market are based on a fundamental understanding which the industry has. It has been possible to eliminate the gradual degradation completely, and today 980nm pump laser diode reliability is limited by a low rate of random sudden failures [79] due to point defects. Only little of this know how has been published and the details are very complex and involved. Here we just give a brief summary on the most important aspects of reliability of 980nm pump laser diodes.

2.6.1 Failure Modes

To gain a very rough understanding of the failure modes of a 980nm pump laser leading to sudden failures, three major topics should be considered:

1. Catastrophic junction meltdown (CMD): A hot spot with thermal run-away resulting in catastrophic junction meltdown, mostly occurring at the front facet (thermally most exposed spot)

2. Heating through non radiative recombination (NRR), initiating a hot spot due to non radiative recombination of electrons and holes through mid-gap states at defects

3. Thermally accelerated decomposition (TAD) at the facets with even trace amounts of oxygen acting as catalyst, generating defects and non-radiative recombination centers.

2.6.2 Catastrophic Junction Meltdown (CMD)

A 9xxnm laser diode, even without any defects, but uneven cooling, can develop at high currents a hot spot with a thermal runaway. In a hot spot, the bandgap is lowered, resulting in higher carrier injection, both from the contacts (current) and the laser beam (absorption). It is assumed that above a critical temperature (temperature difference) this hot spot is leading to catastrophic thermal runaway with junction meltdown (CMD). Experimentally, this critical temperature was measured by initiating thermal runaway with an external heating source (Argon laser spot) [85] and a value (averaged over a 1.5µm spot size) of 120K to 140K above room temperature was measured.

This CMD most often happens at the facets, as they are not well cooled, have the highest current density, highest optical field [86], [87] and usually some parasitic additional heat source (defects, mirror coating) which triggers the thermal runaway. Traditionally, the whole mirror was blown off, stopping the laser to work because of the damaged optical cavity, therefore called catastrophic optic mirror damage (COMD). Because of an improved thermal design, the junction can often melt only microscopically, without any visible defect under the optical microscope [88]. Nevertheless, the diode laser stops working since the molten and re-crystallized junction is electronically dead, i.e. it provides no gain and has a high non-radiative recombination current [89].

No consistent hot spot model leading to CMD is available. Only some of the required material constants have been measured [90]. Effective countermeasures against CMD are: blocking current injection into critical areas which leads to reduced temperatures [91] and uniform heatsinking through appropriate heatspreaders and j-up mounting [81].

2.6.3 Non Radiative Recombination Heating (NRR)

The major additional heating source of aged laser diodes is heating due to nonradiative recombination [15]. NRR is the product of electron, holes and nonradiative recombination center density and thus can be suppressed by suppressing *any* of the three terms. Usually minority carriers or nonradiative recombination centers are suppressed The minority carrier density can be kept low by a so called window laser, and the density of nonradiative recombination can be kept low by an appropriate facet passivation.

Within the window is a larger bandgap to avoid generation of minority carriers by absorption (therefore sometimes also called NAM (non absorbing mirror) and to reduce the number of thermalized minority carriers. In addition, there is usually no p-n junction, to avoid minority carrier injection. Such window lasers have been known for a long time and were initially realized by Zn diffusion [92]. Later on window lasers were implemented through epitaxial growth through the active region [93]. The quality of this regrown interface is very important (and challenging). For very high power lasers the Si-doped and disordered window laser has proven itself [94], [95], [96] over many years and is in heavy use today throughout the industry. Recently, also good progress has been made with vacancy induced disordering [97], [98], [99] to form a window region.

2.6.4 Thermally Accelerated Decomposition (TAD) at the Facets.

It has been known that GaAs lasers degrade at the facets under high power operation [100]. This effect is also seen at a slower rate in so called aluminum free active area laser diodes [101] and accelerated in AlGaAs. It was shown in the late eighties / early nineties in a series of papers that this degradation is thermally accelerated decomposition (TAD) [102], [103], [104], [105]. Only trace amounts (a fraction of a monolayer) of oxygen is enough to start breaking the bonds, decomposing GaAs around the p-n junction. This leaves behind atomic Ga and As and defects, which then act as non radiating recombination centers. Oxygen does not form a stable oxide but acts as catalyst to decompose the facets [106]. Over time non radiative recombination centers are building up, until the laser goes into CMD (or even COMD). Temperature accelerates decomposition and an operation power dependency of the time to COMD [102] is observed.

Temperature is an important measure of the non-radiative recombination rate. Sophisticated tools have been developed to measure temperature directly on the small facet. Methods are: With absolute temperature scale by Raman [107], [108], with high spatial resolution by electron beam-induced current (EBIC) charge thermography [109] and high temperature resolution by thermo reflectance [110].

Decomposition at the facets can be completely stopped if the surface is sealed without any damage and without trace amounts of oxygen. This process is called passivation of the facet. One distinguishes *in-situ* passivation (breaking the wafer in an ultra high vacuum (UHV) system, followed by covering it with a passivation layer) and *ex-situ* passivation: cleaving the wafer in air, then transferring it into a vacuum system followed by a gentle (to minimize structural damage to the laser facet) cleaning-off of the oxygen followed by a passivation layer.

There exist today essentially three *in-situ* processes. All *in-situ* processes are based on a complex UHV system, with load locks to transfer the wafer, and a bar cleaving mechanism operated inside the UHV system. One *in-situ* process is based on the high temperature growth of a single crystal InGaAsP passivation layer [111]. Because of the high temperatures involved, the metallic contacts can only be applied after passivation at the individual bar level. Another one is based on a low temperature ZnSe [112], [113], [114]. The most successful and widely used *in-situ* passivation is based on low temperature and low energy deposition of silicon [115], [116].

Numerous *ex-situ* processes have been tried to reduce cost of passivation. It is suspected that an *ex-situ* process will never be able to produce a completely defect free, stochimetric surface. Therefore the time to C(O)MD is expected to be finite for *ex-situ* passivation, but this time could be well beyond the required useful life. Today, it is understood that passivation through sulphation [117] and nitridation [118], [119] has proven to be difficult to manufacture reproducibly with very high quality, most likely as it does not chemically bind any remaining oxygen completely. Most successful passivation techniques seem to be the ones which include the deposition of silicon (or ZnSe) after removing the oxygen either with a low energy hydrogen plasma [120], [121], [122]or a low energy ion beam, such as in the I3 process [123], [124].

2.7 Failure Rate

Unlike other characteristics of a pump laser package, lifetime cannot be measured readily for each laser package, but has to be estimated from understanding the physics of failure, massive testing and controls on manufacturing stability to reproduce the lifetime. The industry has developed detailed knowledge, especially for the undersea application. Only little of this knowledge has been published, the details are very complex and involved. Here we just give a brief summary of the most important aspects of lifetime estimation of 980nm pump laser packages.

Unfortunately, there are essentially no ways to accelerate aging for the overall package. Packages are qualified according to norms, such as GR-468, which guarantees robustness, but which does not allow for predicting reliable operation. Damage levels are determined by driving it into destruction by overstressing with the various relevant parameters. These damage levels should be at a safe distance from operating conditions, and, from an understanding of the physics of failures, one can attempt at predicting use failure rates.

The design of the FBG stabilization has to be robust so that the spectrum remains stable, even under worst case conditions and fully aged characteristics of the different elements. For this it is important to investigate in detail the aging of the various critical parameters of the involved components [125].

A carefully designed and manufactured 980nm pump diodes has very low failure rates with respect to gradual wear out as well as wear out sudden failures [126]. But even if these two failure modes are completely suppressed one is left with low rate of sudden failures, best described by a constant failure rate, i.e. random sudden failures of the pump diode. As it is difficult to find a physical explanation for a random failure rate, the sudden failures are sometimes also modeled by a lognormal distribution [127] with a large σ (indicating a wide activation energy distribution of underlying physical processes).

It is expected that the failures of the chip can be accelerated by increasing the driving forces behind the degradation, i.e. carrier density in the active region, local temperature in the active region, etc. Unfortunately these parameters are not directly accessible. Thus the failure rate is accelerated by increasing operating temperature and drive current and power. Of course one has to ensure by physical failure mode investigation that the diode running under accelerated conditions produces the same failure modes as observed under use conditions [128], in other words, the laser diode has to be designed to work not only properly at use condition but also at accelerated conditions., i.e. design for use and testing.

The failure rate at use condition is usually extrapolated from the failures rates from blocs of laser diodes (stress cells) with each cell running at different accelerated conditions. Traditionally the following heuristic functional dependence of failure rate on junction temperature (Tj), current density (j) and power density (p) is assumed:

$$\text{Failure rate}\ (j, p, T_j) = FR_0 * j^x * p^y * \exp\left(Ea/kT_j\right)$$

A maximum likelihood calculation is used to find the values x, y and Ea, for which the failure rate in the stress cells is most likely to be observed [129], [130]. From these most likely parameters the most likely failure rate at use condition can be estimated. It has become customary to calculate upper confidence limits for use failure rates, based on Ea, x and y, as determined by maximum likelihood, neglecting the confidence range of the maximum likelihood estimates. This is inconsistent and leads to very optimistic upper confidence limits. It has also been pointed out that the assumed functional dependence has a big impact on failure rate estimation at use conditions [131]. It must also be ensured that manufactured quality corresponds to the qualification sample, which is routinely done by defining and controlling so-called critical process parameters.

Field returns and long life tests in the laboratory are the test of the failure rate estimations. Both terrestrial field returns (below 20FIT on more than 20 billion device hours are estimated by the industry) as well as undersea field returns (<5FIT with 60% confidence for redundant pump pairs [132], [133]) are testimony of this fact.

Long life tests on 980nm pumps (operated for more than 15 years at accelerated conditions) are shown in Fig 7. The gradual increase saturates after a while and the lasers run very stable with one random fail being the only observation. This observation is consistent with failure rate predictions for these accelerated test conditions, thus increasing confidence in the “art” of accelerated stress cell testing.

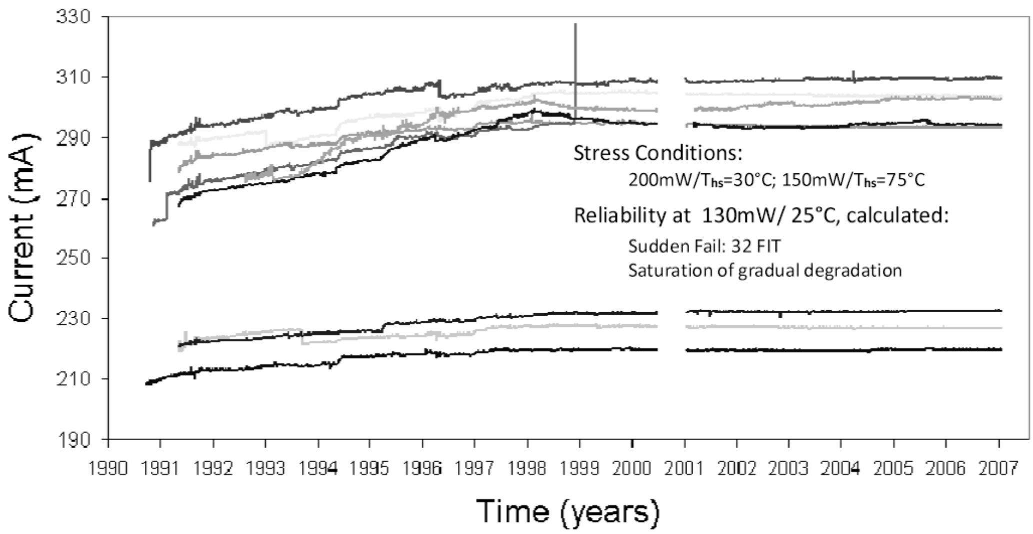

Figure 7: 16 years of constant power operation of 980nm pump diodes at temperature and power stress, courtesy Bookham

3. 1480nm Pumps and 14xxnm High Power Lasers

3.1. 1480nm Pumps

The stronghold of 1480nm pumps clearly is remote pumping of preamplifier EDFAs [9], which requires very high 1480nm power. It is an advantage that 1480nm pump diodes can be produced on the basis of the established 1550nm signal laser technology, using the well known material system of compressively strained multi-quantum well (MQW) InGaAsP layer on InP substrate. 1480nm pumps were initially (and sometimes still are) used for pumping low noise preamplifier and power booster EDFAs. Similar considerations as for 980nm pump optimization have to be applied to optimize the output of 1480nm pumps. Due to inherently higher series resistance, Auger losses, intervalence band absorption and an inherently stronger temperature sensitivity of efficiency and of threshold current it is very challenging to design and fabricate a high power 1480nm pump. Losses in the InGaAsP waveguide at 1480nm have been reduced steadily over the last few years and, with an optimized asymmetric waveguide [134], losses in the range of 3cm^{-1} have been obtained. Nevertheless, multiple quantum wells are necessary to provide enough modal gain to overcome the waveguide losses.

Because of the proximity of the pump wavelength to the signal band reflections have to be suppressed by placing an optical isolator in the package. Such a package requires discrete lenses, which requires a round beam (for low cost lenses, high coupling efficiency). This can be achieved by a multi growth step buried heterostructure [135], [135] as shown in Figure 8. It has been shown that also a simple ridge laser diode, first demonstrated 30 years ago [136]on InP substrate, can be designed to have excellent characteristics, a roll-over power of 1.2W and a beam with an aspect ratio of around 2, using an optical superlattice waveguide design [137], [61].

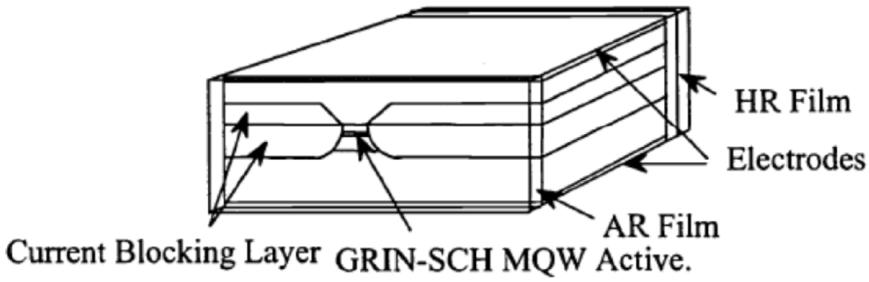

Figure 8: Schematic structure of a 14xxnm diode laser chip [135]

The reliability of 1480nm pump lasers is given by gradual degradation and does not suffer from random sudden failures (like 980nm). Reliability modeling as well as failure rate predictions are quite well understood. However, it is found that the failure rate accelerates quite strongly with temperature (Ea=0.6eV) [135],and thus 1480nm pump lasers packages require a Peltier heat pump to cool the chip to 25 °C. Due to the relatively inefficient chip, practical maximum power available from 1480nm pump lasers is limited by the capability of the pump package to handle the dissipated power from the chip. Special Peltier elements and packages have been developed for 1480nm pump lasers and commercially pigtail powers up to 400mW are available today.

3.1. 14xx High Power Diode Lasers

Research on Raman amplification in optical fibers was started in the early 1970s but the required pump powers at the required wavelength 14xxnm were not readily available. Raman amplifiers have the big advantage that the gain is not limited to any specific spectral band and that amplification works also outside the EDFA C and L band. With the availability of high power 14xx pump laser diodes and the requirement for ever higher capacity, transmission systems based on Raman were investigated in detail and it was demonstrated that record capacity distance products are achieved with Raman amplification [3].

As a consequence of the Ramen process the requirements on the 14xx pump diode with respect to power and noise are quite challenging [3], unlike 1480nm or 980nm pump lasers, where the noise is reduced by the long spontaneous lifetime of the erbium gain. Much progress has been made towards the required “quiet” 14xx high power diode laser by internal frequency stabilization and polarization scrambling [138], [139], [140], [141], [3]. Raman gain blocks are available which contain usually a few 14xx individual diode lasers with different wavelength [142] in order to establish flat gain over a few tens of nm. Diode laser modules with high output powers as well as special fibers are available today and spectacular all Raman amplified systems with record transmission performance have been obtained. However, progress for 14xxnm pumps has slowed down as the industry seems to use EDFAs for cost optimized C and L band and the thirst for bandwidth extension has been small.

4. Multimode Fiber Coupled 9xxnm Pump Lasers

The recent application of the 9xxnm telecom technology to the industrial markets, especially pumps for FL, disk and rod DPSSL (diode pumped solid state lasers), and also in the form of direct diodes for material processing [143] has been very fruitful. Due to a concerted effort with programs for power conversion efficiency (SHEDS) and radiance (ADHELS and BRIOLAS) [8], [144], [7] very exciting results have been obtained in the last few years, especially in the field of multimode fiber coupled 9xxnm pump lasers, one of the key enabling devices of the hermetic, all solid state “Power Photonics”.

4.1. Classification of 9xxnm MM pump Lasers

Available radiances of commercial 9xxnm pump lasers are roughly 1W in a single mode fiber (which has the diffraction limited etendue of $E=\lambda^2=1\mu m^2 sr$ for a 980nm laser). A MM step index fiber with 200 µm/0.22NA has $E=5000\mu m^2 sr$. Thus it should be possible to get 5kW from a 200 µm/0.22NA pump module, even without wavelength and polarization combiners.

Unfortunately it is prohibitively expensive to manufacture such a MM pump, due to two challenges: optical coupling and heat removal. Thus, we classify 9xxnm MM pumps according to these two topics.

4.1.1 Heat Transport Classification

High power multimode diode lasers are thermally limited and need to be soldered *junction down* onto a heatsink. Best heat transport can be achieved by directly mounting the laser diode on a copper, or even better, diamond heatsink. Mismatch in thermal expansion material coefficients is managed by using a soft solder (e.g. Indium) which accommodates the mechanical movements due to temperature changes during manufacturing (soldering) and use. Soft solders change their properties and shape, even under standard use conditions, causing a whole range of failure modes. Despite much work, only a few applications work satisfactorily within these failure modes. It is well known from telecom pump diode technology that reliable systems use hard solders (e.g. AuSn), together with expansion matched substrates (e.g CuW, electrically insulating Al N or, BeO, or, layered Cu/Mo microchannel coolers [145]). Heatsinks need to be coated with a dedicated stack of metal layers (diffusion barrier, strain relief, heatspreader and adhesion promoter) to enable a reproducible and reliable solder joint process. We classify heatsinking into (see Figure 9)

1. Passive cooling (also conductive cooling): 2-dimensional heat transport
2. Active cooling: 1-dimensional heat transport

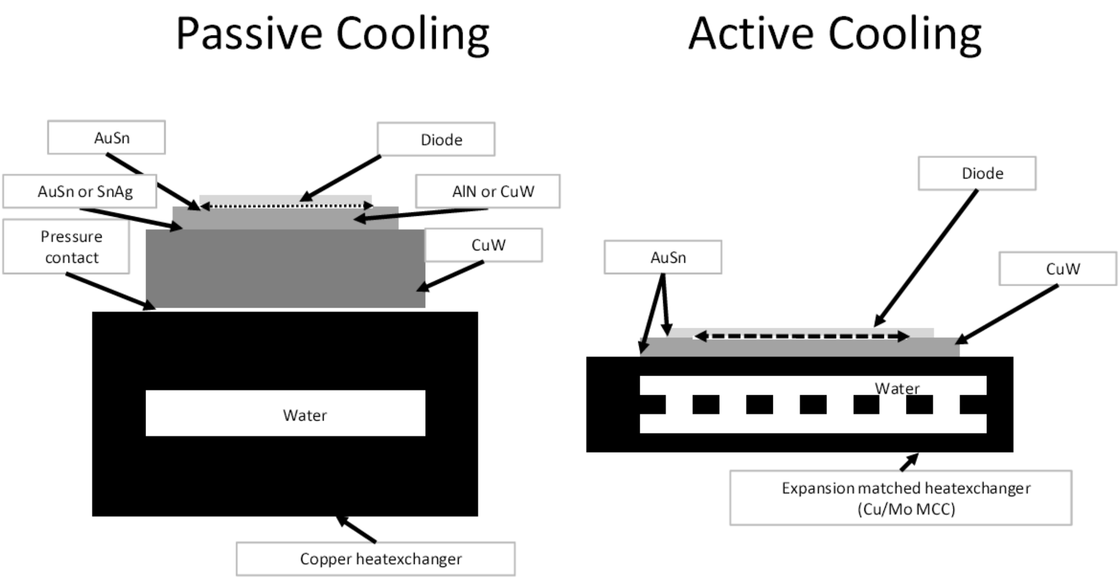

Figure 9: Schematic structure of a passive cooled diode laser and an active cooled diode laser

In the case of passive cooling the heat load is so small that it is possible to spread the heat flow in expansion matched substrates. This package can then be pressed (by mechanical fixture) against cooling fins or a heat exchanger, which can have a different expansion coefficient (due to pressure contact and the small temperature variation at this removed interface). In the case of active cooling the heat load is so big that it has to be removed in close proximity by a heat exchanger. Thus, for active cooling the pump diode has to be attached with a hard solder onto an expansion matched microchannel cooler, possibly with an expansion matched submount in between to ease manufacturing. Experience has taught us that high power and low failure rate applications strictly require expansion-matched materials for solder joints and pressure contacts between non expansion-matched heat sinks.

4.1.2. Optical Classification

A complex optical system might be needed to couple a diode laser into a multimode fiber, which has a tremendous impact on cost. Because of the many degrees of freedom of a general laser beam, it is difficult to systematically classify this topic. Fortunately, if we restrict ourselves to plain broad area laser diodes (with no focal astigmatism) and step index MM fibers (both numerical apertures limited systems), then emission width (diameter), numerical aperture (NA) and power characterize the beam fully. The related optical characteristic parameters are given by: Beam parameter product $BPP = NA*Diameter/2$, etendue $E = \pi^2 * BPP^2$ (approximation for NA<0.5), and *radiance = power/etendue*.

Diode Laser	Beam Width [um]	NA [rad]	Fast axis BPP [um rad]	Slow axis BPP [um rad]	Etendue [um² sr]
Single mode diode	5	0.12	0.3	0.3	1
Standard BA diode at low power	100	0.05	0.3	3	8
Standard BA diode	100	0.09	0.3	5	14
Low NA wide BA diode	200	0.09	0.3	9	28
Low NA minibar	3'200	0.07	0.3	112	340
Fiber	**Core Diameter [um]**	**NA [rad]**		**BPP [um rad]**	**Etendue [um² sr]**
SM fiber	5	0.12		0.3	1
Input fiber for fiber combiners	105	0.15		8	610
Standard material processing delivery	200	0.22		22	4'800
High power material processing delivery	400	0.22		44	19'000
Fiber of cladding pumped laser	400	0.46		92	84'000
High power material processing delivery	1'500	0.46		345	1'200'000

Table 1: Beam parameter product (BPP) and etendue (E) for select pump diode lasers and high power fibers

The pump diode is diffraction limited in the fast axis and thus it is trivial to couple it to any fiber. MM fibers even allow for extensive stacking in this direction. From slow axis considerations we distinguish three classes:

1. Direct coupling: Pump laser width and NA in the slow axis are smaller than diameter and NA of the fiber. A simple fiber tip coupling, as with single mode lasers, is used
2. Simple lens coupling: Pump laser slow axis BPP is smaller than the BPP of the fiber. A simple focusing lens is used.
3. Beam symmetrisation optics coupling: Pump laser slow axis BPP is larger than the BPP of the fiber. The beam has to be reshaped by symmetrisation optics [146].

4.2. Broad Area Pump Diode Laser

What has been discussed on single mode diode laser above (section 2) applies also to broad area laser diodes with the exception of j-down mounting, relaxed requirement on slow axis BPP (lateral beam quality) and frequency stabilization. Broad area pump diodes have continued the progress on length scaling of single mode diode lasers and the respective work is included in section 2.3.2.

4.2.1. Slow Axis BPP

To increase the output power of a diode laser, the emission width is made larger, up to 1cm, the full width of today’s available standard heat sinks. A simple wide contact stripe is sufficient, but sometimes a shallow ridge is etched to reduce lateral current spreading and to limit the lower slow axis NA.

At large widths, the laser is wider than long and suffers from efficiency problems due to lateral ASE (or even lateral lasing). Lateral ASE is suppressed by limiting the width and by introducing optical isolation trenches on either side of the active stripe. Since these trenches go through the active region, they have to be electrically insulated, i.e. placed at a distance. They also serve as powerful mechanical insulation trenches (dislocations in the active area layer cannot propagate beyond these insulation trenches). Usually a subunit of such a divided wide area diode laser is called broad area diode (BA), broad area single emitter (BASE) or multimode single emitter laser diode and has a width between 50µm and a few hundred µm, depending on desired lateral ASE suppression and NA optimization.

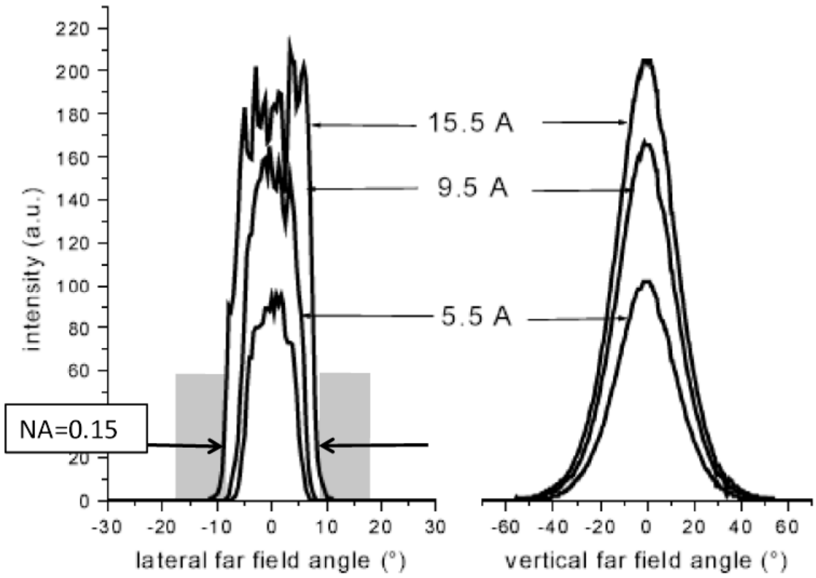

Figure 10: Slow (lateral) and fast (vertical) axis farfields of a 90µm BA diode for various drive currents [147]

One could expect that an ideal BA diode is lasing in the fundamental lateral mode and that the BPP is independent of width (NA should decrease linearly with width). Unfortunately, measurements of the farfield (see figure 10) show that this is not the case. Already at low power the slow axis farfield has a top hat shape with a high BPP and the BPP even increases with power. Major causes for slow axis NA degradation are:

1. Mode filling: Lasing onset of higher order lateral modes which milk the lateral gain profile more effectively than the fundamental mode. At high powers increased by spatial hole burning.
2. Thermal waveguide
3. Gain guiding due to lateral gain/loss profile (resulting in a phase curvature) and carrier-induced index changes. Considered to be less important causes for low loss waveguide and single QW gain active region diode lasers.

Slow-axis NA degradation due to mode filling can be reduced by carefully tailoring the current injection, as proposed quite some time ago [148] and demonstrated by a 2.5W, nearly diffraction limited beam from a broad area laser [149], in the pulse mode with heating absent.

Thermal waveguiding is caused by the positive dependence of index of refraction on temperature. Due to the cooling geometry, the temperature raises in the center by ΔT more than at the edges of the BA laser, causing a lateral index difference of Δn. According to the effective index approach the NA of such an index guided beam is:

$$\mathrm{NA} = \sqrt{(\mathrm{n}+\Delta\mathrm{n})^2 - \mathrm{n}^2} \approx \sqrt{2 * \mathrm{n} * \frac{\Delta\mathrm{n}}{\Delta\mathrm{T}} * \Delta\mathrm{T}}$$

A slow axis NA=0.07 results already for a small ΔT=2K (using $\Delta n/\Delta T = 3*10^{-4}K^{-1}$, n=3.6, [150]). The lateral temperature difference can be reduced by reducing by improving efficiency and heat extraction from the active region (asymmetric waveguide, see also 2.3.2) and by improved heat sinking. In pursuit for higher powers, some of these parameters have been improved over the last few years and so have the slow axis NA. Thermal waveguiding is still the major cause for NA degradation and the remedy, an athermal waveguide (i.e. modal index does not depend on temperature), is still waiting to be developed.

As with narrow stripe laser diodes, techniques have been investigated to improve the slow axis BPP by mode filters, most notably by taper lasers. The bothersome destabilization of the slow axis focal plane with resulting sensitivities to drive current, reflections and, possibly aging, makes it difficult to couple such devices even to MM fibers. Modefiltered diode lasers are still awaiting a breakthrough in focal plane stability and in efficiency.

4.2.2 Frequency Stabilization

Spectral stabilization through Fiber Bragg Gratings (FBG), as used for single mode pump lasers (see section 2.4.), is, due the multimode nature of fiber, not effective. The aluminum-free InGaAsP material system offers the opportunity for a conventional regrown DFB stabilization [151]. A partial DFB with very good characteristics has been fabricated in the InGaAlAs [152]. Frequency can also be stabilized effectively through external elements, such as volume holographic grating [153].

4.3 Passive Cooled 9xxnm MM Pumps

Passive cooled 9xxnm pump packages with a MM pigtail are easily installed by simply attaching electrical wires, splicing a fiber to the pigtail and by clamping them mechanically against a heat sink. Such a heat sink can either be forced air cooled fins or an isothermal plate, temperature stabilized by a Peltier or directly by a heat-exchanging liquid. We distinguish, according to the classification above, between different optical coupling arrangements.

4.3.1 Direct Coupling

The 9xxnm pump with the largest volume and the most pigtailed power shipped every year (a few MW per year) is the direct coupled package. A BA diode laser is directly coupled into a wedge lensed (matching fast axis NA) multimode step index fiber, very much as it is done for telecom pump lasers.

The development of the BA diode lasers has moved in parallel with single-mode narrow stripe lasers, however soldered j-down on a heat sink. CW room temperature roll-over powers from a 100μm BA laser are in the range of 20W at 25A, i.e. 19W at 25A, [152], 18.5W at 23A, [154], 19W at 24A , [155] and the chips have been designed to be temperature insensitive.

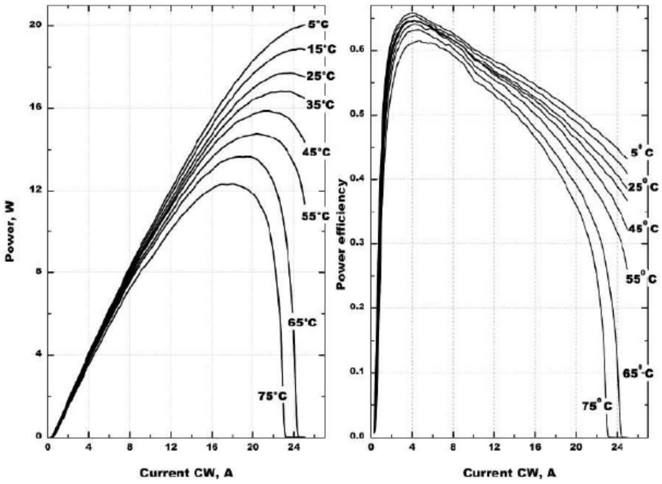

Figure 11: Typical roll-over characteristics and power conversion efficiency as function of current (at various heatsink temperatures) for a 90μm wide BA diode laser [155]

Packaging is based on the telecom packaging technology but made more difficult by the high power densities, for heat removal as well as for optical coupling. Standard fibers for fused couplers are 105/125μm MM step index fibers with NA=0.12, 0.15 or 0.22. To ease alignment the BA diode laser is usually only 95μm wide and it is beneficial for radiance to pick a fiber with an NA matched to the BA slow axis NA. Due to the thin cladding of the 105/125μm fiber and the high powers involved, not only the core coupling (which should be as large as possible) but also the coupling to the cladding (which has to be kept small) have to be optimized, otherwise one runs into issues with burning the protective fiber coating. Markets are cladding pumping of YEDFAs for TV and fiber to the premises (FTTH) boosters (940nm), cladding pumping of FL (920, 940, 960, 976nm), and DD applications (9xxnm). The printing application, requiring high brightness but limited power, usually uses 50/125μm fiber with an NA=0.12.

Power requirements for pumping FL are very demanding and the BA diode is operating at the reliability limit. Requirements for failures under use conditions are usually specified in "time to 5% cumulative failures", TT5% (1 out of 20 failures) with requirements for TT5% being larger than 10kh or 30kh, depending on application. Failure mode statistics and understanding is very much based on single mode 9xxnm pump diode laser experience, nevertheless there are fine but important differences. Testing for failure rate is done with multi-cell test [156] and scaled failure statistics with a Weibull distribution is obtained.

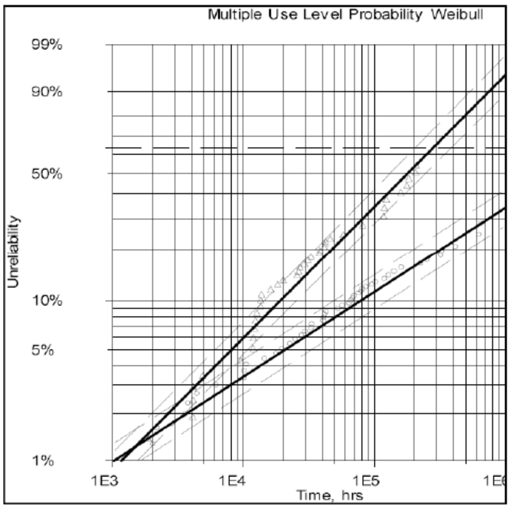

Figure 12: Projected percentage of failures as function of time, based on multicell test, for use conditions of 8W, 30^0C for two types of 100µm BA diode lasers. Projected time to 5% failures are for the two types of BA diode lasers 8'000h and 20'000h, respectively [156]

Reliability requirements are higher for YEDFA applications and thus such pumps are run at a derated power level.

4.3.2. Simple Lens Coupling

With simple lens coupling the slow axis NA of the BA diode is matched to the NA of the fiber (fast axis NA can be matched by fiber tip or a separate simple lens). Because of the simplicity and because the typical NA of the diode is smaller than the NA of the fiber, a high power, wide stripe BA diode can be used. One recent example is the 16W at 20A in a 105/0.22 fiber from a 200µm wide BA laser [154].

4.3.3. Beam Symmetrization Coupling Optics

Already a 50µm NA=0.22µm fiber carries 600 lateral modes (both polarizations). It is therefore theoretically possible to couple 600 single lateral mode narrow stripe diode lasers, each with 1 Watt of power, into such a fiber. To ease this tedious task one resorts to array techniques, i.e. one uses a linear monolithic "Single lateral mode Emitter Array Laser", called SEAL [157] and an array of lenses [158]. Pumps with 50W from a 50µm/0.22 fiber are available [159], one order of magnitude away from the limits, partially due to de-rating of the SEAL vs. the individual laser, for the largest fraction to accommodate for alignment tolerances.

It becomes impractical to individually couple single lateral mode diode lasers into larger fibers (i.e. 40'000 modes in a 400µm,0.22 NA fiber) and thus arrays of BA diode lasers on one bar are used for larger fibers. Limited by the passive cooling, these bars have a low packing density of around 10% to 30% (therefore often called low fill factor (LFF) bars). Powers in the range of 400W in a 200µm,0.22NA fiber are commercially feasible [159], without wavelength and polarization multiplexing.

9xxnm pump packages with a 100µm,0.12NA pigtail, based only a few BA diodes, matched in BPP in the slow direction and stacked in the fast axis, called multiple BA pumps, are predicted to become the next generation workhorse for passive hermetic fiber pumps.

The loss in radiance by coupling pump diode lasers to MM fibers is painful and limited by engineering limits which are still at least one order of magnitude away from the limits imposed by physics.

Numerous beam matching devices have been investigated, but the search for a breakthrough device is going on.

4.4 Active Cooled Pump Diode Packages

In active cooling the heat is removed by a liquid in close proximity. Among the different possibilities (immersion, micro or macrochannel coolers in different materials) the expansion matched (Cu/Mo) microchannel cooler, run with pure water, is presently seen as the best compromise [145] between all the requirements. The requirement for high power and high reliability can only be accommodated by hard-soldering the bar on an expansion matched microchannel cooler, possibly with an expansion matched submount in between, for ease of manufacturing. Routine measurement methods are required to control during production thermal and mechanical integrity of this arrangement such as thermal wavelength shifts [160] and routine stress measurements by monitoring changes in bow. Active cooling systems are expensive. Therefore they are used only for highest powers, which require beam symmetrization optics.

4.4.1 Beam Symmetrization Coupling Optics

It has been a standard for a long time that high power bars, microchannel coolers and lenses are designed for a 1cm wide emission stripe. For ASE and NA optimization, the above-mentioned optical isolation trenches are necessary to subdivide the 1cm wide laser diode. Such a subdivided 1 cm wide laser can also be looked at as closely packed BA laser diodes and is therefore often also called high fill factor bar. For drive current optimization (trading off threshold current vs. power density), the passive space between BA diodes can be increased, thereby reducing the fill factor. In the last few years cw hero powers have been increased from 300W to 1kW from a 1cm aperture, demonstrating the raw capability of a 1 cm diode [161] , [162] , [163] , [164]. At such currents (up to 1000A) one runs into ohmic resistance loss issues in the current supply cables and, as a consequence, the calculated intrinsic (ohmic losses subtracted) power conversion efficiency becomes much less relevant than the measured overall (with or without chiller power included) “wallplug efficieny”.

As solution, a narrower standard for bars, called Maxichip (also “3mm bar”, “1/3 bar”, “minibar”) has been proposed, and products with high radiance (80W from 3200μm/0.08NA) are available [165]. Maxichips, with their compact form factor (3600μm wide and for now 3600μm long, projected to become even longer very soon), might very well be the beginning of the end of the 1cm legacy width for high power bars.

4.5. Pulse Operation

High power diode lasers are thermally limited in roll over power as well as in NA. If the diode laser is pulsed with a length shorter than the respective time constant [166] higher powers can be obtained. At low enough duty factors heat sinking can be reduced allowing for monolithic vertical stacking [167]. At short pulses, the NA and radiance of a simple BA diode laser can be improved [149].

4.6. Combined Power

Power Photonics would not be possible without the availability of all fiber multimode fused fiber combiners (with or without signal feed-through), Bragg gratings and mode field adapters [168]. Key for this technology is their low insertion loss, radiance conservation as well as the capability to handle high powers [169].

5. High Radiance Diode Laser Technologies

Wavelength and polarization division multiplexing to combine beams of the same spacial mode is routinely used to increase the radiance. By wavelength combining a SEAL, a nearly diffraction limited beam with 30W cw power (radiance of 781MW/(cm^{2}sr)) or pulsed beam with 50W of power (3600MW/(cm^{2}sr)), was demonstrated [170].

The holy grail of high radiance diode lasers is coherent coupling of an array of lasers, locked by evanescent fields [171]. Progress to reproducibly lock the phases over a useful power and temperature range has been exceedingly difficult [172], [173], a robust design has not been found yet. With diode laser technology improving, the possibility arises for coherent combination of diodes with individually controlled frequency and phase [174].

6. VCSEL Pump and High Power Diode Lasers

Pump diode lasers are limited by thermal and by optical power density and for this reason a large area vertical cavity surface emitting laser diode (VCSEL) should be an excellent pump source. A VCSEL has a large optical mode size with an already built-in epitaxial surface passivation. Low power VCSELs on GaAs substrates are established high volume technologies for datacom (850nm MM) and sensing (optical PC mouse sensor). Due to the small active volume such VCSELs have a high efficiency and high speed, already at very low currents and powers. In addition, the low NA symmetric beam lends itself to low cost coupling.

In an exemplary effort, the concept of a low power VCSELs was adapted to high power operation at 980nm [175]. In order to control the beam quality at high power, an external optical cavity is added, either with an external mirror or, for lower powers, through an extended cavity. With the external mirror pump modules with 400mW at 1.5A drive current and with the extended cavity an uncooled pumplet, designed for 50mW, were demonstrated. Output power, power conversion efficiency and reliability understanding fell short with respect to the competing edge emitters, in telecom market.

As we understand from edge emitters, the thermal limits of a pump diode laser are ultimately limited by heat generation, given by joule heating and free carrier absorption in the volume overlapping with the mode and the heat removal, given by the thermal resistance between the active region and the heatsink, from the active region.

The cooling area for a high power narrow stripe edge emitting device (5μm*4000μm) and for a typical high power NECSL with 150μm diameter are comparable. It is a distinct characteristic (disadvantage) of a VCSEL configuration that carrier injection, optical mode reflection and heat removal is all concentrated in the bottom distributed Bragg reflector mirror, a GaAs/AlGaAs superstructure with relatively poor material constants with respect to high power operation. A large research effort, for both, GaAs and InP devices, has been directed to ease this heating issue through clever designs and material choices. However, design space and available material impose limits.

Arrays of GaAs based NECSL are ideally suited for intracavity frequency doubling in periodically poled lithium niobate (PPLN) to generate light in the visible spectrum in the Watt regime as RGB light sources for laser projection displays.

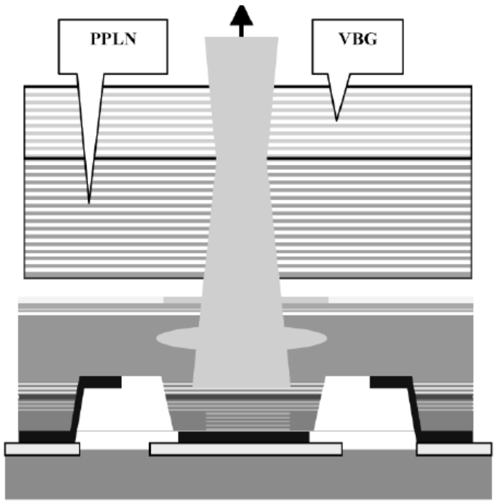

Figure 13: Schematic structure of a NECL array element of a visible light source by frequency doubling [176]

7. Status, Trends and Opportunities

7.1. Status

In the eighties, many different technologies, such as time-division multiplexing, coherent detection, soliton, and WDM were investigated for cost efficient exploitation of the fiber transmission capacity. All these technologies had to carefully manage the “loss budget”. After the pioneering demonstrations work on how to get rid of the loss concerns through Raman amplifiers (Hicks [177]) or EDFA amplifiers (Payne [178],[179] and Desurvire [180]), a concerted and successful effort was started in the late eighties to develop pump diode lasers, key enablers to power up these disruptive technologies. This development was fueled by the deregulation of the telecom industry, the need for long haul communication capacity and the “new economy” financial experiment. Today, after a painful technology and company shake-out, pump diode technology has matured and only a few companies are supplying telecom pump lasers, but in large volume, “powering up the internet”, as initially strived for.

Based on the status of the diode laser technology the optical power supplies of choice are: 980nm pump lasers and 1480nm remote pump laser for C and L band EDFAs [9] and 14xxnm high power diode lasers for C and L band extension by Raman amplification. Best for distribution of TV and FTTH signals is the cladding pumped YEDFA, powered up with an uncooled 940nm multimode pump module.

Power photonics, triggered through the demonstration by Gapontsev in 2002 of a diffraction limited 135W cw *all fiber* fiber laser [6] has since established itself in the printing and material processing market.

7.1. Trends and Opportunities

After the shake-out of telecom pump technologies it is fair to assume that the surviving pump lasers represent already the fittest solution, and no new opportunities will arise for a while. The trend to further reduce cost by gradually increasing power and manufacturing volume will continue.

In this next phase of power photonics the trend to improve 9xxnm MM fiber coupled pumps will continue, mainly based on continuation of the successful length scaling. We do not know today what the limits to length scaling are: material parameters (mobility / free carrier absorption), or financial limits? Instead of the calculated power conversion efficiency, wallplug efficiency (from wallplug to fiber) will be targeted with the goal to top today's 50% across all power ranges. Lowering cost will be achieved through standardization of parts and increased manufacturing volume.

In this new field of power photonics there are many opportunities for pump lasers, just to name a few:

1. Broad area laser with athermal waveguide to reduce high power slow axis NA.
2. Semiconductor with better ratio of mobility/free carrier absorption and thermal properties
3. Pump diode waveguide with loss α<0.2cm^{-1}
4. Expansion matched heat sinks with higher thermal conductivity
5. Low cost beam matcher between pump diode and fiber
6. High power laser with controllable frequency and phase for coherent combination
7. Standardization of products to increase volume and reduce cost

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References:

[1] N.S. Bergano, "Wavelength Division Multiplexing in Long-Haul Transoceanic Transmission Systems," JLT 2005, vol. 23, no. 12, 4125-4139

[2] J. Limpert, F. Roser, S. Klingebiel, T. Schreiber, C. Wirth, T. Peschel, R. Eberhardt and A. Tunnermann, "The Rising Power of Fiber Lasers and Amplifiers," J-STQE 2007, vol. 13, no. 3, 537-5445

[3] J. Bromage, "Raman Amplification for Fiber Communications Systems," JLT 2004, vol. 22, no. 1, 79-93

[4] A. Mooradian, S. Antikichev, B. Cantos, G. Carey, M. Jansen, S. Hallstein, W. Hitchens, D. Lee, J. M. Pelaprat, R. Nabiev, G. Niven, A. Shchegrov, A. Umbrasas and J. Watson, "High Power Extended Vertical Cavity Surface Emitting Diode Lasers and Arrays and Their Applications," MOC, Microoptics Conference, Tokyo 2005, 1-4

[5] B. Schmidt, S. Mohrdiek and C.S. Harder, "Pump Laser Diodes," Optical Fiber Telecommunications IV-A, Academic Press, San Diego 2002

[6] N.S. Platonov, D.V. Gapontsev, V.P. Gapontsev and V. Shumilin, "135 W CW Fiber Laser with Perfect Single Mode Output," CLEO 2002, CPDC3, 1-4

[7] F. Bachmann, "Goals and status of the German national research initiative," SPIE 2007, vol. 6456, 1-12

[8] C.M. Stickley, M.E. Filipkowski, E. Parra and E.E. Hach III, "Overview of progress in super high efficiency diodes for pumping high energy lasers," SPIE 2006, vol. 6104, 42-51

[9] D.G. Foursa, A. Lucero, C.R. Davidson, J.X. Cai, W. Anderson, Y. Cai, P.C. Corbett, W.W. Patterson, H. Li, M. Mazurczyk, M. Nissov, A.N. Pilipetskii and N.S. Bergano, "2 Tb/s (200x10 Gb/s) data transmission over 7,300 km using 150 km spaced repeaters enabled by ROPA technology," OFC 2007, PDP 25, 1-3

[10] K. Fukagai, S. Ishikawa, K. Endo and T. Yuasa, "Current Density Dependence for Dark-Line Defect Growth Velocity in Strained InGaAs / AlGaAs Quantum Well Laser Diodes," Jpn J Appl Phys 1991, vol. 30, no. 3a, L371-L373

[11] R.G. Waters, D.P. Bour, S.L. Yellen and N.F. Ruggieri, "Inhibited Dark-Line Defect Formation in Strained InGaAs / AlGaAs Quantum Well Lasers," PTL 1990, vol. 2, no. 8, 531-533

[12] S.E. Fischer, R.G. Waters, D. Fekete, J.M. Ballantyne, Y.C. Chen and B.A. Soltz, "Long-lived InGaAs quantum well lasers," Appl Phys Lett 1989, vol. 54, no. 19, 1861-1862

[13] W.T. Tsang, "Extension of lasing wavelengths beyond 0.87 µm in GaAs / AlxGa1-xAs double-heterostructure lasers by In incorporation in the GaAs active layers during molecular beam epitaxy," Appl Phys Lett 1981, vol. 38, no. 9, 661-663

[14] J. Stohs, D.J. Bossert, D.J. Gallant and S R. J. Brueck, "Gain, Refractive Index Change, and Linewidth Enhancement Factor in Broad-Area GaAs and InGaAs Quantum-Well Lasers," JQE 2001, vol. 37, no. 11, 1449-1459

[15] L.A. Coldren and S.W. Corzine, "Diode Lasers and Photonic Integrated Circuits," John Wiley & Sons, Wiley-Interscience, New York 1995

[16] D. Rodríguez, I. Esquivias, S. Deubert, J.P. Reithmaier, A. Forchel, M. Krakowski, M. Calligaro and O. Parillaud, "Gain, Index Variation and Linewidth-Enhancement Factor in 980-nm Quantum-Well and Quantum-Dot Lasers," JQE 2005, vol. 41, no. 2, 117-126

[17] S.C. Auzanneau, N. Michel, M. Calligaro, M. Krakowski, S. Deubert, J.P. Reithmaier and A. Forchel, "High Brightness (1 W with M^2=2.9) GaInAs / (Al)GaAs index guided quantum-dot tapered lasers at 980 nm with a high wavelength stability," SPIE 2004, vol. 5452, 1-13

[18] M. Pessa, J. Nappi, A. Ovtchinnikov, P. Savolainen and H. Asonen, "Aluminium-free 980-nm laser diodes for Er-doped optical fiber amplifiers," SPIE 1995, vol. 2397, 333-341

[19] M. Krakowski, M. Calligaro, C. Larat, M. Lecomte, N. Michel, O. Parillaud, B. Boulant and T. Fillardet, "High-Brightness tapered laser diode bars and optical modules with Al-free active region (λ = 980 nm)," SPIE 2004, vol. 5620, 128-136

[20] H. Wenzel, A. Klehr, M. Braun, F. Bugge, G. Erbert, J. Fricke, A. Knauer, P. Ressel, B. Sumpf, M. Weyers and G. Trankle, "Design and realization of high-power DFB lasers," SPIE 2004, vol. 5594, 110-123

[21] M. Peters, V. Rossin and B. Acklin, "High Efficiency, High Reliability Laser Diodes at JDS Uniphase," SPIE 2005. vol. 5711, 142-151

[22] S.M. Yeh, S.Y. Huang and W.H. Cheng, "A New Scheme of Conical-Wedge-Shaped Fiber Endface for Coupling Between High-Power Laser Diodes and Single-Mode Fibers," JLT 2005, vol. 23, no. 4, 1781-1786

[23] C.A. Edwards, H.M. Presby and C. Dragone, "Ideal Microlenses for Laser to Fiber Coupling," JLT 1993, vol. 11, no. 2, 252-257

[24] H. Yoda and K. Shiraishi, "A New Scheme of a Lensed Fiber Employing a Wedge-Shaped Graded-Index Fiber Tip for the Coupling Between High-Power Laser Diodes and Single-Mode Fibers," JLT 2001, vol. 19, no. 12, 1910-1917

[25] K. Kurokawa and E.E. Becker, "Laser Fiber Coupling with a Hyperbolic Lens," MTT 1975, vol.. 23, no. 3, 309-311

[26] E.E. Becker, K. Kurokawa, "Hyperbolic type optical fiber lens coupler for coupling the fiber to an optical line source," U.S. Patent No. 3910677

[27] V.S. Shah, L. Curtis, R.S. Vodhanel, D.P. Bour and W.C. Young, "Efficient Power Coupling from a 980-nm, Broad-Area Laser to a Single-Mode Fiber Using a Wedge-Shaped Fiber Endface," JLT 1990, vol. 8, no. 9, 1313-1318

[28] T. Takuji, S. Michitomo, "Optical fiber with lens and method of manufacturing the same," U.S. Patent No. 5845024

[29] J. Xu, S. Kenji, A. Takayuki, "Lensed optical fiber having high coupling efficiency, process of production and apparatus for production of same, and laser diode module," U.S. Patent No. 6597835

[30] R.L. Thornton, R.D. Burnham, T.L. Paoli, N. Holonyak, and D.G. Deppe, "Low threshold planar buried heterostructure lasers fabricated by impurity-induced disordering," Appl Phys Lett 1985, vol. 47, no. 12, 1239-1241

[31] D.F. Welch, D.R. Scifres, P.S. Cross and W. Streifer, "Buried heterostructure lasers by silicon implanted, impurity induced disordering," Appl Phys Lett 1987, vol. 51, no. 18, 1401-1403

[32] H. Horie, N. Arai, Y. Mitsuishi, N. Komuro, H. Kaneda, H. Gotoh, M. Usami and Y. Matsushima, "Greater than 500-mW CW Kink-Free Single Transverse-Mode Operation of Weakly Index Guided Buried-Stripe Type 980-nm Laser Diodes," PTL 2000, vol. 12, no. 10, 1304-1306

[33] H. Horie, S. Nagao, K. Shimoyama and T. Fujimori, "Weakly Index Guided Buried-Stripe Type 980nm Laser Diodes Grown by a Combination of Gas Source Molecular Beam Epitaxy and Metalorganic Vapor Phase Epitaxy with an AlGaAs / InGaP / GaAs Double Etch Stop Structure," Jpn J Appl Phys 1999, vol. 38, no. 10, 5888–5897

[34] C.S. Harder, P. Buchmann and H.P. Meier, "High-Power Ridge-Waveguide AlGaAs GRIN-SCH Laser Diode," EL 1986, vol. 22, no. 20, 1081-1082

[35] J.N. Walpole, "Slab-coupled optical waveguide lasers: a review," SPIE 2004, vol. 5365, 124-132

[36] J.P. Donnelly, R.K. Huang, J.N. Walpole, L.J. Missaggia, C.T. Harris, J. J. Plant, R.J. Bailey, D.E. Mull, W.D. Goodhue and G.W. Turner, "AlGaAs–InGaAs Slab-Coupled Optical Waveguide Lasers," JQE 2003, vol.39, no. 2, 289-298

[37] J.C. Chang, J.J. Lee, A. Al-Muhanna, L.J. Mawst and D. Botez, "Comprehensive above-threshold analysis of large-aperture (8–10 mm) antiresonant reflecting optical waveguide diode lasers," Appl Phys Lett 2002, vol. 81, no. 26, 4901-4903

[38] S. Pawlik, S. Traut, A. Thies, B. Sverdlov and B. Schmidt, "Ultra-High Power RWG Laser Diodes with Lateral Absorber Region," ISLC 2002, 163-164

[39] M. Yuda, T. Hirono, A. Kozen and C. Amano, "Improvement of Kink-Free Output Power by Using Highly Resistive Regions in Both Sides of the Ridge Stripe for 980-nm Laser Diodes," JQE 2004, vol. 40, no. 9, 1203-1207

[40] M. Buda, H.H. Tan, L. Fu, L. Josyula and C. Jagadish, "Improvement of the Kink-Free Operation in Ridge-Waveguide Laser Diodes Due to Coupling of the Optical Field to the Metal Layers Outside the Ridge," PTL 2003, vol. 15, no. 12, 1686-1688

[41] D.P. Bowler, "Semiconductor laser with kink suppression layer," U.S. Patent No. 6366595

[42] J. Guthrie, G.L. Tan, M. Ohkubo, T. Fukushima, Y. Ikegami, T. Ijichi, M. Irikawa, R.S. Mand, and J.M. Xu, "Beam Instability in 980-nm Power Lasers: Experiment and Analysis," PTL 1994, vol. 6, no. 12, 1409-1411

[43] M.F. Schemmann, C.J. van der Poel, B.A. van Bakel, H.P. Ambrosius, A. Valster, J.A. van den Heijkant and G.A. Acket, "Kink power in weakly index guided semiconductor lasers," Appl Phys Lett 1995, vol. 66, no. 8, 920-922

[44] M. Achtenhagen, A.A. Hardy and C. S. Harder, "Coherent Kinks in High-Power Ridge Waveguide Laser Diodes," JLT 2006, vol. 24, no. 5, 2225-2232

[45] D.F. Welch, D.G. Mehuys, D.R. Scifres, "Semiconductor gain medium with multimode and single mode regions," U.S. Patent No. RE37051

[46] S. O'Brien, D.F. Welch, R.A. Parke, D. Mehuys, K.Dzurko, R.J. Lang, R. Waarts and D. Scifres, "Operating Characteristics of a High-Power Monolithically Integrated Flared Amplifier Master Oscillator Power Amplifier," JQE 1993, vol. 29, no. 6, 2052-2057

[47] R.J. Lang, K. Dzurko, A.A. Hardy, S. Demars, A. Schoenfelder and D.F. Welch, "Theory of Grating-Confined Broad-Area Lasers," JQE 1998, vol. 34, no. 11, 2196-2210

[48] A. Guermache, V. Voiriot and J. Jacquet, "Investigations of 14xx-nm pump lasers formed by active MMI waveguide," SPIE 2006, vol. 6115, 1-10

[49] S. O'Brien, A. Schoenfelder and R.J. Lang, "5-W CW Diffraction-Limited InGaAs Broad-Area Flared Amplifier at 970 nm," PTL 1997, vol. 9, no. 9, 1217-1219

[50] J. Weber, M.T. Kelemen, S. Moritz and M. Mikulla, "High-Power High-Brightness 3 W tapered amplifiers tunable from 940 nm to 980 nm," SPIE 2006, vol. 6104, 1-7

[51] K. Paschke, B. Sumpf, F. Dittmar, G. Erbert, J. Fricke, A. Knauer, S. Schwertfeger, H. Wenzel and G. Trankle, "Nearly-diffraction limited 980nm tapered diode lasers with an output power of 6.7 W," ISLC 2004, 43- 44

[52] A. Guermache, V. Voiriot, D. Locatelli, F. Legrand, R. M. Capella, P. Gallion and J. Jacquet, "Experimental Demonstration of Spatial Hole Burning Reduction Leading to 1480-nm Pump Lasers Output Power Improvement," PTL 2006, vol. 17, no. 10, 2023-2025

[53] B. Schmidt, S. Pawlik, N. Lichtenstein, "High power semiconductor laser diode and method for making such a diode," U.S. Patent No. 6798815

[54] K. Shigihara, K. Kawasaki, Y. Yoshida, S. Yamamura, T. Yagi and E. Omura, "High-Power 980-nm Ridge Waveguide Laser Diodes Including an Asymmetrically Expanded Optical Field Normal to the Active Layer," JQE 2002, vol. 38, no. 8, 1081-1088

[55] B. C. Qiu, S.D. McDougall, X.F. Liu, G. Bacchin and J.H. Marsh, "Design and Fabrication of Low Beam Divergence and High Kink-Free Power Lasers," JQE 2005, vol. 41, no. 9, 1124-1130

[56] B. Schmidt, N. Lichtenstein, B. Sverdlov, N. Matuschek, S. Mohrdiek, T. Pliška, J. Muller, S. Pawlik, S. Arlt, H. U. Pfeiffer, A. Fily and C.S. Harder, "Further development of high power pump laser diodes," SPIE 2003, vol. 5248, 43-54

[57] M. V. Maximov, Y.M. Shernyakov, I.I. Novikov, S.M. Kuznetsov, L.Y. Karachinsky, N.Y. Gordeev, I.P. Soshnikov, Y.G. Musikhin, N.V. Kryzhanovskaya, A. Sharon, U. Ben-Ami, V.P. Kalosha, N.D. Zakharov, P. Werner, T. Kettler, K. Posilovic, V.A.

Shchukin, N.N. Ledentsov and D. Bimberg, "Longitudinal photonic bandgap crystal laser diodes with ultra-narrow vertical beam divergence," SPIE 2006, vol. 6115, 1-13

[58] A. Maląg, A. Jasik, M. Teodorczyk, A. Jagoda and A. Kozłowska, "High-Power Low Vertical Beam Divergence 800-nm-Band Double-Barrier-SCH GaAsP–(AlGa)As Laser Diodes," PTL 2006, vol. 18, no. 15, 1582-1584

[59] G. Lin, S.T. Yen, C.P. Lee and D.C. Liu, "Extremely Small Vertical Far-Field Angle of InGaAs-AlGaAs Quantum-Well Lasers with Specially Designed Cladding Structure," PTL 1996, vol. 8, no. 12, 1588-1590

[60] P. Crump, W. Dong, M. Grimshaw, J. Wang, S. Patterson, D. Wise, M. DeFranza, S. Elim, S. Zhang, M. Bougher, J. Patterson, S. Das, J. Bell, J. Farmer, M. DeVito and R. Martinsen, "100-W+ Diode Laser Bars Show > 71% Power Conversion from 790-nm to 1000-nm and Have Clear Route to > 85%," SPIE 2007, vol. 6456, 1-11

[61] N. Lichtenstein, A.C. Fily, B. Reid, "High power semiconductor laser with a large optical superlattice waveguide," U.S. Patent No. 7085299

[62] C.R. Giles, T. Erdogan and V. Mizrahi, "Reflection-Induced Changes in the Optical Spectra of 980-nm QW Lasers," PTL 1994, vol. 6, no. 8, 903-906

[63] I.A. Avrutsky, R. Gordon, R. Clayton and J.M. Xu, "Investigations of the Spectral Characteristics of 980-nm InGaAs–GaAs–AlGaAs Lasers," JQE 1997, vol. 33, no. 10, 1801-1809

[64] B.F. Ventrudo, G. Rogers, "Fibre-grating-stabilized diode laser," U.S. Patent No. 5485481

[65] B.F. Ventrudo. G.A. Rogers. G.S. Lick, D. Hargreaves and T.N. Demayo, "Wavelength and intensity stabilisation of 980 nm diode lasers coupled to fibre Bragg gratings," EL 1994, vol. 30, no. 25, 2147-2149

[66] T. Pliška, S. Arlt, R. Battig, T. Kellner, I. Jung, N. Matuschek, P. Mauron, B. Mayer, S. Mohrdiek, J. Muller, S. Pawlik, H. U. Pfeiffer, B. Schmidt, B. Sverdlov, S. Teodoropol, J. Troger, B. Valk and C.S. Harder, "Wavelength stabilized 980 nm uncooled pump laser modules for erbium-doped fiber amplifiers," Opt Laser Eng 2005, vol. 43, 271–289

[67] M. K. Davis, G. Ghislotti, S. Balsamo, D.A. Loeber, G.M. Smith, M.H. Hu and H.K. Nguyen, "Grating Stabilization Design for High-Power 980-nm Semiconductor Pump Lasers," J-STQE 2005, 1197-1208

[68] N. Matuschek, S. Mohrdiek, T. Pliska, "Laser source with high relative feedback and method for making such a laser source," U.S. Patent No. 7099361

[69] T. Pliška, N. Matuschek, S. Mohrdiek, A. Hardy and C.S. Harder, "External Feedback Optimization by Means of Polarization Control in Fiber Bragg Grating Stabilized 980-nm Pump Lasers," PTL 2001, vol. 13, no. 10, 1061-1063

[70] M. Achtenhagen, S. Mohrdiek, T. Pliška, N. Matuschek, C.S. Harder and A. Hardy, "L–I Characteristics of Fiber Bragg Grating Stabilized 980-nm Pump Lasers," PTL 2001, vol. 13, no. 5, 415-417

[71] R. Badii, N. Matuschek, T. Pliška, J. Troger and B. Schmidt, "Dynamics of multimode diode lasers with strong, frequency-selective optical feedback," Phys Rev E 2003, vol. 68, no. 3, id. 036605, 1-12

[72] J. Wang and D.T. Cassidy, "Investigation of Partially Coherent Interaction in Fiber Bragg Grating Stabilized 980-nm Pump Modules," JQE 2004, vol. 40, no. 6, 673-681

[73] A. Ferrari, G. Ghislotti, S. Balsamo, V. Spano and F. Trezzi, "Subkilohertz Fluctuations and Mode Hopping in High-Power Grating-Stabilized 980-nm Pumps," JLT 2002, vol. 20, no. 3, 515-518

[74] I. Kostko and R. Kashyap, "Modeling of self-organised coherence-collapse and enhanced regime semiconductor fibre grating reflector lasers," SPIE 2004, vol. 5579, 367-374

[75] S. Mohrdiek, "Stabilized laser source," U.S. Patent No. 6771687

[76] T. Pliška, N. Matuschek, J. Troger, B. Schmidt, S. Mohrdiek, C.S. Harder, "A compact, narrow band, and low noise 800 mW laser source at 980 nm," SPIE 2005, vol. 5738, 380-387

[77] J.A. Sharps, "Reliability Of Hermetically Packaged 980 nm Diode Lasers," LEOS 1994, vol. 2, 35-36

[78] D.W. Hall, P.A. Jakobson, J.A. Sharps, R.F. Bartholomew, "Packaging of high power semiconductor lasers," U.S. Patent No. 5770473

[79] A. Oosenbrug, "Reliability Aspects of 980-nm Pump Lasers in EDFA Applications," SPIE 1998, Vol. 3284, 20-27

[80] R. Battig, H.U. Pfeiffer, N. Matuschek and B. Valk, "Reliability Issues in Pump Laser Packaging," LEOS 2002, vol. 2, 542-543

[81] X. Liu, M. H. Hu, C.G. Caneau, R. Bhat and C.E. Zah, "Thermal Management Strategies for High Power Semiconductor Pump Lasers," ITHERM 2004, vol. 2, 493-500

[82] M. A. Bettiati, C. Starck, F. Laruelle, V. Cargemel, P. Pagnod, P. Garabedian, D. Keller, G. Ughetto, J.C. Bertreux, L. Raymond, G. Gelly and R.M. Capella, "Very high power operation of 980 nm single-mode InGaAs / AlGaAs pump lasers," SPIE 2006, vol. 6104, 130-139

[83] B. Sverdlov, B. Schmidt, S. Pawlik, B. Mayer and C.S. Harder, "1 W 980 nm Pump Modules wit h Very High Efficiency," ECOC 2002, vol. 5, 1-2

[84] R. Nagarajan, V.V. Rossin, H.Ransom, N. Morozova, A. Kanjamala, R. Parke, D. Dawson, T.J. Kim, H. Clarke, K. Uppal, D. Coblentz and J.S. Major, "Grating stabilized 0.5 W, 980 nm pump modules," ISLC 2000, 27-28

[85] W.C. Tang, H.J. Rosen, P. Vettiger and D.J. Webb, "Raman microprobe study of the time development of AlGaAs single quantum well laser facet temperature on route to catastrophic breakdown," Appl Phys Lett 1991, vol. 58, no. 6, 557-559

[86] H.P. Dietrich, M. Gasser, A. Jakubowicz, E.E. Latta, P. Roentgen, "Semiconductor lasers and method for making the same," U.S. Patent No. 5940424

[87] A. Baliga, D.C. Flanders, R. Salvatore, "Long, high-power semiconductor laser with shifted-wave and passivated output facet," U.S. Patent No. 6519272

[88] A. K. Chin, Z. Wang, K. Luo, A. Nelson and Z. Xu, "Failure-mode analysis of high-power, single-mode, 980 nm, pump laser-diodes," SPIE 2003, vol. 4993, 84-90

[89] R.E. Mallard, R. Clayton, D. Mayer and L. Hobbs, "Failure analysis of high power GaAs-based lasers using electron beam induced current analysis and transmission electron microscopy," J Vac Sci Technol A 1998, vol.16, nr. 2, 825-829

[90] F. Beffa, H. Jackel, M. Achtenhagen, C.S. Harder and D. Erni, "High-temperature optical gain of 980 nm InGaAs / AlGaAs quantum-well lasers," Appl Phys Lett 2000, vol. 77, no. 15, 2301-2303

[91] C. Hanke, F.U. Herrmann and S. Beeck, "Investigation of the Mirror Temperature of Narrowstripe GaAs / AIGaAs Quantum Well Lasers with Segmented Contacts," ISLC 1990, 156-157

[92] H.0. Yonezu, M. Ueno, T. Kamejima and I. Hayashi, "An AIGaAs Window Structure Laser," JQE 1979, vol. 15, no. 8, 775-781

[93] J. Ungar, N. Bar-Chaim and I. Ury, "High-Power GaAlAs Window Lasers," EL 1986, vol. 22, no. 5, 279-280

[94] R.L. Thornton, D.F. Welch, R.D. Burnham, T L. Paoli and P.S. Cross, "High power (2.1 W) 10-stripe AlGaAs laser arrays with Si disordered facet windows," Appl Phys Lett 1986, vol. 49, no. 23, 1572-1574

[95] D.F. Welch, D.R. Scifres, "Window laser with high power reduced divergence output," U.S. Patent No. 4845725

[96] S. Yamamura, K. Kawasaki, K. Shigihara, Y. Ota, T. Yagi and Y. Mitsui, "Highly Reliable Ridge Waveguide 980nm Pump Lasers Suitable for Submarine and Metro Application," OFC 2003, vol. 1, 398-399

[97] D.A. Yanson, J.H. Marsh, S. Najda, S.D. McDougall, H. Fadli, G. Masterton, B. Qiu, O.P. Kowalski, G. Bacchin and G. McKinnon, "High-Power, High-Brightness, High-Reliability Laser Diodes Emitting at 800-1000 nm," SPIE 2007, vol. 6456, 1-8

[98] J.H. Marsh, C.J. Hamilton, "Semiconductor laser," U.S. Patent No. 6760355

[99] Y. Yamada, Y. Yamada, T. Fujimoto and K. Uchida, "High power and highly reliable 980nm lasers with window structure using Impurity Free Vacancy Disordering," SPIE 2005, vol. 5738 , 40-46

[100] K. Isshiki, T. Kamizato, A. Takami, A. Shima, S. Karakida, H. Matsubara and W. Susaki, "High-Power 780 nm Window Diffusion Stripe Laser Diodes Fabricated by an Open-Tube Two-step Diffusion Technique," JQE 1990, vol. 26, no. 5, 837-842

[101] K.H. Park, J.K. Lee, D.H. Jang, H.S. Cho, C.S. Park, K.E. Pyun, J.Y. Jeong, S. Nahm and J. Jeong, "Characterization of catastrophic optical damage in Al-free InGaAs / InGaP 0.98 µm high-power lasers," Appl Phys Lett 1998, vol. 73, no 18, 2567-2569

[102] A. Moser, E.E. Latta and D.J. Webb, "Thermodynamics approach to catastrophic optical mirror damage af AIGaAs single quantum well lasers," Appl Phys Lett 1989, vol. 55, no. 12, 1152-1154

[103] A. Moser, "Thermodynamics of facet damage in cleaved AlGaAs lasers," Appl Phys Lett 1991, vol. 59, no. 5, 522-524

[104] A. Moser, A. Oosenbrug, E. . Latta, T. Forster and M. Gasser, "High-power operation of strained InGaAs / AIGaAs single quantum well lasers," Appl Phys Lett 1991, vol. 59, no. 21, 2642-2644

[105] A. Moser and E.E. Latta, "Arrhenius parameters for the rate process leading to catastrophic damage of AlGaAs-GaAs laser facets," J Appl Phys 1992, vol. 71, no. 10, 4848-4853

[106] F.A. Houle, D.L. Neiman, W.C. Tang and H.J. Rosen, "Chemical changes accompanying facet degradation of AlGaAs quantum well lasers," J Appl Phys 1992, vol. 72, no. 9, 3884-3896

[107] H. Brugger and P.W. Epperlein, "Mapping of local temperatures on mirrors of GaAs / AlGaAs laser diodes," Appl Phys Lett 1990, vol. 56, no. 11, 1049-1051

[108] P.W. Epperlein, "Temperature, stress, disorder and crystallization effects in laser diodes: Measurements and impacts," SPIE 1997, vol. 3001, 13-28

[109] A. Jakubowicz, "Microcharacterization of Semiconductor Laser Diodes - Materials and Devices," SPIE 1994, vol. 2780, 344-354

[110] E. Schaub, "Optical Absorption Rate Determination, on the Front Facet of High-Power GaAs Laser Diodes, by Means of Thermoreflectance Technique," Jpn J Appl Phys 2001, vol. 40, 2752–2756

[111] K. Hausler, N. Kirstaedter, "Method and device for passivation of the resonator end faces of semiconductor lasers based on III-V semiconductor material," U.S. Patent No. 7033852

[112] M. McElhinney, P. Colombo, "Semiconductor lasers having single crystal mirror layers grown directly on facet," U.S. Patent No. 6590920

[113] D. Crawford, M. McElhinney, R. McGowan, P. Thiagarajan, J. Cahill, S. Nelson, S. Olson, P. Pederen and C. Lennon, "Design and performance of 980 nm pump laser modules exhibiting greater than 400 mW kink-free fiber-coupled power," OFC 2002, 482-483

[114] N. Chand, "Passivated faceted article comprising a semiconductor laser," U.S. Patent No. 5665637

[115] M. Gasser, E.E. Latta, "Method for mirror passivation of semiconductor laser diodes," U.S. Patent No. 5063173

[116] L.W. Tu, E.F. Schubert, M. Hong and G.J. Zydzik, "In-vacuum cleaving and coating of semiconductor laser facets using thin silicon and a dielectric," J Appl Phys 1996, vol. 80, no. 11, 6448-6451

[117] H. Kawanishi, T. Morimoto, S. Kaneiwa, H. Hayashi, N. Miyauchi, S. Yano, M. Matsumoto, K. Sasaki, M. Kondo, S. Shiomoto, S. Yamamoto, "Semiconductor laser device with a sulfur-containing film provided between the facet and the protective film," U.S. Patent No. 5208468

[118] L.K. Lindstrom, N.P. Blixt, S.H. Soderholm, S.A. Srinivasan, C.F. Carlstrom, "Method to obtain contamination free laser mirrors and passivation of these," U.S. Patent No. 6812152

[119] R.W. Lambert, T. Ayling, A.F. Hendry, J.M. Carson, D.A. Barrow, S. McHendry, C.J. Scott, A. McKee and W. Meredith, "Facet-Passivation Processes for the Improvement of Al-Containing Semiconductor Laser Diodes," JLT 2006, vol. 24, no. 2, 956-961

[120] M. Hu, L.D. Kinney, E.C. Onyiriuka, M.X. Ouyang, C. E. Zah, "Passivation of semiconductor laser facets," U.S. Patent No. 6618409

[121] P. Ressel, G. Erbert, U. Zeimer, K. Hausler, G. Beister, B. Sumpf, A. Klehr and G. Trankle, "Novel Passivation Process for the Mirror Facets of Al-Free Active-Region High-Power Semiconductor Diode Lasers," PTL 2005, vol. 17, no. 5, 962-964

[122] P. Ressel, G. Erbert, "Method for the passivation of the mirror-faces surfaces of optical semi-conductor elements," U.S. Patent No. 20050287693

[123] H. Horie, H. Ohta and T. Fujimori, "Reliability Improvement of 980-nm Laser Diodes with a New Facet Passivation Process," J-STQE 1999, vol. 5, no. 3, 832-838

[124] H. Horie, H. Ohta, T. Fujimori, "Compound semiconductor light emitting device and method of fabricating the same," U.S. Patent No. 6323052

[125] G. Gelly, "Design and Technology for Highly Reliable 980nm Submerged Pump Modules," SubOptic 2004, paper We 11.2, 1-3

[126] M. Usami, N. Edagawa, Y. Matsushima, H. Horie, T. Fujimori, I. Sakamoto and H. Gotoh, "First Undersea-Qualified 980 nm Pump Laser Diode Module evaluated with Massive Life Test," OFC/IOOC 1999, vol. suppl., PD39, 1-3

[127] G. Ghislotti and F. Fantini, "Design and Screening of Highly Reliable 980-nm Pump Lasers," T-DMR 2002, vol. 2, no. 2, 26-29

[128] S. Arlt, H. U. Pfeiffer, I.D. Jung, A. Jakubowicz, M. Schwarz, N. Matuschek, T. Pliška, B. Schmidt, S. Mohrdiek and C.S. Harder, "Reliability proving of 980 nm pump lasers for metro applications," ISLC 2002, 167-168

[129] H.U. Pfeiffer, S. Arlt, M. Jacob, C.S. Harder, I.D. Jung, F. Wilson, T. Oldroyd and T. Hext, "Reliability of 980 nm pump lasers for submarine, long-haul terrestrial and low cost metro applications," OFC 2002, 483-484

[130] G. Yang, G.M. Smith, M.K. Davis, D.A. Loeber, M. Hu, C.E. Zah and R. Bhat, "Highly Reliable High-Power 980-nm Pump Laser," PTL 2004, vol. 16, no. 11, 2403-2405

[131] J. Gardner, B. Dean and A. Shadagopan, "The 980 nm Pump Laser Experience: Prediction and Practice," SubOptic 2004, paper Tu B 2.4, 1-3

[132] B. Dean and J. Gardner, "Reliability by design – in practice and in the field," Subtelforum 2003, no. 11, 20-25

[133] B. Dean and P. Laverty, "Managing Reliability in a Changing Supplier Market," SubOptic 2004, paper We 11.5, 1-3

[134] Y. Nagashima, S. Onuki, Y. Shimose, A. Yamada and T. Kikugawa, "1480-nm pump laser with asymmetric quaternary cladding structure achieving high output power of >1.2 W with low power consumption," ISLC 2004, 47-48

[135] N. Tsukiji, J. Yoshida, T. Kimura, S. Koyanagi and T. Fukushima, "Recent Progress of High Power 14XXnm Pump Lasers," SPIE 2001, vol. 4532, 349-360

[136] I.P. Kaminow, R.E. Nahory, M.A. Pollack, L.W.Stulz, J.C. Dewinter, "Single-mode c.w. ridge waveguide laser emitting at 1.55mm," EL 1979, vol. 15, no. 23, 763-765

[137] N. Lichtenstein, A. Fily, C. Hermens, B. Schmidt, C.S. Harder, G. Knight, B. Reid, T.Oldroyd, D. Riley, N. Zayer, "1 Watt 14xy InGaAsP / InP Ridge Waveguide Pump Laser Diodes with Low Vertical Farfield and High Efficiency," OFC 2003, vol. 1, 396-397

[138] T. Fukushima, N. Tsukiji, J. Yoshida, T. Kimura and N. Hayamizu, "High Power 14XXnm Pump Lasers for Next Generation," SPIE 2002, vol. 4905, 47-61

[139] K.L. Bacher, C. Fuchs, J.S. Paslaski, R.P. Espindola, A. Benzoni, W C. Dautremont-Smith, S. Srinivasan, G.C. Cho and L. Monro, "High Power l4xx nm Pump Laser Modules for Optical Amplification Systems," SPIE 2001, vol. 4533

[140] R.P. Espindola, K.L. Bacher, K. Kojima, N. Chand, S. Srinivasan, G.C. Cho, F. Jin, C. Fuchs, V. Milner and W.C. Dautremont-Smith, "High power, low RIN, spectrally-broadened 14xx DFB pump for application in co-pumped Raman amplification," ECOC 2001, vol. 6 , 36- 37

[141] N. Tsukiji, "Advances in diode laser pumps for Raman amplification," OFC 2004, vol. 1

[142] D. Garbuzov, A. Komissarov, I. Kudryashov, M. Maiorov, R. Roff and J. Connolly, "High Power Raman Pumps Based on Ridge Waveguide InGaAsP/InP Diode Lasers," OFC 2003, vol. 1, 394-396

[143] N. Lichtenstein, B. Schmidt, A. Fily, S. Weiß, S. Arlt, S. Pawlik, B. Sverdlov, J. Muller and C.S. Harder, "DPSSL and FL Pumps Based on 980nm-Telecom Pump Laser Technology: Changing the Industry," SPIE 2004, vol. 5336, 77-83

[144] C.M. Stickley, M. E. Filipkowski, E. Parra and M. Sandrock, "High Power Laser Diodes and Applications to Direct Diode HELs," LEOS 2006, 468-469

[145] M. Leers, "Microchannel heat sink with adjusted thermal expansion," http://www.ilt.fraunhofer.de/eng/100904.html

[146] F. Bachmann, P. Loosen and R. Poprawe (editors), "High Power Diode Lasers. Technology and Applications," Springer Series in Optical Sciences, Berlin 2007

[147] S. Pawlik, B. Sverdlov, R. Battig, B. Schmidt, H.U. Pfeiffer, S. Arlt, N. Lichtenstein, J. Muller, J. Troger, B. Valk, C.S. Harder, "9xx high power pump modules," SPIE 2006, vol. 6104, 1-8

[148] C.P. Lindsey, A. Yariv, "Method for tailoring the two-dimensional spatial gain distribution in optoelectronic devices and its application to tailored gain broad area semiconductor lasers capable of high power operation with very narrow single lobed farfield patterns," U.S. Patent No. 4791646

[149] J.R. O'Callaghan, J. Houlihan, V. Voignier, G. Huyet, J.G. McInerney, B. Corbett and P.A. O'Brien, "Focusing Properties of High Brightness Gain Tailored Broad-Area Semiconductor Lasers," PTL 2002, vol. 14, no. 1, 9-11

[150] S. Gehrsitz, F.K. Reinhart, C. Gourgon, N. Herres, A. Vonlanthen an H. Sigg, "The refractive index of Al(x)Ga(1-x)As below the band gap: Accurate determination and empirical modeling," J Appl Phys 2000, vol. 87, no. 11, 7825-7837

[151] M. Kanskar, J. Cai, C. Galstad, Y. He, S.H. Macomber, E. Stiers, S.R. Tatavarti-Bharatam, D. Botez and L.J. Mawst, "High Power Conversion Efficiency and Wavelength Stabilized, Narrow Bandwidth 975 nm Diode Laser Pumps," SPIE 2006, vol. 6216, 1-7

[152] M. Peters, V. Rossin, M. Everett and E. Zucker, "High Power, High Efficiency Laser Diodes at JDSU," SPIE 2007, vol. 6456, 1-11

[153] C. Schnitzler, S. Hambuecker, O. Ruebenach, V. Sinhoff, G. Steckman, L. West, C. Wessling and D. Hoffmann, "Wavelength Stabilization of HPDL Array – Fast-Axis Collimation Optic with integrated VHG," SPIE 2007, vol. 6456, 1-7

[154] S. Pawlik, B. Sverdlov, J. Muller, R. Battig, B. Schmidt, H.U. Pfeiffer, S. Arlt, B. Valk and N. Lichtenstein, "Broad area single emitter (BASE) modules with improved brightness," CLEO Europe 2007, CB14-1-THU, 1

[155] V. Gapontsev, I. Berishev, G. Ellis, A. Komissarov, N. Moshegov, A. Ovtchinnikov, O. Raisky, P. Trubenko, V. Ackermann and E. Shcherbakov, "9xx nm single emitter pumps for multi-kW systems," SPIE 2006, vol. 6104, 1-11

[156] V. Rossin, M. Peters, E. Zucker and B. Acklin, "Highly Reliable High-Power Broad Area Laser Diodes," SPIE 2006, vol. 6104, 61-70

[157] N. Lichtenstein, Y. Manz, P. Mauron, A. Fily, B. Schmidt, J. Muller, S. Pawlik, B. Sverdlov, S. Weiß, A. Thies, C.S. Harder, "High-Brightness 9xx and 14xx Single-Mode Emitter Array Laser Bars," SPIE 2005, vol. 5711, 101-108

[158] V. Lissotschenko, A. Mikhailov, I. Mikliaev, M. Darsht, "Method and device for influencing light," U.S. Patent No. 20070127132

[159] C. Naumer, N. Lichtenstein, B. Schmidt, P. Bruns, F. Kubacki, P. Harten, O. Lissotschenko, "Brightness Required! More Efficient Laser Diodes with Refractive Micro-Optics," Laser+Photonik 2007, no. 3, 26-29

[160] J. Troger, M. Schwarz and A. Jakubowicz, "Measurement Systems for the Investigation of Soldering Quality in High-Power Diode Laser Bars," JLT 2005, vol. 23, no. 11, 3889-3892

[161] N. Lichtenstein, Y. Manz, P. Mauron, A. Fily, B. Schmidt, J. Muller, S. Arlt, S. Weiß, A. Thies, J. Troger and C.S. Harder, "325 Watt from 1-cm wide 9xx Laser Bars for DPSSL- and FL-applications," SPIE 2005, vol. 5711, 1-11

[162] P. Crump, J. Wang, T. Crum, S. Das, M. DeVito, W. Dong, J. Farmer, Y. Feng, M. Grimshaw, D. Wise and S. Zhang, "> 360W and > 70% Efficient GaAs-Based Diode Lasers," SPIE 2005, vol. 5711, 21-29

[163] J. Sebastian, H. Schulze, R. Hulsewede, P. Hennig, J. Meusel, M. Schroder, D. Schroder and D. Lorenzen, "High Brightness – High Power 9xx nm Diode Laser Bars: Developments at JENOPTIK Diode Lab," SPIE 2007, vol. 6456, 1-11

[164] H. Li, T. Towe, I. Chyr, D. Brown, T. Nguyen, F. Reinhardt, X. Jin, R. Srinivasan, M. Berube, T. Truchan, R. Bullock and J. Harrison, "Near 1 kW of Continuous-Wave Power From a Single High-Efficiency Diode-Laser Bar," PTL 2007, vol. 19, no. 13, 960-962

[165] Y.M. Manz, M. Krejci, S. Weiss, A. Thies, D. Schulz, A. Fily and N. Lichtenstein, "Brightness Scaling of High Power Laser Diode Bars," Cleo Europe 2007, CB-37-WED, 1

[166] D. Schleuning, M. Griffin, P. James, J. McNulty, D. Mendoza, J. Morales, D. Nabors, M. Peters, H. Zhou and M. Reed, "Robust hard-solder packaging of conduction cooled laser diode bars," SPIE 2007, vol. 6456, 1-11

[167] M. Behringer, F. Eberhard, G. Herrmann, J. Luft, J. Maric, S. Morgott, M. Philippens and W. Teich, "High Power Diode Lasers Technology and Application in Europe," SPIE 2003, vol. 4831, 4-13

[168] F. Gonthier, L. Martineau, N. Azami, M. Faucher, F. Seguin, D. Stryckman and A. Villeneuve, "High-power All-Fiber components: The missing link for high power fiber lasers," SPIE 2004, vol. 5335, 266-276

[169] A. Wetter, M. Faucher, M. Lovelady and F. Seguin, "Tapered fused-bundle splitter capable of 1kW CW operation," SPIE 2007, vol. 6453, 1-10

[170] R.K. Huang, B. Chann, L.J. Missaggia, J. P. Donnelly, C.T. Harris, G.W. Turner, A.K. Goyal, T.Y. Fan and A. Sanchez-Rubio, "High-Brightness Wavelength Beam Combined Semiconductor Laser Diode Arrays," PTL 2007, vol. 19, no. 4, 209-211

[171] D. Scifres, W. Streifer and R. Burnham, "Experimental and Analytic Studies of Coupled Multiple Stripe Diode Lasers," JQE 1979, vol. 15, no. 9, 917-922

[172] D. Botez, "High-Power, High Brightness Semiconductor Lasers," SPIE 2005, vol. 5624, 203-212

[173] F. Causa and D. Masanotti, "Observation and Analysis of Phase-Locking in Parabolic Bow-Tie Laser Arrays," JQE 2006, vol. 42, no. 10, 1016-1022

[174] A. Kewitsch, G. Rakuljic, A. Yariv, "Semiconductor Lasers in Optical Phase-Locked Loops," U.S. Patent No. 20060239312

[175] E.M. Strzelecka, J.G. McInerney, A. Mooradian, A. Lewis, A.V. Shchegrov, D. Lee, J.P. Watson, K.W. Kennedy, G.P. Carey, H. Zhou, W. Ha, B.D. Cantos, W.R. Hitchens, D.L. Heald, V.V. Doan and K.L. Lear, "High power, high brightness 980 nm lasers based on the extended cavity surface emitting lasers concept," SPIE 2003, vol. 4993, 57-67

[176] G.T. Niven and A. Mooradian, "Trends in Laser Light Sources for Projection Display," IDW 2006, 1936-1939

[177] J.W. Hicks, "Optical communication systems using Raman repeaters and components therefor," U.S. Patent No. 4616898

[178] S.B. Poole, D. N. Payne and M.E. Fermann, "Fabrication of Low-Loss Optical Fibres containing Rare-Earth Ions," EL 1985, vol. 21, no. 17, 737-738

[179] R.J. Mears, L. Reekie, I.M. Jauncey and D.N. Payne, "Low-Noise Erbium-Doped Fibre Amplifier Operating at 1.54 µm," EL 1987, vol. 23, no. 19, 1026-1028

[180] E.B. Desurvire, J.R. Simpson and P.C. Becker, "High-gain erbium-doped traveling-wave fiber amplifier," Opt Lett 1987, vol. 12, no. 11, 888-890