High-brightness near- and mid-infrared diode lasers

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High-power diode laser quality was once described by only total output power and electro-optical efficiency. Today's applications require better characterisation of diode lasers by their brightness, which is the "usable" output power.

Conventional high-power diode lasers in the near-infrared wavelength regime typically have a brightness below 30 MW/cm². The development of diode lasers with much higher brightness levels was driven by the success of fibre lasers and their pump source requirements. The diode laser resonator design, which is used primarily for pump lasers, is distinguished by its broad stripe width $w_{lateral}$. This stripe is

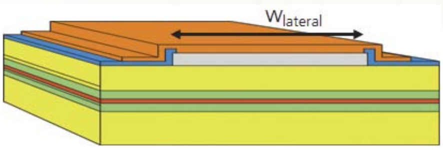

Figure 1: Principle design of a broad-area laser

determined by etching of the semiconductor layers (**figure 1**) and limiting the electrical current injection into the diode laser.

Brightness

The brightness of any laser is measured by the power per area within a solid angle, and includes optical output power along with beam properties at a particular wavelength. The brightness is defined by:

$$B = P / (\lambda^2 M^2_{vertikal} M^2_{lateral}) = P / (\lambda^2 M^2_{vertikal} (\pi/4\, w_{lateral}\, \theta_{lateral})) \quad \textbf{(Eq.1)}$$

M^2 defines the beam quality in both propagation directions of the emitted laser beam. The diode laser stripe controls the optical output power P by variations in the stripe width $w_{lateral}$. The beam cross section of a broad-area diode laser is elliptical: While the beam is highly divergent in the vertical direction, because of its Gaussian beam profile, beam shaping can be done very easily through suitable lenses. For the lateral direction, a set of optical modes lead to a non-Gaussian intensity distribution, where the beam profile shows intensity fluctuations (filaments). The width $\theta_{lateral}$ of the lateral far field is defined by inclusion of 95% of the optical output power.

The following laser design concepts discussed here are all based on single emitters, but of course they can be transferred to other diode laser bars. Typically, single emitters are mounted on sub mounts by hard soldering. These sub mounts are themselves mounted on gold-coated copper heat sinks, which are passively cooled (**figure 2**).

Broad-area NIR diode lasers

Diode lasers that emit near-infrared (880–1080 nm) wavelengths are based on the system of GaAs materials. Whereas waveguide and cladding layers are typically composed of AlGaAs with different Al concentrations, the active area consists of InGaAs. The wavelength of the laser can be adjusted by variation of the Indium (In) content.

According to equation (1), the brightness of the beam is defined by the inverse product of stripe width and far field width. Recent increases in the brightness of broad-area lasers have been achieved by reduction of the stripe width from 200 µm down to 100 µm. However, a critical disadvantage of the stripe-width reduction in constant output power applications is an increasing expansion of the lateral far field with higher operation current. The chief reason for this connection is the increased deterioration of the heat dissipation caused by a reduced active area.

Therefore, improvements in the brightness levels of broad-area diode lasers requires reductions in the stripe width, yet rapid expansions of the lateral far field must be avoided. Meanwhile, the easiest way to improve the heat dissipation is to enlarge the resonator length. While doing this, however, the electro-optical efficiency must be kept on the same high level as before. As a result, modern pump lasers for fibre lasers are based on resonator lengths between 3 mm and 5 mm and offer electro-optical efficiencies between 55% and 65%.

These relatively long diode laser resonators, in combination with high electro-optical efficiencies, can be only realised by vertical laser designs with very low internal losses of less than 1 cm^{-1}. Internal losses refer to losses of carriers in the semiconductor layers after the current injection reducing the light emitting efficiency. One example of such low internal losses can be achieved by a suitable design of the doping concentrations in the different AlGaAs/GaAs layers of the laser. Furthermore,

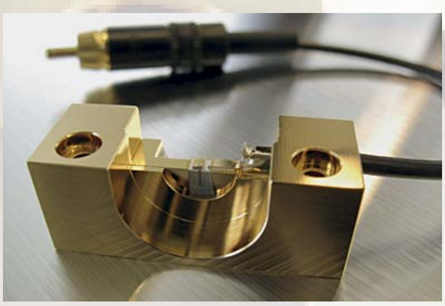

Figure 2: Example of a high-power diode laser, mounted on a passively cooled heat sink

by choosing an optimised combination of semiconductor layers, the heat dissipation inside the diode laser can be optimised. Modern epilayer designs make high demands on the used epitaxial systems, such as molecular beam epitaxy systems. In addition, the blowing of the lateral far field with operation current can be reduced by adapted processing.

An additional fundamental limitation for the brightness stems from the limited power density per facet width, enabled by facet coating technologies today. Therefore, for an output power of 10 W, the stripe width in the resonator design stems from a compromise between a maximum for the power density per emitter width, which enables a certain lifetime by the particular facet coating technology. A small stripe width is preferable to optimise the brightness of the laser.

As an example for an innovative laser design with 90 µm stripe width and 5 mm resonator length with an output power of 10 W and a lateral far field width of 8° this results in a brightness of more than 100 MW/cm² [1] which is three times higher than for conventional broad-area lasers (**figure 3**).

Brightness in the mid-infrared

For the mid-infrared (1800–2500 nm) wavelength regime, only solid-state lasers (Ho:YAG, Tm:YAG) or fibre lasers with certain emission wavelengths are available. Indeed, on the basis of InP, there are also diode lasers with emission wavelengths up to 1900 nm available. However, at emissions above 1800 nm, the electro-optical efficiency decreases rapidly, thereby limiting the utility.

Based on GaSb/AlGaAsSb/InGaAsSb semiconductor materials, there are now high efficiency high-power diode lasers with optical output power of 2 W in cw or 10 W in pulsed

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mode available also in the mid-infrared.

In this special wavelength range, many applications need high power densities, such as for laser surgery, the processing of plastics, or pumping of laser systems. This higher power requirement also means a high brightness. However, it is not possible to transfer just the well-known concepts from the near-infrared (GaAs material system) into the mid-infrared. As an example, the large optical cavity concepts well-known in the 800–1000 nm regime lead to vertical far fields in the GaSb material system of more than 120° and are therefore not practical.

The use of narrow waveguide structures [2] some years ago was an important development step to push the GaSb lasers towards such applications. Those waveguide designs, in combination with optimised doping levels, enable laser structures with 80° far field divergences (95% power included), which enable fibre coupling efficiencies of up to 80%. Such lasers are useful in medical or pumping applications.

But narrow waveguide structures have the disadvantage that the optical wave partly runs in higher doped semiconductor layers leading to relatively high internal losses of 10 cm^{-1}. Therefore, only resonator lengths of 1 mm or 1.5 mm are feasible at the moment. This limits the area for heat dissipation, which again leads to a blowing of the lateral far field. In summary, output powers of up to 1 W for single emitters are classified as commercially usable in the mid-infrared, and can be coupled into fibres with core diameters of 200 µm or more [3].

In summary, the brightness of a broad-area laser is practically limited by:

- the selected facet coating technology
- the selected stripe width
- the thermal blowing of the lateral far field
- and the quality requirements for the epitaxy process

Alternative resonator design: tapered laser

The use of tapered laser designs avoids some limitations of the broad-area laser designs. A tapered laser consists of two components monolithically integrated on one chip. The so called ridge-waveguide section is a mono-mode diode laser, often used as a pump sources for the second section. In the following tapered section, the active width enlarges from the typically 3 µm ridge section width towards an output facet width of several micrometers, depending on the chosen section length and taper angle. For an initial power of several 10 mW at the rear end of the taper section, it is possible to amplify the optical output power to several Watts at the output facet (**figure 4**).

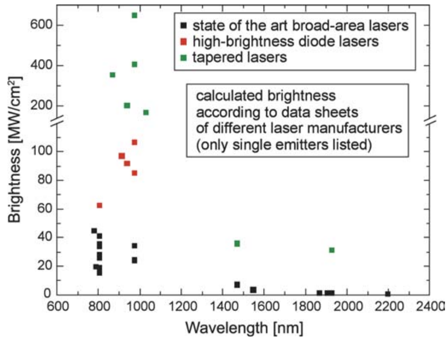

Figure 3: Brightness of different high-power diode lasers (only single emitter)

Because of the tapered geometry, the minimal lateral beam waist in the focus depends on the width of the ridge waveguide section, and not on the width of the output facet. In comparison to broad-area lasers with identical output power, this leads to a beam width reduced by a factor of 25. The far field, also important for the beam quality, is given by the taper angle.

By stretching the length of the taper section, the output facet will be broadened, and thus, the output power can be increased. Both the minimal beam width and the far field will remain maintained, and therefore, the beam quality does not change. So based on this relationship, the facet coating technology will no longer remain the limiting factor for the broad-area lasers.

However, a major disadvantage of the tapered diode laser concept is the output beam astigmatism. Astigmatism means the difference between the positions of the focus of the beam in lateral and vertical directions. For a broad-area laser, the position of the focus is identical in both directions based on the symmetric geometry of the chip design. Therefore, the astigmatism of a broad-area laser is zero. For a tapered diode laser, the positions of the foci in both directions are different. The position of the focus in lateral direction, and therefore also the astigmatism, depend on the length of the taper section, as well as on the effective index of refraction of the epitaxial layer design used. Because the effective index of refraction depends on temperature and operation current, the astigmatism can be changed by manipulation of these operation conditions.

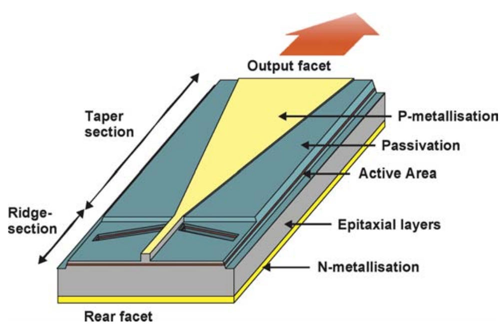

Figure 4: Principle design of a tapered laser

In practice, tapered diode lasers with output powers between 5 W and 10 W, offer diffraction limited beams [4] and result in brightness levels between 200 MW/cm^2 and 600 MW/cm^2.

In the mid-infrared wavelength range, tapered diode laser designs allow for a significant increase in brightness for high-power applications. A tapered diode laser, with 2.5 mm overall resonator length and 6° taper angle at 1930 nm emission wavelength, has achieved the same output power as a broad-area laser with a 150 µm stripe width at the same emission wavelength, but with an improved brightness of 32 MW/cm^2. However, if broad-area diode lasers are used in pump modules, the change of the beam astigmatism with the operation current must be taken into account [5].

Conclusion

Driven by the success of fibre laser technologies, a new generation of high-brightness high-power diode lasers have been developed in the near- as well as in the mid-infrared wavelength regimes. Today broad-area diode lasers with 10 W output from a 90 µm stripe width give a 3 times increased brightness in comparison to conventional broad-area lasers. The tapered diode laser concept allows for an additional increase of the brightness of pump lasers.

Literature:

[1] J. Gilly, P. Friedmann, H. Kissel, J. Biesenbach, M.T. Kelemen, *5mm long broad-area lasers with 65% wall-plug efficiency*, SPIE Proc., Vol. 7198, Paper 10, 2009

[2] M. Rattunde, J. Schmitz, G. Kaufel, M. Kelemen, J. Weber, J. Wagner, *GaSb-based 2.X µm quantum-well diode lasers with low beam divergence and high output power*, Appl. Phys. Lett. **88**, 081115, 2006

[3] M. T. Kelemen, J. Gilly, M. Haag, J. Biesenbach, M. Rattunde, J. Wagner, *Diode laser arrays for 1.8 to 2.3µm wavelength range*, SPIE Proc., Vol. 7230, paper 56, 2009

[4] P. Friedmann, J. Gilly, S. Moritz, R. Ostendorf, M. T. Kelemen, *5W frequency stabilized 976nm tapered diode lasers,* SPIE Proc., Vol. 6876, Paper 54, 2008

[5] C. Pfahler, G. Kaufel, M. Kelemen, M. Mikulla, M. Rattunde, J. Schmitz, J. Wagner, *GaSb-based tapered diode lasers at 1.93 µm with 1.5-W nearly diffraction limited power*, IEEE Photonics technology Letters, VOL. 18, NO. 6, 2006

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