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HIGH POWER SEMICONDUCTOR LASER DIODES

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Abstract : In the last decade the output power of semiconductor laser diodes has increased dramatically. Starting from a power range of several milliwatts, which is sufficient for a range of mass applications in the field of optical communication and optical storage systems, now semiconductor laser systems with an output power in the kilowatt range are available.

The progress in the development of high-power edge- and surface-emitting lasers emitting is described. The sophisticated design of large optical cavity lasers, the advanced production and mounting technology lead to usable cw-ouput powers in the range up to 70 W for a single laser bar. The concept of the monolithic vertical integration of several lasers leads to nanostack lasers with high power capabilities under short and long pulse operation. Vertical emitting lasers (VCSEL) also show promising high power performance.

The main advantage of diode lasers are the small volume, the high overall efficiency up to 60%, the availability of a wide spectral range and the high reliability. This combination together with the high output power opens a wide field of applications covering e. g. pumping of solid state lasers and amplifiers, transfer to printing plates, soldering and direct machining.

Polprevodniške laserske diode velikih moči

Ključne besede: polprevodniki, laserji močnostni, laserji diodni, moči velike, moči izhodne do 4 Kw, laserji sevajoči z roba, VCSEL laserji sevajoči s površine iz votline vertikalne, COMD poškodba zrcala optičnega uničevalna, aplikacije

Izvleček : Izhodna moč polprevodniških laserskih diod je v zadnji dekadi močno narasla. Od nekaj mW, kar zadostuje za množično uporabo na področju optičnih komunikacijah in optičnem shranjevanju podatkov, so dandanes na voljo polprevodniški laserski sistemi z izhodno močjo v kW območju.

V prispevku opisujemo napredek pri razvoju laserskih diod velikih moči z robno in površinsko emisijo. Inovativna sestava velikih optično votlinskih laserjev ter napredna proizvodnja in tehnike montaže so pripeljale do uporabnih CW laserskih izhodnih moči do 70W na lasersko palico. Koncept monolitne vertikalne integracije v laserske skladovnice pa pripelje do velikih izhodnih moči pri pulznem delovanju. Ravno tako laserji z vertikalno emisijo (VCSEL) kažejo obetajoče možnosti doseganja visokih izhodnih moči.

Glavne prednosti diodnih laserjev so majhen volumen, visok izkoristek, tudi do 60%, široko spektralno območje in visoka zanesljivost. Naštete lastnosti skupaj z visoko izhodno močjo odpirajo široka področja uporabe, kot so črpanje ojačevalnikov in laserjev iz trdne snovi, prenos slik na tiskalne plošče, spajkanje in direktno obdelovanje materialov.

1. Introduction

Laser diodes are attractive light sources due to the high conversion efficiency, the small volume, the high frequency modulation capability, the good beam quality, the wide wavelength range and the long lifetime. They find wide spread applications comprising especially optical data storage (CD, DVD) and optical communication over fibres. But also other fields are emerging like sensing, measurement and medical applications. The diode laser outperforms all other laser systems in the number of produced devices. Over the last years high power laser diodes steadily increased the performance in maximum output power and efficiency enabling new cost effective applications like pumping solid state lasers and amplifiers, transfer to printing plates and even direct machining.

2. Basics of high power laser diodes

For high power applications the semiconductor diode laser has to be specially designed to meet the specifications. The following items are common to all approaches:

- Maximum power in pulsed or cw-operation
- High overall efficiency
- Beam quality according to the application
- High reliability and long lifetime

A semiconductor laser diode is essentially a pn-diode in which the active zone is formed by a direct band gap material e.g. InGaAlAs or InGaAsP. Current is injected by forward biasing the pn-structure and leads to an excess carrier density, which is high enough to ensure optical gain by stimulated emission. In modern laser diodes the active zone consists of one or more very thin layers embedded in a material of higher bandgap forming a so-called double heterostructure. The thickness is in the range of a few nanometers and leads to quantum size effects in one direction. These quantum wells exhibit a high optical gain and the emission wavelength can be tailored by the alloy composition and the thickness. The kind of the optical resonator divide the lasers in two principle categories, the edge- and the surface emitting lasers. Within each category a lot of different approaches have been realised in research and production leading to a wide variety of laser diodes whose description lies beyond the scope of this paper.

2.1 Edge emitting lasers

The edge emitting laser diode consists of a layer structure epitaxially grown on a substrate comprising the active zone providing the optical gain and a planar waveguide structure for the transversal confinement of the propagating optical mode. The resonator is formed by cleavage of the semiconductor along its crystal planes (Fig.1) and has a typical length from 200 to 2000 µm. In this type of laser the radiation propagates in the plane of the layers and is emitted through the mirrors perpendicular to the layers.

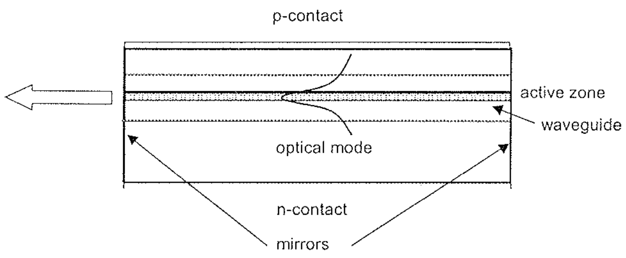


Fig. 1: Cross section of an edge emitting laser

The lateral confinement of the optical mode depends on the beam quality necessary for the application. Usually index guided structures are used for diffraction limited single mode applications e.g. for coupling into monomode fibres. For multimode operation gain guided structures are preferred due to a less demanding technology. The emission patterns for edge emitting lasers are usually characterised by an elliptical beam with different widths in the vertical and lateral direction.

2.2 Surface emitting lasers

In the VCSEL (**V**ertical **C**avity **S**urface **E**mitting **L**aser) the radiation propagates perpendicular to the layer structure. The partial reflecting mirrors are formed by layers with alternating composition and refractive index. Due to the small thickness of the active layer and the short cavity length in the order of several microns the available gain is small and the mirror reflectivities must be high close to 100 %.

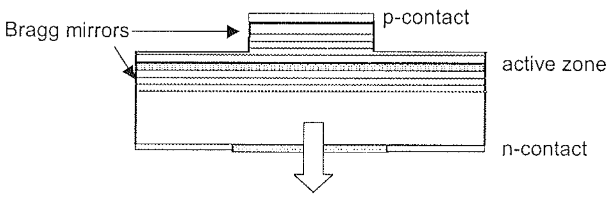


Fig. 2: Cross section of a bottom emitting VCSEL

Usually the emitting lateral aperture has a circular geometry leading to round emission patterns.

2.3 Physical limitations of the maximum output power

When a laser diode is driven by an increasing current there is a limitation of the maximum output power due different physical effects. The thermal limitation is characterised by an rollover of the power current relation and is usually reversible. The applied electrical power is not fully transferred to optical power in a laser diode, so electrical and optical losses lead to an increase of the chip temperature depending on the geometry and the thermal mounting of the device. With increasing temperature of the active zone the threshold current increases exponentially and the differential efficiency decreases. So with increasing current the output power will reach a maximum and will then decrease. Usually no permanent damage is introduced by this effect. To increase the rollover power, the internal efficiency has to be optimised by reducing the electrical and optical losses. The temperature rise can be reduced by increasing the chip area and by proper mounting of the device on heatsinks e. g. junction down where a minimum distance from the active zone to the heat removing body is achieved.

Especially in GaAlAs-based edge emitting semiconductor laser diodes another limitation occurs. At a certain level the optical power decreases suddenly and will not recover by reducing the operating current. Careful inspection of the mirror often reveal a crystalline damage due to melting in the area of the laser emission indicating a process where high temperatures occur. At the mirror surface the excess electron-hole pairs in the active zone recombine nonradiatively leading to heat generation at the surface. Due the induced bandgap shrinkage this region absorbs the generated laser radiation and the carrier density is increased. At a power density in the range of several MW/cm^3, which can easily be reached due to the strong confinement of the optical mode, there is a positive feedback leading to a thermal runaway. By that mechanism temperatures above the melting point are reached in a small volume of several cubic microns leading to permanent damage of the mirror. This so called catastrophic optical mirror damage (COMD) depends strongly on the surface recombination properties of the mirror, which can be improved by surface passivation.

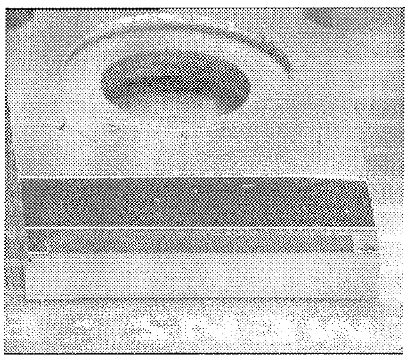
3. Techniques for increasing the maximum power

3.1 Wide aperture lasers and laser bars

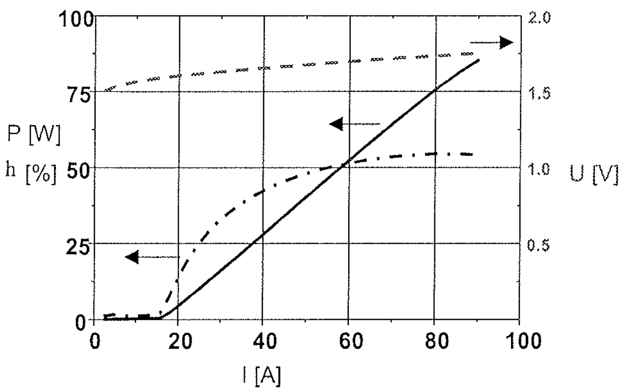
The COMD-effect depends on the optical power density at the mirror. So a straight forward strategy to increase to maximum output power of a laser diode is the increase of the emitting aperture in the lateral and transversal direction. The large optical cavity (LOC) design increases the transversal waveguide width and spreads the optical mode. This has an additional benefit in decreasing the width of the far-field distribution.

In the lateral direction the aperture is increased by array- or broadarea-configurations. In contrast to single mode laser with an aperture of several microns, the width in high power laser diodes ranges from 20 to approximately 500 µm. Due to the high mode volume several lateral modes will oscillate simultaneously and the incoherent superposition of these modes degrades the beam quality.

A further step is the monolithic integration of several broad-area or array lasers on one single bar. There is a quasi industry standard for 1cm long bars. In Fig. 3 such a bar is shown mounted on a water cooled heat sink.



a) mounted on a heatsink



b) CW-laser characteristics: Power P, wall-plug efficiency h and voltage drop U

Fig. 3: *InGaAlAs-laser bar (L=1cm)*

The characteristics of such a laser bar with an InGaAlAs double quantum well active zone for an emission wavelength of 808 nm is shown in Fig. 3b. The laser mirror are asymmetrically coated to enhance the front mirror power. The threshold current at room temperature is 18 A and the slope efficiency has a value of 1.1 W/A. Due to the low series resistance of 2.2 mΩ the wall-plug efficiency is 55 % at an output power of 60 W. The progress in the quality of the epitaxial growth process (MOVPE) and the incorporation of a single quantum well active zone led to a steady increase of the usable power of laser bars and values of 70 W with a reasonable operating time are available today.

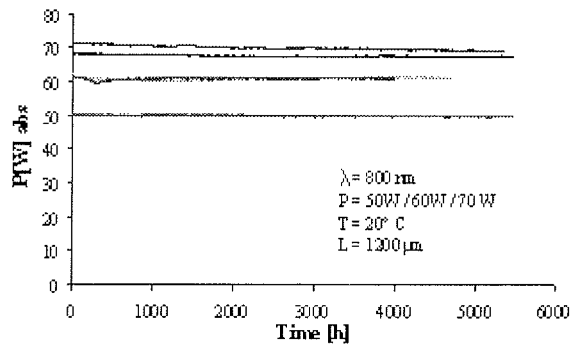


Fig. 4: *Degradation behaviour InGaAlAs-SQW laser bars at high power levels under constant current control*

Even at an output power of 70 W the degradation rate is only 0.5%/khr, which corresponds to an estimated lifetime of more than 40 khr.

Still higher output powers can be achieved by the assembly of laser bars mounted on heat sinks into modules resulting in two dimensional arrays. These modules can scale the power up to the kilowatt range. For many applications the beam quality is a crucial parameter and sophisticated combining optics have to be used to meet the specifications.

3.2 Nanostack Lasers

An unconventional way to increase the emission area of an edge emitting laser is the monolithic integration of several independent laser structures vertically /1/. The principle of the so-called nanostack laser is shown in the following Fig. 5.

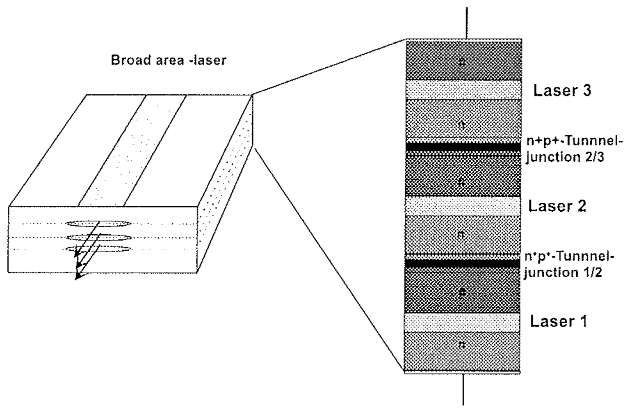


Fig. 5: *Principle of a triple-nanostack laser*

Each independent laser consists of a conventional LOC-structure with an AlInGaAs-double quantum well as active layer. In order to drive the lasers in series with high efficiency low-resistance tunnel-junctions have to be implemented. By optimizing the MOVPE growth process tunnel-junctions with a specific differential resistivity of 2.5×10^{-4} Ωcm^2 could be obtained. These junctions are suitable for the monolithic interconnection of the laser-structures.

Double and triple nanostack lasers with a specially designed transversal structure for low divergence angles have been developed. Single element broad area lasers with AR/HR-coating have been mounted junction up and tested under short pulse operation.

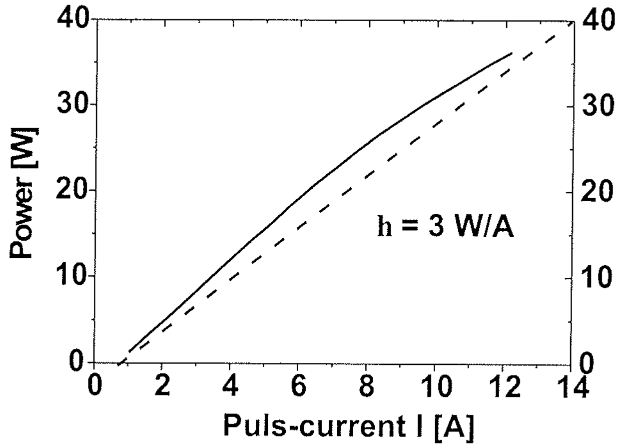


*Fig. 6: P/I-characteristic of a single broad area triple-nanostack laser (200*600 μm²) under short pulse operation (1 μs/10 kHz)*

The threshold current at room temperature is around 700 mA and the slope efficiency lies above 3 W/A. The slight bending of the P/I-curve comes from the thermal heating at high drive levels. The transversal farfield pattern has a FWHM of 23°. Under operation with short pulses (20 ns) even higher peak powers over 100 W can be obtained from a single chip. A comparison between test lasers with one, two or three integrated laser structures shows, that the slope efficiency and the turn-on voltage scales with the number of lasers. Due to the low-resistance tunnel-junctions there is no additional voltage drop which would decrease the overall efficiency. Double nanostack-lasers have been also successfully tested in the bar-configuration up to 250 W in QCW-operation with a pulse length of 200 μs and a duty cycle of 20 %.

3.3 High power VCSELs and Arrays

The benefit of VCSELs is the production and testing on a full wafer scale leading to low costs. In datacom field the VCSEL has found widespread application in single and parallel channel links. The VCSEL-concept is demanding with respect to high power applications /2/. Due to the short cavity- and gain-length high injection levels are necessary to reach threshold. On the other hand the high reflectivity Bragg-mirror introduce additional optical and electrical losses. The strategy is to minimise the series resistance and the optical absorption of the mirrors by tailoring the composition and the doping profile of the layers. For the lateral optical and electrical confinement several approaches are possible. The oxide confined structure implements an insulating aperture by lateral oxidation of an AlAs-layer /3/. In implanted VCSELs the region outside the active area is electrically and optically inactive due to a deep implantation of protons. Both versions have been tested as single VCSELs with circular apertures up to 135 μm and in arrays with a honeycomb structure of 19 elements with an aperture of 40 μm. As an example, data for an implanted bottom emitting array, mounted junction down on a TO-header, are given below. The VCSEL is realised in the InGaAlAs-system with an emission wavelength around 920 nm where the GaAs-substrate is transparent (Fig. 2).

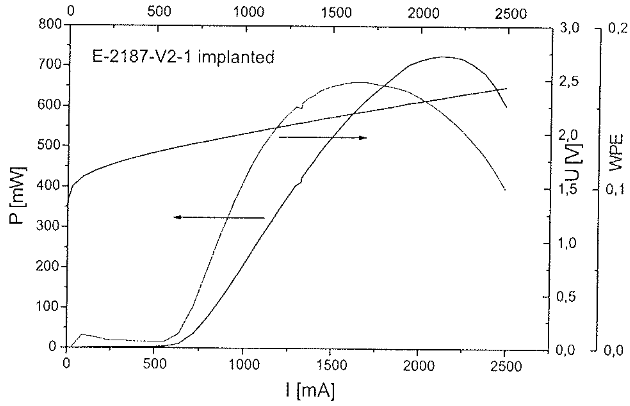
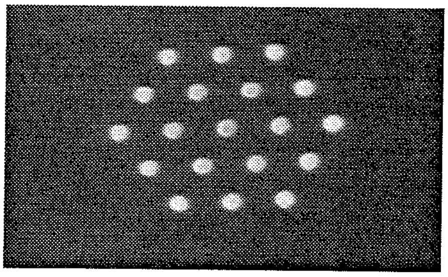
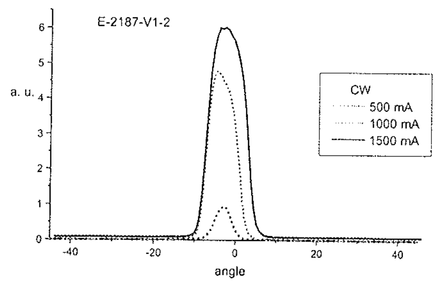


*Fig. 7: CW-laser characteristics of a 19*40μm-VCSEL-array P: output power, U: voltage drop, WPE: wall-plug efficiency*

The threshold current is 650 mA and a maximum power of 750 mW is achieved, which is limited by thermal rollover. COMD as described above is no problem for VCSELs because the active area is buried and no carriers interact with the radiation at the mirror surface. The wall-plug efficiency of 17 % is essentially lower than for an edge emitting laser, where values up to 60 % are possible.



nearfield



farfield

*Fig. 8: Emission patterns of a 19*40μm-VCSEL-array*

The nearfield pattern of the VCSEL-array shows an inhomogeneous distribution within each laser due to a high number of oscillating lateral modes. The farfield distribution at various currents is symmetric and has FWHM-values in the range between 7°-10°, which are substantially lower than typical values of 30°-40° for edge emitting lasers.

4. Applications of high power laser diodes

The attractive features of high power laser diodes like small volume, high efficiency, long lifetime and the availability of a wide spectral range open a wide field of application. The most prominent is the pumping of solid state lasers like Nd:YAG or Yb:YAG. Due to the high wall plug efficiency and the narrow spectrum laser diodes are ideally suited to replace the usually installed flashlamps, thus improving essentially the overall efficiency, the lifetime and the maintenance cost of the laser system. Today diode pumped solid state lasers with an output power of 4 kW are on the market. Due to the progress in beam combining of laser arrays the beam quality is high enough for direct application of diode lasers in industrial processes like soldering, welding, hardening or laser assisted turning of brittle materials like ceramics. The small volume of these laser system with output powers up to several kilowatts allows the integration on robotic arms for automated manufacturing processes. There are research efforts to use diode lasers directly, via solid state laser pumping and second harmonic generation to generate visible radiation with high beam quality for the application in laser television.

5. Conclusion

There is rapid progress in the development of high power edge- and surface emitting laser diodes. Due to the implementation of optimised transversal and lateral structures single laser bars with reliable powers up to 70 Wcw are available. The new approach of the monolithic integration of several lasers in a single chip leads to the nanostack-laser which has a high potential as pulsed light source for sensing applications. The high power VCSEL has a restricted maximum power and efficiency and will find niche applications where the symmetric low divergence farfield is required.

6. Acknowlegdement

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7. References

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