# 3 W – high brightness tapered diode lasers at 735nm based on tensile strained GaAsP-QWs

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## ABSTRACT

Tensile strained GaAsP quantum wells embedded in AlGaAs waveguide structures are used to realize high power, high brightness short wavelength tapered laser diodes. At 735nm these laser diodes show up to 3W nearly diffraction limited output power with a wall plug efficiency of about 40%. Single spectral mode behavior is observed at output power levels up to 1W.

From aging test a high reliability with lifetime exceeding 5000 can be derived comparable to results obtained from broad area laser diodes with the same aperture width. There are only small changes of the beam quality during aging.

In conclusion it is shown that well designed tapered laser are a step forward to high efficient, diffraction limited light sources in the Watt-range which can easily fabricated in high volumes

**Keywords:** high power diode lasers, tensile strained quantum wells, beam quality, reliability

## 1. INTRODUCTION

There is an increasing demand for high brightness laser diodes with output powers of more than 1Watt to replace conventional low efficient laser systems and to enable new applications in laser technology.

Most promising to obtain high power, high brightness emission with high efficiency are tapered diode lasers /1,2,3/. These diode lasers consist of a ridge waveguide part supporting in best cases only one spatial mode and of a flared part for power amplification. The optical resonator corresponds to an unstable configuration, which is typically used for lasers with high gain /4/. The flared part for power amplification results in a lower facet load and enables reliable power levels in the Watt range.

In this paper we report on tapered lasers at 735nm. Diode lasers emitting at 735nm are used in medicine, e.g. photodynamic therapy (PDT), for pumping fs-laser systems based on Cr:LiCaF crystals and enable UV light sources by frequency doubling.

Results on 735nm - broad area (BA) diode lasers have been reported by several groups using InAlGaAs quantum wells (QW) embedded in AlGaAs waveguide layers /5,6/ and Al-free QWs using AlInGaP waveguide structures /7/.

We used tensile strained GaAsP QWs embedded in AlGaAs waveguides. BA laser devices fabricated from these structures exhibited a high performance and reliability /8/. Simulation of the complex dielectric function based on 8x8kp band structure calculations have shown that the refractive index of tensile strained GaAsP QWs depends only weakly on the carrier density, i.e. the value for the $\alpha$ - factor is low ($\alpha \approx 1.5$) /9/. A low $\alpha$ - factor reduces the dependence of beam quality on operation level and should allow high output power with a small beam quality factor M².

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## 2. Fabrication

A schematic picture of the tapered laser structure is shown in picture 2.1.The fabrication process uses a combination of established processing tools for ridge waveguide (RW) and BA laser diodes.

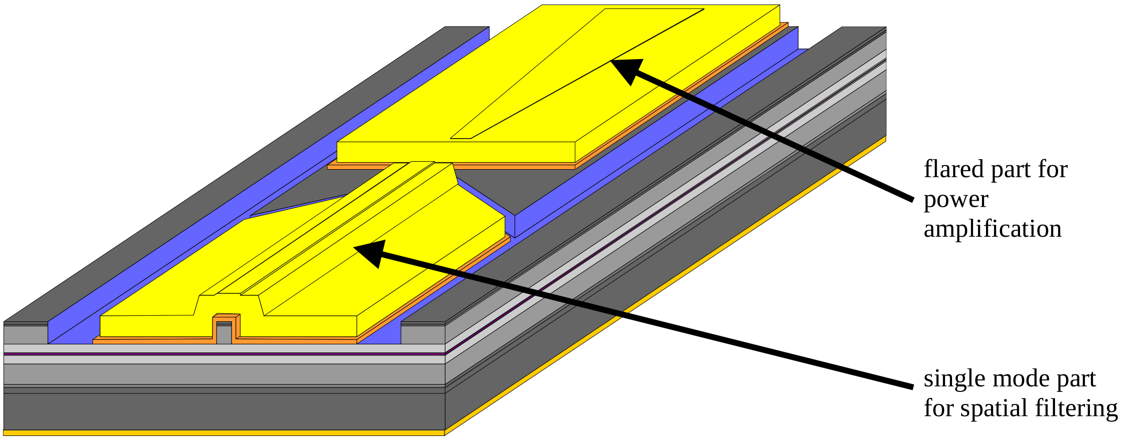

Fig. 2.1 Schematic picture of a tapered laser structure

The vertical laser structure was grown by low pressure metal-organic vapor phase epitaxy (MOVPE). The layer sequence is shown in figure 2.2. The waveguide structure consist of a 1µm thick core layer with a relatively high content of AlAs (x=0.65). The high Al content gives quite high barriers for the carriers. The Al-content of the cladding layers was only slightly increased in comparison to the content of the waveguide layers. In combination with the large waveguide thickness a low confinement factor $\Gamma$ of about 1% and a small vertical beam angle (27° FWHM) were achieved.

The composition and thickness of the GaAsP QW was optimized for a reproducible growth process and is well below the critical thickness /10/.

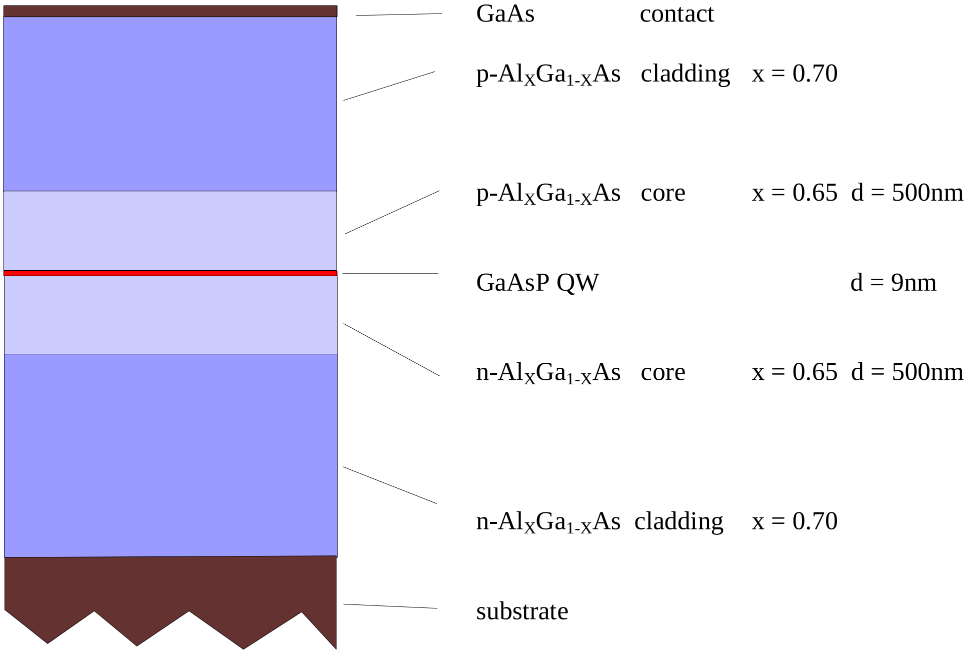

Fig. 2.2 Layer sequence for 735nm diode lasers

The fabrication of the lateral laser structure included processing steps to form a single mode RW and a second process part to create the contact window in the tapered section. The single mode RW section was fabricated by dry etching. The stripe width was typical about 3µm. The etch depth was around 1.5µm depending on desired step for the effective index. The RW length was varied from 500µm to 1250µm in our studies. No “ cavity spoilers” as mode filter were inserted. Outside of the contact windows the semiconductor material was covered by an insulator before the whole structure was metallized by a typical standard sequence of Ti/Pt/Au layers. For soldering purposes an about 3µm thick Au – layer was electro - plated allowing p-down mounting with AuSn solder. After scribing and cleaving the facets were coated using a Ion beam sputtering process. For the rear facet on the RW part, we used a reflectivity of about 94%. The front side reflectivity was 1%.

The laser were mounted p-down on T-cBN and CuW submounts using AuSn solder /11/. In comparison to CuW submounts T-cBN has a better thermal conductivity however a higher thermal expansion mismatch to GaAs. So we used T-cBN for shorter (resonator length L ≤ 2mm) and CuW for longer devices. The subassemblies were mounted on standard C-mounts for measurement and characterization.

## 3. Results

### 3.1 Typical data of the laser structure

The basic properties of the laser structure were tested by measuring uncoated 100µm stripe width BA laser with different resonator lengths from 400µm to 2000µm. The typical devices parameters are compiled in table 3.1 in comparison to published values from other laser structures for 735nm laser diodes.

Table 3.1: Basic data of 735nm laser structures

| Quantum well | GaAsP | InGaAsP | InAlGaAs | AlGaAs TQW |
|---|---|---|---|---|
| Composition waveguide structure | AlGaAs | AlInGaP | AlGaAs | AlGaAs |
| $I_{th}$ (L = 1000µm) /mA | 285 | 450 | 281 | 375<br>(L = 500µm) |
| $\Gamma G_0$ /cm$^{-1}$ | 20 | 23 | | |
| $\eta$ | 0.8 | 0.75 | 0.52 | |
| $\alpha$ /cm$^{-1}$ | 0.9 | 2 | 1.2 | |
| $\theta_\perp$ (FWHM) /deg | 27 | 38 | | 41 |
| $T_0$ (L = 1000µm) /K | 60 | 115 | 37 | 152 |
| reference | /10/ | /7/ | /6/ | /5/ |

$I_{th}$ – threshold current; $\Gamma G_0$ – modal gain coefficient; $\eta$ - internal efficiency; $\alpha$ - internal loss; $\theta_\perp$ - vertical divergence;

The laser structure with GaAsP QW and AlGaAs waveguide layers shows the best values for threshold current, divergence and efficiency despite the low value for the confinement factor. For operation at room temperature the disadvantage of a low $T_0$ = 60K was not critical. Due to the low internal loss the resonator length for broad area and tapered lasers could be chosen to be 2mm and longer without substantial decrease in external efficiency.

### 3.2 Broad area and ridge wave guide devices

The properties of BA and RW diode lasers were investigated for comparison and the understanding of the tapered laser structures. The Fig. 3.1 shows the power current characteristics of such devices.

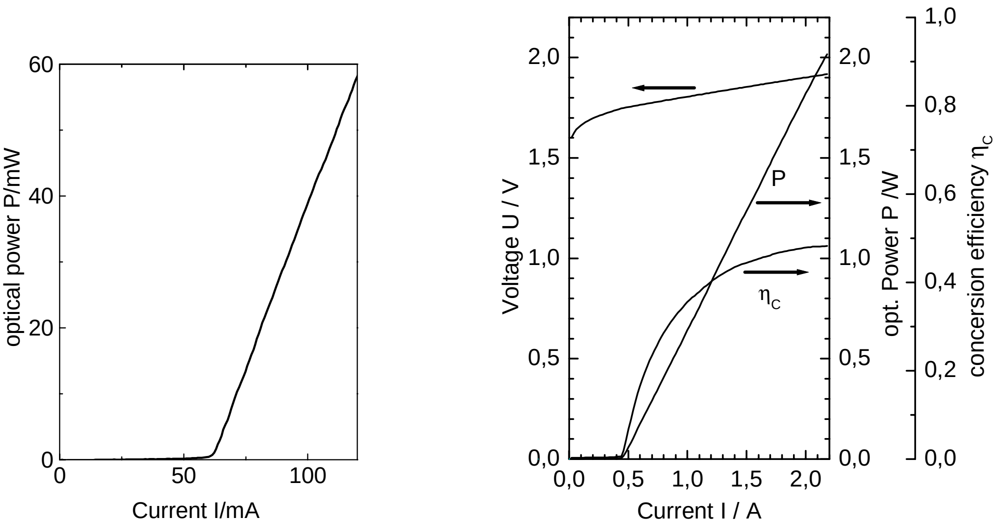

Fig. 3.1 Power current characteristics of 735nm laser diodes
left – 3µm stripe ridge waveguide laser, L = 1.5mm; right – 100µm stripe width broad area laser, L = 2mm

Despite the relatively linear power current characteristics the RW devices showed onset of higher order modes at relatively low output power. The fundamental mode power of these devices did not exceed about 25mW. The BA devices showed a very good conversion efficiency over 50% at 2W output power. As expected their beam quality shown in picture 3.2 was poor. The value of 6° FWHM at 1W was comparable or slightly better to other broad area diode lasers due to the long resonator length and low modal $\alpha$ - factor. However the determined $M^2$ - values (typically 15) were far from diffraction limit.

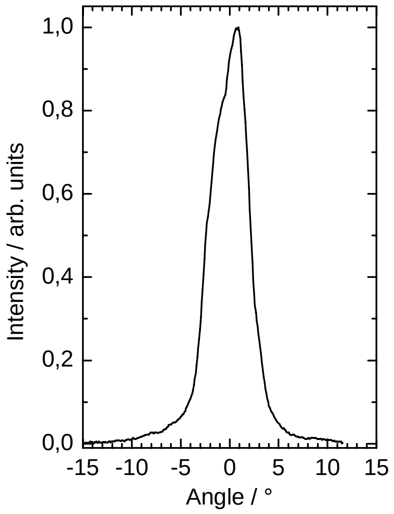

Fig. 3.2 lateral far field distribution of a 100µm stripe width broad area diode laser at 735nm, P = 1W

### 3.3 Tapered lasers with 4° taper angle

Firstly tapered lasers with a taper angle of 4° were studied. This value corresponds to the lateral divergence of RW devices.

The total resonator length was 2mm. The length of the RW was varied to optimize beam quality.

The measurement of lateral beam quality were based on ISO 11746-Annex A. This method does not take in account parts of the output beam below the $1/e^2$ - level. For practical use the amount of power in the central lobe was determined additionally. This power is for many purposes the “usable practical” power for the given $M^2$ - value.

In Fig. 3.3 the $M^2$ values for tapered lasers with different RW length waveguide at a different power levels are shown.

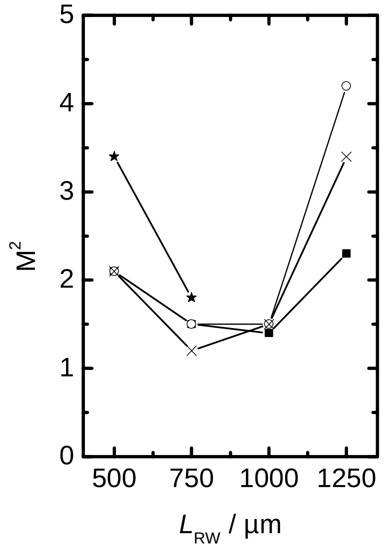

Fig. 3.3 Beam quality factorof 735nm tapered laser diodes with 4° taper angle in dependence from the RW length . total resonator length L = 2mm.
■ - P = 500mW; ○ - P = 1000mW; × - P = 1500mW; ★ - P = 2000mW

An optimal length for the RW mode filter was found in the range of750µm to 1000µm. These results can be explained by the small mode filtering efficiency for a ridge wave guide length smaller 750µm. For a length larger than 1000µm the power density at the end of the ridge waveguide part seems to be too high, which might lead to onset of filamentation and decreasing beam quality again.

In Fig. 3.4 the power - current characteristics of a tapered laser with 750µm ridge waveguide length is shown.

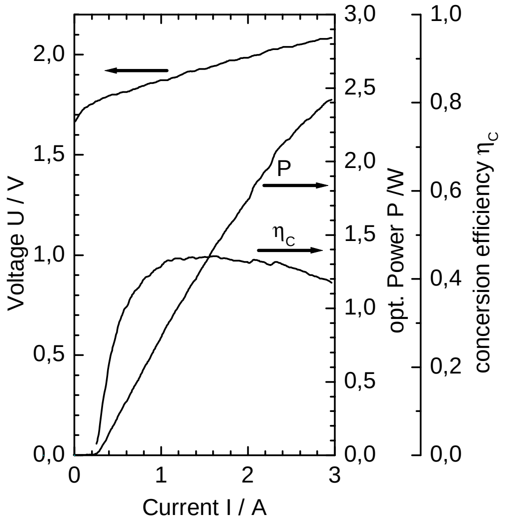

Fig. 3.4 power - current characteristics of a 735nm tapered laser
taper angle 4°; resonator length 2mm; output aperture 90µm

The power current characteristics is nearly linear up to 1.5W. The wall plug efficiency is about 45%, only slightly lower than the value of broad area lasers. The lateral beam characteristics is shown in Fig. 3.5.

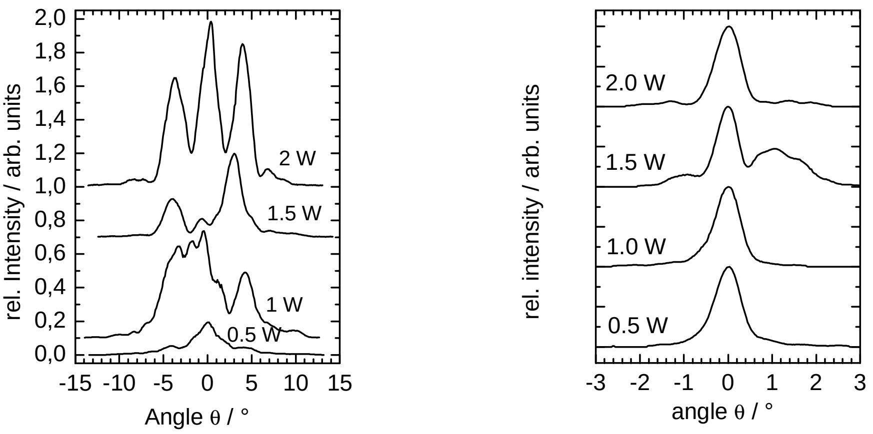

Fig. 3.5 lateral far field (left) and effective lateral far field (right) of a 735nm tapered laser
resonator length 2mm; ridge waveguide length 750µm; ridge width 3µm; taper angle 4°;

The lateral beam characteristics is relatively stable up to 1W. At higher output power the mode pattern changes due to stronger occurrence of higher order modes. At a power level of 2W the beam characteristics looks more symmetric with a lower beam quality factor.
The spectral properties measured up to 1.5W show a similar behavior as found for ridge waveguide laser. We achieve single mode output power at certain operating currents. However the spectral characteristics is very sensitive to external feedback.

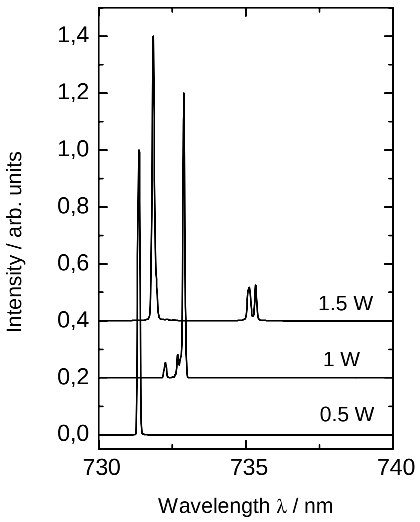

Fig.3.6 spectral characteristics of a 735nm tapered laser
resonator length 2mm; RW length 750µm; ridge width 3µm; taper angle 4°;

In summary compared to RW devices the power of tapered lasers with small taper angle of 4° was increased by a factor of 40 to about 1W in fundamental mode. The divergence of the tapered laser in both axis were small making collimation relatively easy.

### 3.4 Tapered lasers with 6° taper angle

To increase the output power without onset of filamentation the power density in the amplifier section should be relatively low. One possibility to increase power but not power density is a higher spreading of the optical energy in the taper section. Therefore a larger index step for the ridge waveguide laser is necessary , which ensures a higher divergence in the amplifier section. On the other hand a larger flare

angle of the taper results in a big lateral angle for the lateral far field. Together with the large astigmatism the beam collimation becomes more and more difficult. So we used as a compromise a taper angle of 6°, which leads to far field angle of about 15°.
In Fig. 3.7 the power - current characteristics of a tapered laser with 6° taper angle, 750µm RW length and 2.75mm resonator length is shown.

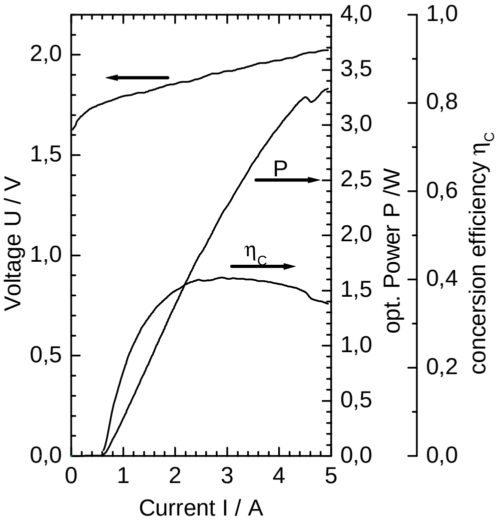

Fig. 3.7 power current characteristics of a 735nm tapered laser
taper angle 6°; resonator length 2.75mm

We achieved an output power of more than 3W. The conversion efficiency is 40% and only slightly lower in comparison to the shorter devices with smaller taper angle. A strong improvement was achieved concerning the beam quality. In Fig. 3.8 the effective lateral far field is shown. The main lobe of the beam characteristics (image of the waist) contains more than 80% of power and is nearly diffraction limited with M²-values below 1.5.

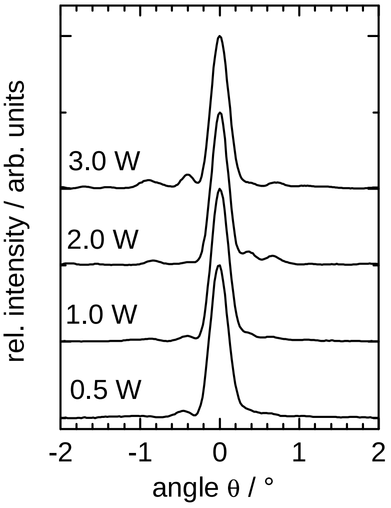

Fig. 3.8 effective lateral far field distribution of a 735nm tapered laser
taper angle 6°; resonator length 2.75mm; aperture width 180µm

## 4. Reliability

Tapered laser were tested at facet loads between 6mW/µm and 12mW/µm corresponding to BA lasers /12/. 5 tapered lasers with 2mm resonator length and 90µm aperture were aged at constant optical power of 1W over 1000h at 25°C. In Fig. 4.1 the dependence of operating current on aging time is shown.

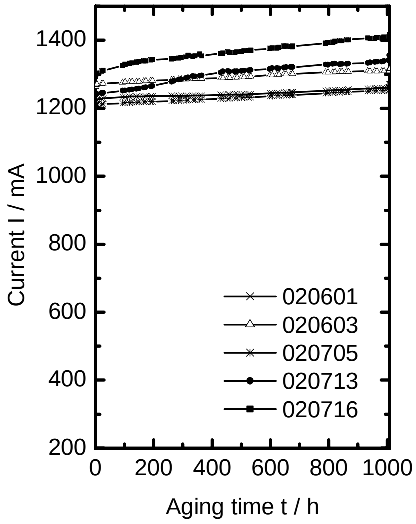

Fig. 4.1 Aging test of 735nm tapered diode lasers with aperture width of 90µm at P=1W and 25°C resonator length 2mm, taper angle 4°

All lasers survived aging times of 1000h. Moreover, the beam quality at operating power of 1W did not change ($M^2 \leq 2$) with one exception. Three lasers let expect a lifetime of about 10000h from the degradation rate.

The tapered laser with 2.75mm resonator length and 6° taper angle were tested firstly over 1000h at constant optical power of 1W, too. All devices survived with low degradations rates. In the next step the power was increased to 1.5W. One laser had a relatively high degradation rate, but did not fail. For the other lasers the operating current remained nearly constant. The three lasers with the lowest degradation rate survived the following test at 2W output power with low degradation rates, too. An overview on the aging tests is shown in Fig. 4.2

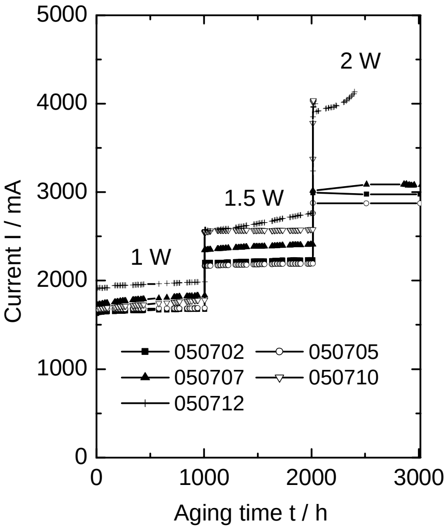

Fig. 4.2 Aging test of 735nm tapered diode lasers with aperture width of 180µm resonator length 2.75mm, taper angle 6°

The lateral beam characteristics of these lasers was measured before and after the aging tests at an output power of 2W, shown in picture 4.3. Only a small change in the intensity distribution was observed. The power in the main lobe ( image of the internal waist ) remained nearly constant.

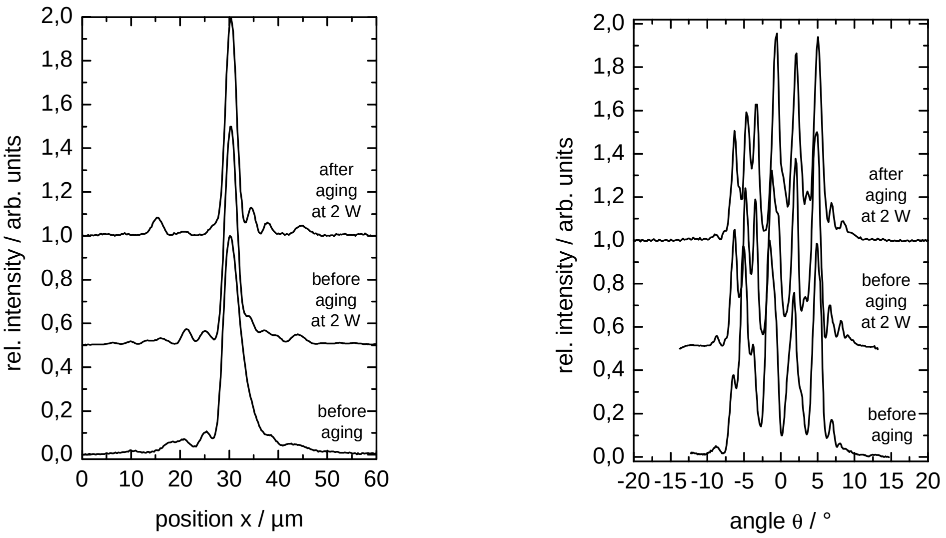

Fig. 4.3 Beam characteristics of 735nm tapered lasers dependence on aging

## 5. Conclusion

Tapered diode lasers are very promising structures for the improvement of the brightness of diode lasers. At 735nm we compared different types of diode lasers. In comparison to fundamental mode lasers with low mode width , for example ridge waveguide laser, the output power of tapered diode was at least a of factor ten higher with comparable beam quality and spectral properties. In comparison to broad area devices a similar output power was achieved. However the beam quality factor was improved from about 15 to values below 2 for the central lobe. First tests of reliability have shown promising results at output powers between 1W and 2W depending on output aperture (taper angle and length) with only small changes in beam quality. For further improvement there are a lot of parameters which can/must be optimized. Increasing the resonator length might be the most promising one.

In combination with the development of optics matched for the large astigmatisms of tapered lasers diffraction limited efficient and reliable diode laser sources at power levels of 5W and more will be expected in future.

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