High-Power High-Brightness Lasers and Amplifiers at 15xx nm

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ABSTRACT

High-power spatially single-mode diode lasers at 15xx nm wavelengths are of interest for Light Detection and Ranging (LIDAR) at eye-safe wavelengths, as pump lasers for Raman and rare-earth doped fiber amplifiers as well as for material processing. A cost-efficient way to realize high-power in combination with high-brightness is the tapered resonator concept. We demonstrate InGaAsP/InP based diode lasers and tapered amplifiers with fast axis far fields of 36° FWHM and wavelengths around 1550 nm which were grown by MOCVD. From processed broad area lasers with 2mm resonator length and 100µm stripe width and 1mm long ridge-waveguide lasers, parameters for the logarithmic gain model are evaluated. With their implementation in 2-dimensional BPM simulations, an optimized resonator geometry has been derived for aiming 1W in cw operation and 2W in pulsed mode. The optimised design consists of a ridge section length of 310µm and a taper section length of 2190µm. Different taper designs have been processed and investigated in detail. In dependence on the taper angle ridge widths are between 4 and 5µm. For narrow-linewidth operation, the tapered devices are provided with anti-reflection coatings of less than 0.01% on the rear facets and spectrally stabilized with an external grating. Beside the electro-optical characterisation, beam quality has been characterized in terms of beam waist analysis and M2.

Keywords: High-Power, High-Brightness, Tapered Diode Laser, Tapered Amplifier, 15xx, InGaAsP/InP, eye-safe

1. INTRODUCTION

There is a growing interest in high-power high-brightness diode lasers at wavelengths between 1.4µm and 1.6µm. Employed as pump lasers in Raman amplifiers and Erbium doped fiber amplifiers, they are a key component for future DWDM networks. Unlike GaAs based devices, they also operate in an eye-safe wavelength region which makes them attractive for direct materials processing at moderate power levels, e.g. for plastics welding. Another application of great potential is LIDAR at eye-safe wavelengths, which for example allows a fast tracking of wind velocity. Besides high power and beam quality, called in combination high brightness, this application requires narrow-linewidth operation with high side-mode suppression ratios (SMSR).

The brightness of a diode laser is a measurement for the power per area and solid angle and defined by:

$$B=P/(\lambda^2 M^2_{vertical} M^2_{lateral})=P/(\lambda^2 M^2_{vertical}(\pi/4 w_{lateral}\theta_{lateral}) \qquad \text{(equation 1)}$$

M^2 defines the beam quality in both propagation directions of the emitting laser beam. The beam of a diode laser is elliptical: Although in vertical direction the beam is highly divergent, because of its Gaussian beam profile, beam shaping can be done very easily by adequate lenses. In lateral direction, a set of optical modes lead to a non-Gaussian intensity distribution and the beam profile shows intensity fluctuations called filaments.

The resonator design mostly used today for getting high optical power levels is the broad-area laser design, which allows to control the optical output power P by the lateral width $w_{lateral}$ of the stripe. But the brightness of such broad-area lasers is limited by heat dissipation ($\theta_{lateral}$) and facet coating technology. The ridge waveguide tapered diode laser design has proven a successful concept to avoid these limitations and to combine high output power with high beam quality [1-3], leading to commercially available products for the GaAs material system [4]. This design consists of two sections monolithically integrated on one chip. The so-called ridge-waveguide section acts as a mono-mode diode laser used as a pump source for the second section. In the following tapered section, the active width enlarges from the typically 4-5µm stripe width of the ridge section towards an output facet width of several 100µm, depending on the chosen taper section length and the taper angle. For an initial power of several milliwatt at the rear end of the taper section it is possible to amplify the optical output power to the Watt level at the output facet. A schematic of the taper design is shown in figure 1.

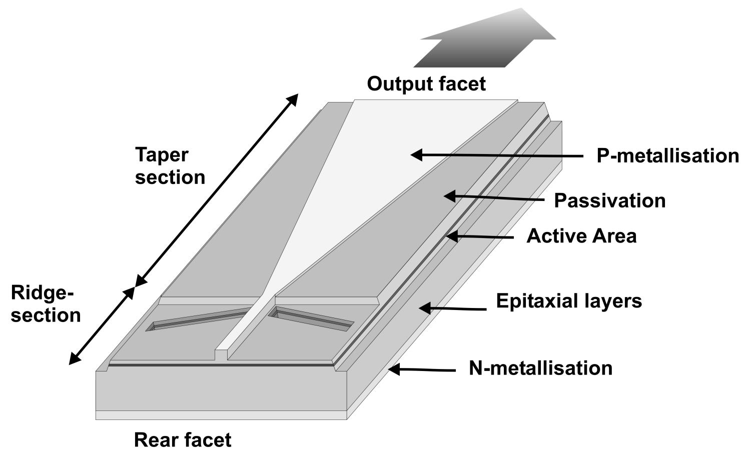

Figure 1: Schematic of a gain-guided tapered amplifier with a ridge-waveguide section for mode filtering.

For InP based lasers, the applicability of the taper concept was demonstrated in individual cases [5-7] but a wider acceptance has so far not been accomplished. Until now high-brightness InP based diodes mostly rely on a narrow stripe geometry design. Power levels in excess of 1 W have been shown here [8-9] but these can only be achieved with a highly elaborate vertical layer design and with assembly at the limits of feasibility. In contrast, the taper design already allows for high power levels with a fairly simple epilayer structure, and it offers a large potential for power scaling.

In this paper, we present high-power tapered diodes as Fabry-Perot lasers and as amplifiers in narrow-linewidth operation within an external cavity. In section 2 we review design considerations for the device design as well as for the fabrication process. From basic broad-area and ridge-waveguide designs, internal parameters are derived (section 3) which are implemented in BPM simulations for taper device optimization. Section 4 gives an overview of our results on tapered diode lasers, section 5 finally the results on tapered amplifiers operated as gain medium in an external cavity setup.

2. FABRICATION OF HIGH-BRIGHTNESS LASERS AND AMPLIFIERS

The eye-safe spectral range can be covered by InGaAs/InP based structures between 14xx nm and 18xx nm. For demonstration in this letter, we have used laser structures for the common wavelengths 1500 to 1550nm. Two different InGaAs/InP based laser structures were grown by MOCVD on 4” wafers: a standard epi structure (ED-1) used already for broad-area single emitters and laser bars and a new epi structure (ED-2) optimized for higher efficiency and therefore better heat dissipation. Both epitaxial structures have been designed for 36° FWHM fast axis divergence.

Due to much higher internal losses compared to GaAs based structures, we have chosen a ridge section length of 310µm and a taper section length of 2190µm resulting in an overall resonator length of 2,5mm according to figure 1. We have investigated different taper angles between 5° and 8°. For the tapered amplifiers, the ridge-waveguide and taper sections are processed by optical contact lithography and a mixture of dry and wet chemical etching. The ridge section width is 5µm. The ridge height is chosen appropriately for the propagating wave to fill the taper angle and has been carefully adapted to the epi designs. Cavity-spoiling groves on both sides of the ridge section are defined by chemically assisted ion beam etching and suppress undesired Fabry-Perot modes. P-Metal structuring was done by lift-off. After substrate thinning and depositing the n-metallization, the wafers were cleaved into laser bars for coating.

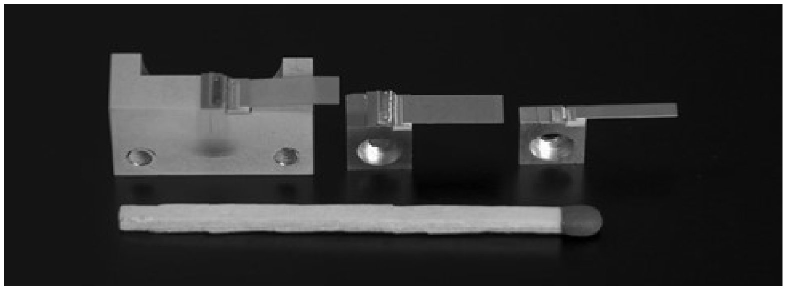

Figure 2: Different heat sink types: DHP-mount and C-mounts for amplifiers and lasers.

Facet coatings have been performed by a sputter system. Rear facets of Fabry-Perot lasers are coated by a double stack of SiO2/Si (>95% reflectivity), front facets with a single layer of SiN. The front facet reflectivity depends on the type of Fabry Perot laser: 10% for ridge-waveguide lasers, 5% for broad-area lasers and 2% for tapered lasers. To obtain amplifiers for narrow-linewidth operation in an external cavity, the rear facet coating is replaced by an SiON single layer, yielding 0.01% reflectivity. All devices were mounted p-side down on CuW submounts with AuSn solder. The submounts were mounted either on standard C-mounts or home-designed DHP-mounts (figure 2). Finally, uniform pumping of the laser medium is achieved by current injection via bond wires.

Compared to a stripe design, a tapered resonator exhibits increased losses because the major part of light reaching the front facet is reflected out of the cavity. The total losses are

$$\begin{aligned} \alpha_{ges} &= \alpha_i + \alpha_m + \alpha_{geom} \\ &\approx \alpha_i - \frac{1}{2L}\ln(R_1R_2) - \frac{1}{2L}\ln\left(\frac{w^2 n_{eff}}{4\lambda L_{Taper}}\right) \end{aligned} \qquad \text{(equation 2)}$$

where α_i are the internal losses, α_m are the mirror losses, and α_{geom} describes the additional geometrical losses. L and L_{Taper} are the total device length and taper length, respectively. w depicts the ridge width and n_{eff} is the effective index of refraction. α_{geom} is of the order of $10cm^{-1}$. The relatively high total losses must be taken into consideration when designing the epilayer sequence in order to provide sufficient gain.

3. Broad-Area and Ridge Waveguide Lasers

We have processed broad area lasers with 2mm resonator length and 100µm stripe width and 1mm long ridge-waveguide lasers to characterize both epitaxial designs and to evaluate parameters for the logarithmic gain model. All lasers have been mounted on C-mounts and CuW submounts by AuSn soldering.

In Fig. 3, the CW output power versus operation current characteristic recorded at a heat sink temperature of 20°C, is shown for both epi designs together with the corresponding spectral behaviour. The threshold current is 0.45A for ED-1 and 0.65A for ED-2 and the initial slope efficiency amounts to 0.44 W/A for both epi designs. The maximum output power equals 2.8W at a current of 9A. ED-2 was designed for better heat dissipation which leads to a lower voltage of only 1.25V compared to 1.6V for ED-1. This results in a much higher wall-plug efficiency of 27% for ED-2 compared to only 21% for ED-1 at 9A. In contrast, the maximum power conversion efficiency approaches 35% at 2.8A for ED-1 and 32.5% at 3.9A for ED-2. Figure 2 shows spectra at different operation currents at 20°C heat sink temperature for broad-area lasers based on ED-2. Operation wavelength at 8A is at 1.54µm.

From the same epi design EP-1 we have also fabricated ridge-waveguide lasers with resonator lengths of 1mm and a ridge width of 4µm. The ridge height has been chosen appropriately for single-mode operation and has been realized by ICP etching. At 20°C heat sink temperature we could demonstrate 150mW at 300mA with a wall-plug efficiency of 24%. The beam quality parameter was measured according to ISO 11146 with a commercial beam profile analyser and has been calculated with the common cut method. In the power range, up to 100mW, the ridge-waveguide lasers at 15xx nm show a nearly diffraction-limited behaviour corresponding to M values of 1.1 (figure 4). Table 1 summarizes all results.

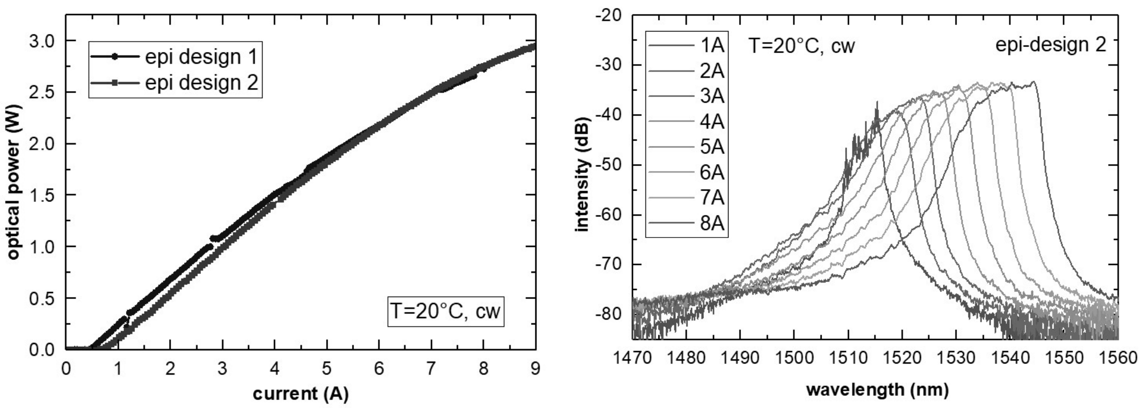

Figure 3: Output power-vs.-current characteristics (left) and optical spectra (right) for broad-area lasers at 1550nm with 2mm long resonator and 100µm stripe width. The measurements have been carried out in continuous wave (cw) mode at a heat sink temperature of 20°C.

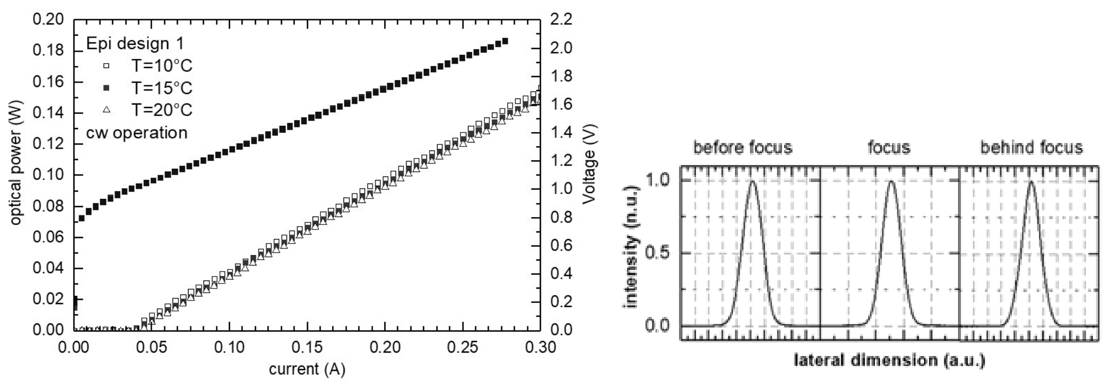

Figure 4: Output power-vs.-current characteristics (left) and beam waists (right) for a ridge-waveguide laser based on ED-1 with 1mm long resonator and 4µm stripe width. The measurements have been carried out in cw mode at different temperatures. Beam waists have been measured at 70mW in the focus position, before and behind the focus by a BeamScope system at 20°C.

Broad-Area Diode Laser					
Epi	Output power @ 8A [W]	Efficiency @ 8A [%]	Slope efficiency [W/A]	Voltage @ 8A [V]	Series resistance [Ω]
Design 1	2.7	21	0.44	1.6	0.096
Design 2	2.8	27	0.44	1.25	0.034
Ridge-Waveguide Diode Laser					
Epi	Output power @ 0.3A [W]	Efficiency @ 0.3A [%]	Slope efficiency [W/A]	Voltage @ 0.3A [V]	Series resistance [Ω]
Design 1	0.15	24	0.6	2.0	4

Table 1: Comparison of electro-optical results for broad-area and ridge-waveguide diode lasers based on epi designs ED-1 and ED-2. The measurements have been carried out in continuous wave mode at a heat sink temperature of 20°C.

4. TAPERED LASERS

With the implementation of the key parameters we received from the results of the basic laser designs in 2-dimensional BPM simulations, an optimized taper resonator geometry has been derived for aiming 1W in cw operation and 2W in pulsed mode. The ridge section consists of a section length of 310µm and a ridge width of 5µm whereas the taper section length was chosen to 2190µm. Based on epi design ED-1, different taper angles have been analysed experimentally. Figure 5 summarizes the individual output power-vs.-current characteristics for tapered lasers with different taper angles. All measurements have been carried out in continuous wave mode at a heat sink temperature of 10°C and upt o maximum operation currents of 4.5A. Output power and wall-plug efficiency decreases from 1.2W and 22% for a taper angle of 5° to only 0.5W and 10% by increasing the taper angle to 8° (table 2). This result contrasts with the expectation since with larger taper angle and therefore larger active areas, heat dissipation should be better. The reason for this behaviour is the additional term in equation 2 for the losses of a tapered design. The larger taper angle leads to larger losses, higher threshold currents and lower slope efficiencies, which overrides the positive effect of a larger active area for heat dissipation. So as a result, the taper angle has been fixed to 5 degrees for all tapered lasers and amplifiers.

taper angle	5°	6°	7°	8°
output power @ 4.5A [W]	1.21	1.07	0.89	0.50
wpe @ 4.5A [%]	22	20	15	10

Table 2: Output power and wall-plug efficiencies for tapered lasers based on epi-design EP-1 with different taper angles. The measurements have been carried out in continuous wave mode at a heat sink temperature of 10°C.

Figure 6 shows cw power-current characteristics of a tapered laser based on ED-1 and with a taper angle of 5° for different heat sink temperatures. Heating up the heat sink temperature from 10°C to 20°C leads to a rapid power loss from 1.2W down to 100mW at 4.5A. Therefore, we have designed epi design ED-2 with lower voltages (see section 2) and better thermal behaviour. The result can be seen in figure 7. Although with tapered lasers based on ED-2 (again with taper angle of 5 degree), at 10°C heat sink temperature at 4.5A we have received a lower power with 0.97W compared to LD-1, we are able to operate these lasers up to 8A resulting in an output power of 1.52W and 16% wall-plug efficiency. At 20°C we still have 1.25W at 8A and at 30°C the power level is still well beyond 900mW at 7A. Heat dissipation is the most limiting factor and the power is mainly limited by thermal rollover for the tapered lasers in the 15xx nm range. Therefore, for demonstration we performed pulsed measurements with 100µs pulses at 1% d.c. (Figure 6, pulsed). Under these conditions, a peak power of more than 2W is reached at 8A together with 21% wall-plug efficiency. Figure 6 shows on the right hand side typical spectra of tapered lasers at different operation currents at 20°C heat sink temperature. Since the tapered lasers are Fabry-Perot lasers, spectra are still broad and not usable for applications like ranging.

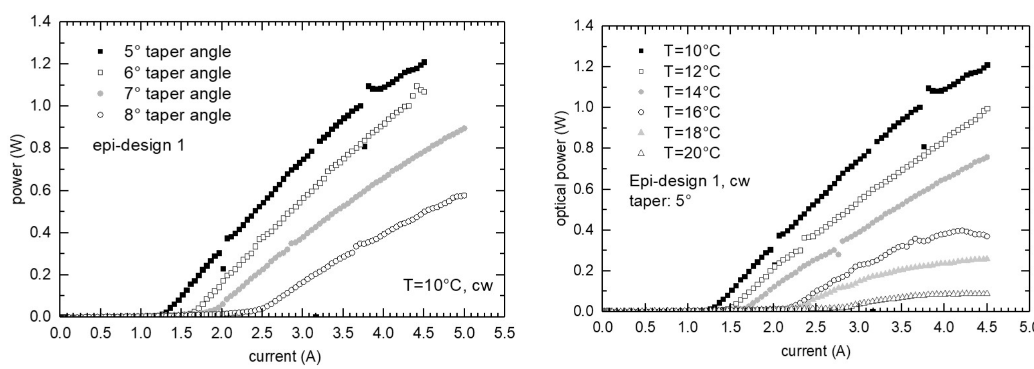

Figure 5: Output power-vs.-current characteristics for tapered lasers based on epi design 1 with different taper angles at a heat sink temperature of 10°C (left) and with a taper angle of 5 degree at different heat sink temperatures (right). All measurements have been carried out in continuous wave mode.

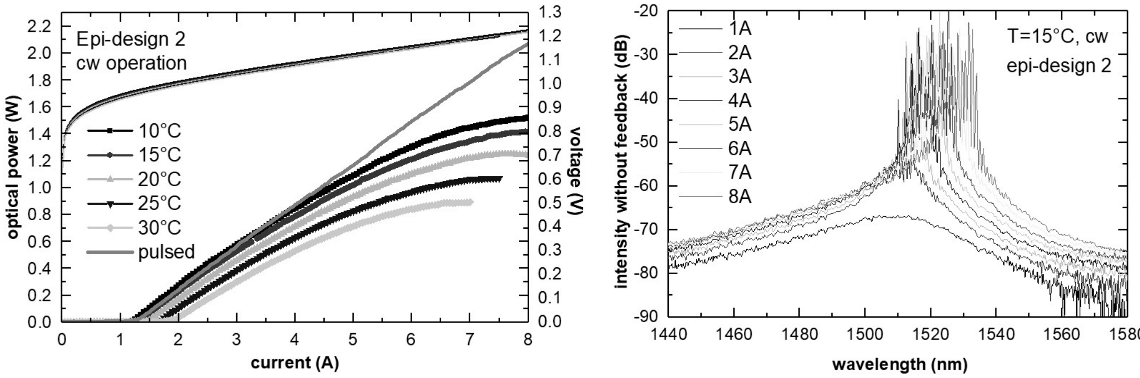

Figure 6: Output power-vs.-current characteristics and current dependent voltage for tapered amplifiers based on epi-design ED-2 with 5° taper angle for different heat sink temperatures (left). Spectra of a tapered laser with epi-design 2 for different operation currents (right). All measurements have been carried out in continuous wave mode.

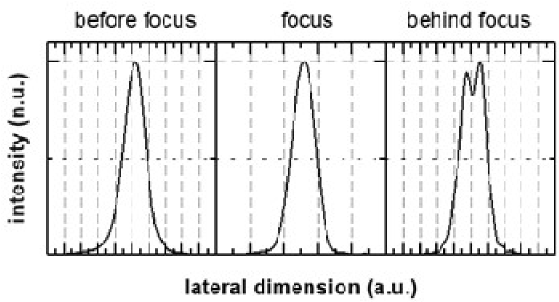

Figure 7: Beam waists of a tapered laser based on ED-2 with 5-degree taper angle in the focus position, before and behind the focus. Beam profile show a (nearly) Gaussian profile each resulting in a M^2 of 1.1. All measurements have been carried out in cw mode at 20°C.

Figure 7 demonstrates the beam quality of the tapered lasers in figure 8. Here the beam waists in the focus, before and behind the focus all show a nearly Gaussian beam profile resulting in a M^2 value of 1.1 which is comparable with the beam quality of the ridge-waveguide laser from section 3, but at a factor of 10 higher power level.

5. TAPERED AMPLIFIERS IN EXTERNAL CAVITY SETUP

To aim for narrow-linewidth operation, the tapered lasers based on LD-2 were coated as amplifiers as described in section 2 and placed in an external cavity setup [10]. Light emitted at the rear facet is collimated and reflected by a grating (600 l/mm) in Littrow configuration. For more efficient use of the grating, a half-wave plate between device and grating rotates the polarization by 90±. With feedback at the gain maximum, output powers of 890 mW are obtained at 8A (see figure 10), which corresponds to 58% of the Fabry-Perot device output in figure 6. Beam quality is shown in figure 8 to be comparable to tapered lasers in the range of M^2=1.1.

The advantage of the tapered amplifier in an external cavity setup compared to a tapered laser is the tunability according to the gain curve of the diode, a high side mode suppression ratio and a small linewidth suitable for spectroscopic or ranging applications. As plotted in figure 12 the mode suppression ratio (SMSR) is more than 40 dB, the central wavelength is around 1510nm, the tuning range between 1488nm and 1535nm offers 47nm tuning range and is defined by getting a constant power level of 500mW within a maximum operation current of 6A at a heat sink temperature of 20°C (according to commercial products in the GaAs wavelength regime).

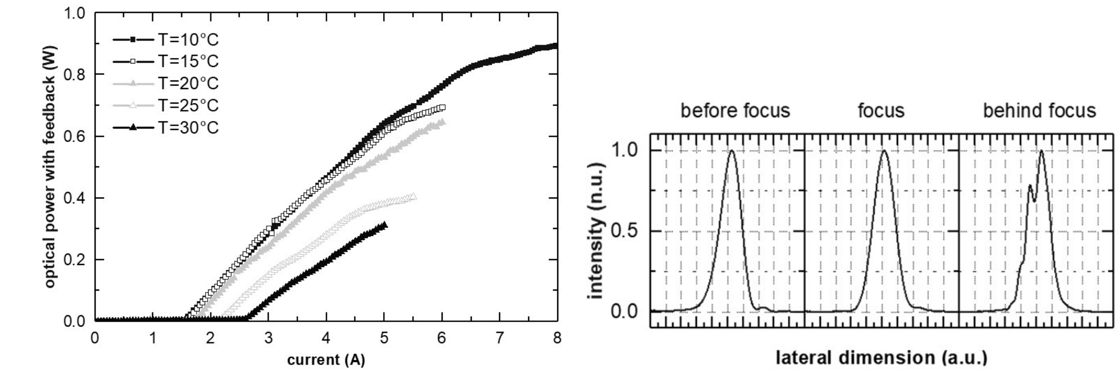

Figure 8. CW output power vs. operation current characteristics for tapered amplifiers in external cavity setups at 1510m. All measurements have been done at feedback at 1510nm in continuous wave operation (left). Beam waists of a tapered amplifier at 500mW in the focus position, before and behind the focus (right). All measurements have been carried out in cw mode at 20°C heat sink temperature.

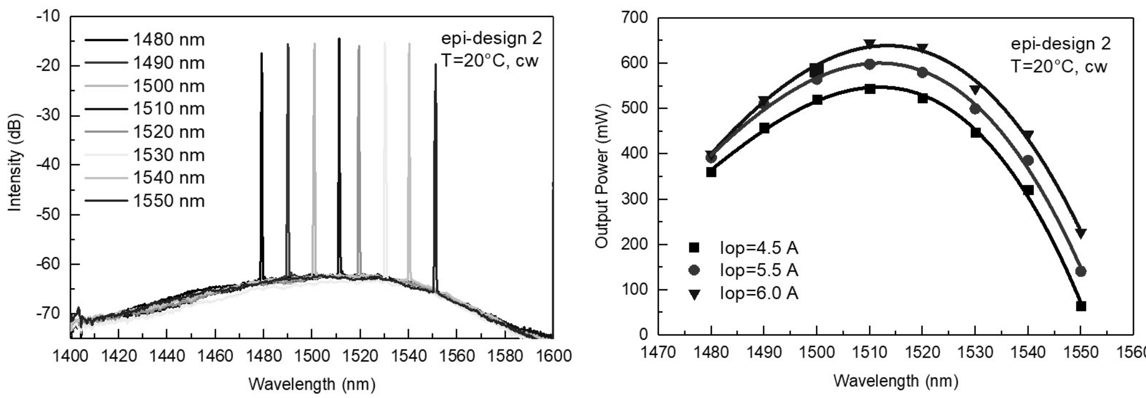

Figure 9. Spectrum of a tapered amplifier in an external cavity setup with feedback at different wavelengths (left) and output power vs. tuned wavelength at different operation currents (right). All measurements have been done at 20°C heat sink temperature.

6. CONCLUSION

In summary, we have realized MOCVD-grown InGaAsP/InP ridge-waveguide tapered diode lasers and amplifiers with high spatial beam quality and - when operated with an external grating - with high side mode suppression ratio. For standard devices, we demonstrated nearly 3W at 9A for broad-area lasers with 100µm stripe width and ridge-waveguide lasers with 150mW power level. Output powers of more than 1.5W in continuous wave and 2W in pulsed operation have been demonstrated at room temperature for tapered lasers. Tapered amplifiers within an external cavity setup offer more than 500mW within a tuning range of 47nm with excellent mode suppression ratio (SMSR) of more than 40dB. For ridge-waveguide lasers as well as tapered lasers and amplifiers beam quality show values of 1.1 favourable for single-mode fiber coupling. Due to its simple fabrication and large potential for power scaling we regard the ridge-waveguide tapered resonator design a promising concept for cost-efficient InP based high brightness devices.

7. ACKNOWLEDGMENT

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