

Watt-Class Fiber Coupled Laser Modules for Future Cold-Atom Space Applications

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ABSTRACT

We report on the design, electro-optical characteristics and improved thermal management for realizing high-power laser modules based on our space-qualified MiLas® architecture. The polarized light with precisely controlled wavelength in the range 760 to 780 nm is amplified using a tapered amplifier (TPA) to obtain optical powers approaching 1 W from the single-mode polarization-maintained fiber output. Step-wise accelerated life testing of equally designed tapered lasers results in a reliability exceeding 99% over 10,000 h of continuous operation. In this contribution we investigate the suitability of TPA for integrability into the laser module by measurements, test and simulation.

Keywords: tapered amplifier, high power, space qualified laser module, reliability

1. INTRODUCTION

Laser cooling of neutral atoms such as potassium at precisely adjusted wavelengths of 766.701 nm and rubidium at 780.246 nm is a key enabling technology for quantum sensors and long-term quantum experiments under microgravity [1]. Future satellite-based cold-atom instruments require laser modules that combine high spectral quality, efficient single-mode fiber coupling, compact and robust integration, and long-term reliability under mission-relevant operating conditions. In our previous contribution [2], we demonstrated the suitability of ridge-waveguide (RW) semiconductor optical amplifiers for reliable operation at moderate output power levels in laser systems developed for the Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) on the International Space Station (ISS) and for hybrid quantum-based inertial sensors (HYQIS). Building on this work, the present contribution represents a further step toward a technology demonstrator for future space missions by investigating tapered-amplifier (TPA)-based modules for higher fiber-coupled output power in the wavelength range from 760 nm to 780 nm.

While moderate power levels are sufficient for current implementations such as BECCAL and HYQIS, increased fiber-coupled power is highly attractive for next-generation satellite missions beyond the ISS. Higher output power provides larger optical power margins, supports larger beam diameters at sufficient intensity, facilitates optical power distribution within more complex architectures, and improves robustness against insertion losses, contamination, and long-term aging. Watt-class single-mode fiber-coupled sources in this spectral range therefore represent an important technological extension of established semiconductor laser modules for future deployable and highly integrated cold-atom payloads.

In this contribution, we compare the electro-optical performance of tapered amplifiers based on symmetric and asymmetric large-optical-cavity epitaxial designs and assess their suitability for module integration. In section 2, we describe the design variants, processing and assembly steps for the TPA chips, their electro-optical characteristics, and their implementation inside the MiLas module. The simulation of optical beam paths in the MOPA and thermal FEM analysis are summarized in section 3. The experimental sections (4 and 5) comprise a comparative study of TPA characteristics among two variants, coupling experiments towards high power until thermal destruction, life testing for high power and long endurance. Finally, a FEM simulation is presented aimed at improving the thermal management in order to suppress the failure mode due to thermal run-away at high power levels.

2. DESIGN AND MANUFACTURING

At Ferdinand-Braun-Institut (FBH) we are operating a fully vertically integrated semiconductor epitaxy-, wafer processing-, assembly and integration fab including test facilities and high-class clean-room environment. Our processes, product and quality assurance efforts have been proven since over two decades to provide customer specific development and small-series production of space qualified components, semiconductor chips, modules and sub-systems. Especially for atom-cooling under micro gravity we have developed and qualified a wavelength-controlled master oscillator power amplifier (MOPA) module with extended cavity diode laser and ridge waveguide amplifier (RWA) referred to as MiLas® module [3]. Those are qualified for power levels of up to 0.5 W with high reliability over a long mission time [2]. In this section we summarize our work for developing and manufacturing the TPA chips intended for replacement of the RWA in the MiLas module.

Amplifier chip design

In this work, three different III-V semiconductor layer structures were realized: one highly asymmetrical large optical cavity design with a 2.5 μm wide $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ waveguide layer (aloc-2.5), the second one with a 1.5 μm thick asymmetrical waveguide (aloc-1.5) and the third one having a 1 μm thick symmetrical waveguide (sloc-1.0). The layers were deposited on 3-inch Si n-doped GaAs (100) wafers with metal-organic vapor phase epitaxy (MOVPE). In any case, the p-side side waveguide layers were 0.5 μm thick and the cladding layers were $\text{Al}_{0.70}\text{Ga}_{0.30}\text{As}$ with slightly higher Al-content. The doping was silicon (Si) on the n-side and carbon (C) on the p-side. The quantum wells were identically composed of 11 nm thick tensile strained GaAsP layers with P mole fraction of 25-27% for 770 ± 10 nm TM-polarized emission at maximum optical gain. The single quantum wells were embedded in 10 nm thick AlGaAs graded-index barrier layers. The sloc-2.5 structure is identical to the epitaxial design of the ridge-waveguide 767-780 nm amplifiers (RWA) as reported in our previous work [2].

The electro-optical characteristics were obtained from light-current-voltage (LIV) and spectral measurements at broad area test samples of 100 μm width and 1 mm length of the cavity. The data, wavelength (WL), threshold current density (J_{Tr}), slope efficiency (S), internal efficiency (η_i), internal loss α_i , confined gain factor Γg_0 , fast axis 95% divergence θ_{FA} and the characteristic threshold temperature T_0 are listed in table 1. Note, that the divergence, the confinement factor, and thus Γg_0 , as well as the internal loss, decrease with increasing thickness of the waveguide (1... 2.5 μm) – originating from the overlap of the optical field with the quantum well and with the doping profile in the waveguide.

Table 1: Electro-optical characteristics of the symmetrical (sloc) and asymmetrical (aloc) large optical cavity structures with indicated waveguide thickness (μm). The data were obtained from broad area lasers (100 $\mu\text{m} \times 1$ mm) measurements.

Parameter: Design Unit:	WL nm	J_{Tr} A/cm ²	S W/A	η_i	α_i cm ⁻¹	Γg_0 cm ⁻¹	θ_{FA} deg	T_0 K
sloc-1	765	115	0.63	0.85	1.04	19	28	170
aloc-1.5	762	113	0.63	0.82	0.66	17	25	138
aloc-2.5	760	133	0.63	0.81	0.37	15	17	99

The lateral taper structure was manufactured using standard photolithography, wet-chemical etching, SiN-isolation for current confinement, n-AuGeNi and p-Au metallization with TiPt diffusion barriers in between and 5 μm thick galvanic Au layers as heat spreaders and contact pads on the p-side.

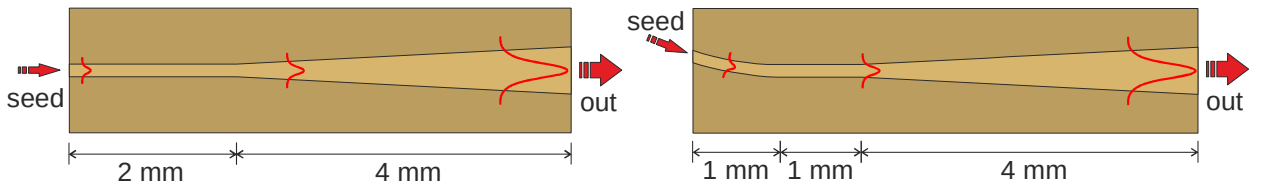


Fig 1: variants of lateral design with straight (a) – or tilted RW section (b)

The amplifier structure consists of a 3 μm wide and 2 mm long RW-section and a 4 mm long taper section widened with an either 6° or 4° taper angle to result in an aperture width at the front facet of 422 μm or 282 μm , respectively. The amplifier front and rear facets were ZnSe-passivated against mirror degradation and coated with dielectric anti-reflection

mirror stacks to obtain a reflectivity $R < 0.1\%$ for both facets of the TPA and $R_b = 96\%$ at the back facet and $R_f = 1\%$ at the front facet of the TPL, respectively. The ridge was either straight or tilted by 4° towards the rear facet with a continuous bending along 1 mm followed by a straight section of 1 mm. The tilt angle was chosen for a sinusoidal slope to yield an anti-reflectivity with $R < 0.1\%$ stable against small variations of the tilting for both sloc-1 and asloc-1.5 designs as computed with the beam-propagation software Fimmwave (PhotonDesign). The lateral design variants are sketched in Fig. 1.

The semiconductor chips were soldered p-side up onto AlN submount with AuSn hard solder in the ζ -phase. The TPL were soldered with PbSn onto C-mounts. The TPA chip-on-submount assemblies were soldered with PbSn onto a micro-optical bench. The RW and TPA sections were separately contacted with Au wire bonds.

In the following, we will show and discuss the results of asloc-2.5 and sloc-1 structures with the straight RW-design (1.a). The other variants are still under investigation and the results are intended to be published.

Module design

The module design is based on the MiLas® architecture, which was developed, tested and qualified for space applications at the FBH [2]. The original MiLas module is equipped with a ridge waveguide amplifier (RWA) as described in our previous work [3]. The fully assembled module with a tapered non-tilted amplifier (TPA) is shown in Fig. 2.

The laser beam is generated by an extended-cavity diode laser (ECDL) between a volume holographic Bragg grating (VHBG) assembled on a small thermoelectric cooler (μ TEC) acting as a thermally wavelength-tunable reflector and an RWL serving as the master oscillator (ECDL chip).

The back reflection is imaged as a monitor signal onto a fiber collimator serving as an auxiliary port via mirrors, an optical isolator, and a microlens. The main beam from the ECDL is coupled into the amplifier (TPA) via several lenses and an optical isolator in the path between the ECDL and the amplifier.

The module housing is equipped with hermetically sealed lid and feed-throughs for electrical connection and fiber main (Fig. 2 right) and auxiliary output (left). The module is thermally stabilized with a thermo-electric cooler (TEC) attached to the bottom of the housing.

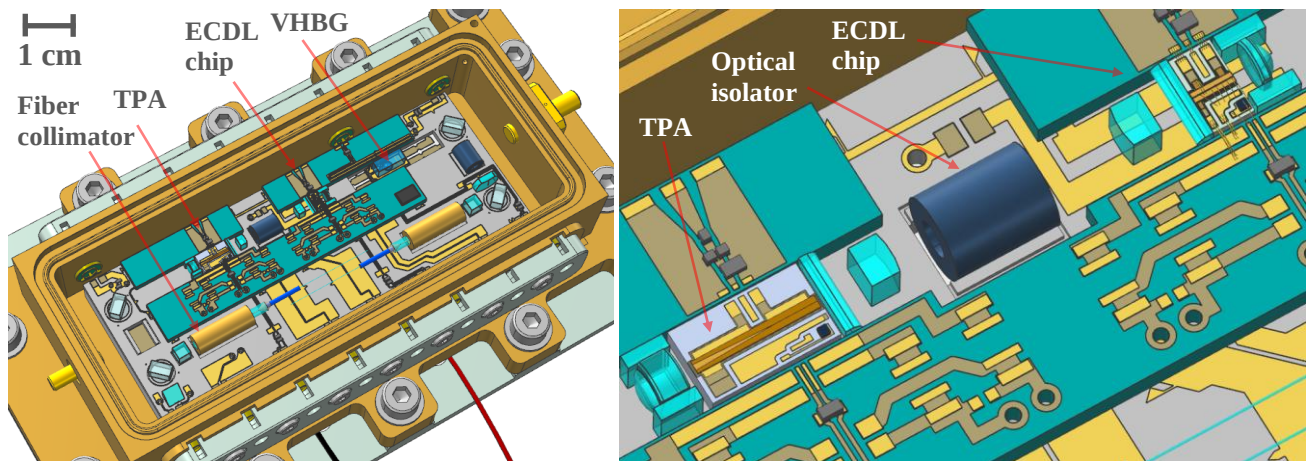


Fig. 2: Design of the modified MiLas® laser module: open housing (left), TPA (right) with ECDL chip (zoomed)

3. SIMULATIONS

Simulations of the beam path

The beam path was simulated using BeamXpert™ software. The simulations were used to select the passive optical components - in particular, the collimator lenses, slow-axis (SAC) and fast-axis (FAC) collimators - and to estimate the coupling efficiency when injecting into the SM fiber.

Figure 3 shows the beam path from the fiber (seed, green from the left) through the collimating lens into the TPA (center), from the TPA (red) through an FAC, followed by an SAC, to image the collimated radiation onto a screen. Fig. 3(a) shows the top view (slow axis in the image plane). The lateral dimension of the SAC and the vertical dimension of the FAC are chosen such that the components remain as small as possible while the beam is collimated as completely as possible.

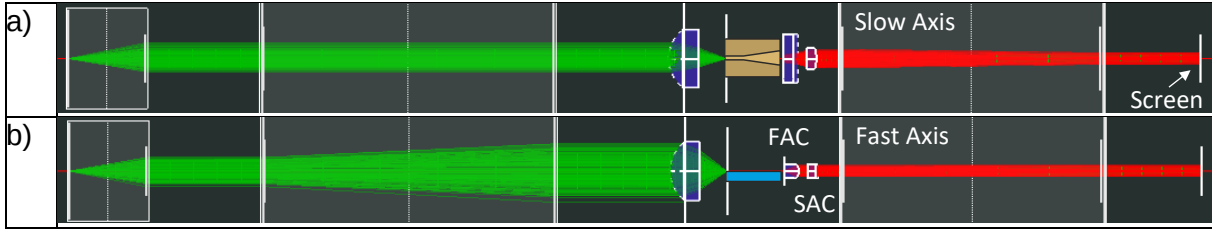


Fig. 3: Beam path in slow axis (a) and fast axis (b) from the fiber (left passing the collimator lens, the amplifier, followed by the FAC and SAC onto the screen (right).

For the simulated intensity distribution, a Gaussian beam profile was assumed for the light from the amplifier. This assumption is valid only as long as the “central lobe”, i.e., the distribution in the center is Gaussian to a high percentage ($\gg 50\%$). This condition is always met for the given TPA design at low power levels (some 100 mW). From the distribution, the coupling into the optical fiber can be calculated. This amounts to $> 90\%$ for the Gaussian portion of the central lobe. At higher power levels (> 1 W), the TPA tends to show filamentation causing a significant deviation from a Gaussian beam and a pronounced drop of coupling efficiency. This issue will be addressed in the experimental (section 4).

Simulations of Heat Flux and Temperature Distribution in the Module

The simulations of the laser module’s thermal steady state under operating conditions were performed for a 3D model with the material’s thermal conductivities using finite element model (FEM) analysis computed with the software ANSYS. The major heat sources are located at the amplifier chip due to the electro-optical conversion efficiency $\eta_{CE} < 50\%$ and at the fiber coupler due to heating by coupling losses at a coupling efficiency of $\eta_C \sim 50\%$. The results of the simulation are summarized in section 6.

4. ELECTRO-OPTICAL CHARACTERISTICS

The amplifier characteristics were measured on an optical table (bread board) using a hexapod (Physics Instruments PI) for adjusting the FAC lens and linear nano stages (SmarAct) for positioning of the coupling lens at the input and the SAC lens at the output of the TPA with high precision of less than 100 nm. The polarized single-mode emission of an external DBR laser was used to seed the TPA at a thermally tunable wavelength adjusted to 767 nm at an optical power of typically 8 mW.

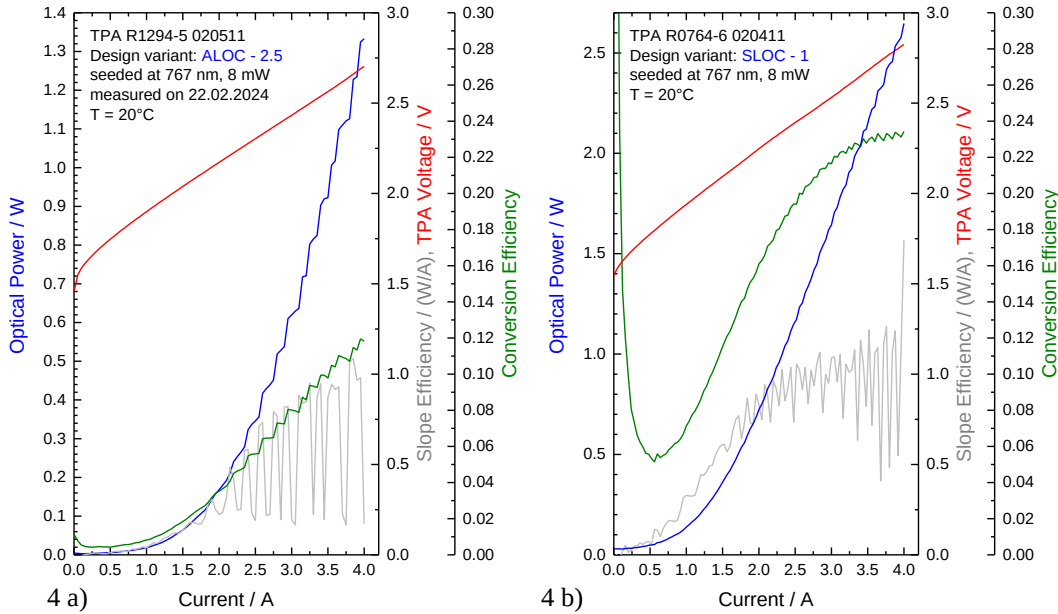


Fig. 4: LIV characteristics, slope efficiency (gray) and conversion efficiency of the TPA, seeded at 767 nm with an optical power of $P_{seed} = 8$ mW, of design aloc-2.5 (left) and sloc-1 (right)

The drive currents through the PT- and RW-sections were independently controlled using low-noise laser diode drivers (LDX from ILX Lightwave). The optical power was measured using a thermoelectric detector (Thorlabs). The optical spectra were recorded – after the beam passed through a beam splitter, an optical isolator and an attenuator – using a high-resolution optical spectrum analyzer (Anritsu).

Figures 4 a) and b) show the LIV characteristics of typical straight TPAs of the design variants aloc-2.5 and sloc-1, respectively. The voltage (red), optical power (blue), slope efficiency (gray) and conversion efficiency (green) are plotted as functions of the amplifier current at a constant RW current (100 mA) and a constant seed power of 8 mW at 767 nm. At the maximum applied amplifier current of $I_A = 4$ A the maximum optical power is $P_{op} = 1.3$ W and the conversion efficiency is $\eta_{CE} = 12\%$ for the aloc-2.5. For the symmetric waveguide (sloc-1) the optical power at $I_A = 4$ A is twice as high, it is $P_{op} = 2.6$ W at a conversion efficiency of $\eta_{CE} = 25\%$. Further, the undulations in the slope efficiency are much less pronounced for the sloc-TPA than for the aloc version indicating less sensitivity to parasitic optical feedback originating from the coupling lenses.

The optical spectra in the wavelength range from 750 nm to 790 nm are displayed in Fig. 5 for the TPA of both design variants aloc-2.5 (5a) and sloc-1 (5b) with the peak power scaled to the optical powers from the LI curves. The spectra are shown for currents ranging from 0.5 A to 4 A in 0.5 A increments. In both cases, the ASE maximum shifts toward shorter wavelengths as the amplifier current increases – due to the carrier density decrease with increasing amplifier gain. Both the ASE intensity and the peak intensity increase with the amplifier current, reaching a main-peak to ASE-peak ratio of about 50 dB.

The ASE gain spectra of the aloc-2.5 TPA are considerably broader, about twice the FWHM (3 dB below the maximum) compared to the sloc-1 TPA. The ratio of the integrated amplified laser peak intensity to the integrated ASE intensity reaches up to 25 dB (factor 300) for the aloc-2.5 TPA, and 29 dB (factor 800) for the aloc-1 TPA at 1 A. This ratio drops below 50 (17 dB) at 3 A for the aloc-2.5 structure, and it is more than 120 (31 dB) for the sloc-1 TPA at 4 A drive current (2.5 W optical power).

The measurement results are representative for the investigated structures and were reproduced with other samples. Those structures were selected to conduct a comparative study of the influence of beam profile width and the associated beam quality on the characteristics of the TPA amplifier. The asymmetric structure was also investigated because it had already been tested and qualified for RWA (ridge waveguide amplifiers) with a 5 μm wide mesa in the predecessor projects (BECCAL among others [2]). The data indicate that a drive current of 4 A is sufficient to obtain amplified optical powers exceeding 2 W for the symmetric structure, but not for the asymmetric 2.5 μm thick waveguide structure. In the following, we report on the coupling from the TPA into the optical fiber.

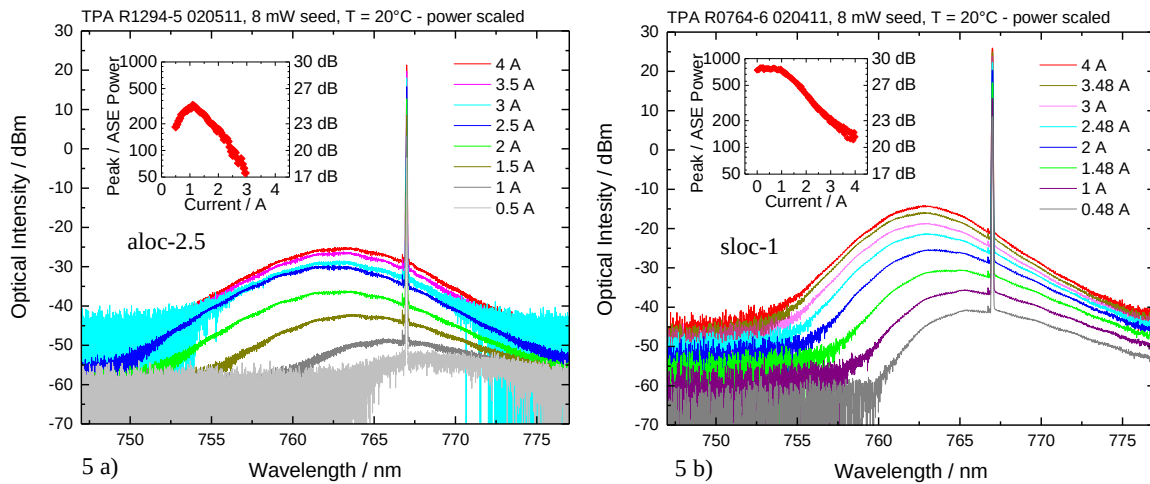


Fig. 5: Optical spectra and peak / ASE power ratio (insert) of the TPA, seeded at 767nm with $P_{seed} = 8$ mW, of design aloc-2.5 (left) and sloc-1 (right)

Fiber coupling experiments

The optical fiber, equipped with a collimator, was acquired from an external supplier specialized on fiber collimation. The polarization maintained (PM) single mode (SM) fiber with 4.5 μm core diameter, model PM 780-HP from HP is suitable

for the 760–780 nm wavelength range. The collimator / fiber assembly was verified by the manufacturer for a power class in the range of > 1 W for collimated laser radiation in the specified spectral range.

The measurement results of a typical coupling experiment, using a TPA of sloc-1 design, are summarized as follows: At low power level, $P_{\text{TPA}} = 150$ mW from the TPA, the coupling efficiency was $\eta_C = 61\%$ yielding an output power of $P_{\text{FIB}} = 90$ mW from the fiber. Nearfield and farfield measurements indicate a nearly Gaussian distribution with small elliptical eccentricity. At increasing power, the field distribution indicates a lateral structuring due to filamentation. At a moderate power level of $P_{\text{TPA}} = 1$ W, the coupling efficiency drops slightly to $\eta_{\text{CE}} = 57\%$ resulting in 0.6 W optical power ex fiber. In order to achieve a power of $P_{\text{FIB}} = 1$ W ex fiber, an optical TPA power of $P_{\text{TPA}} = 2$ W was needed, since the coupling efficiency dropped to $\eta_C = 50\%$ due to strong filamentation. The (unscaled) far field distribution of the TPA emission, imaged with a CCD camera, is displayed in Fig. 6. The distribution in fast axis is nearly Gaussian, whereas the slow axis (lateral) distribution shows several peaks superimposed to an asymmetric distribution of intensity.

At this power level, the dissipated power of $P_W = P_{\text{TPA}} - P_{\text{FIB}} = 1$ W caused a thermal destruction of the uncooled joint between the collimator and the fiber. This issue could not be resolved even with the best-of-class chips of the current design, but it can be addressed by attaching a heat sink to the fiber collimator as shown in the next section.

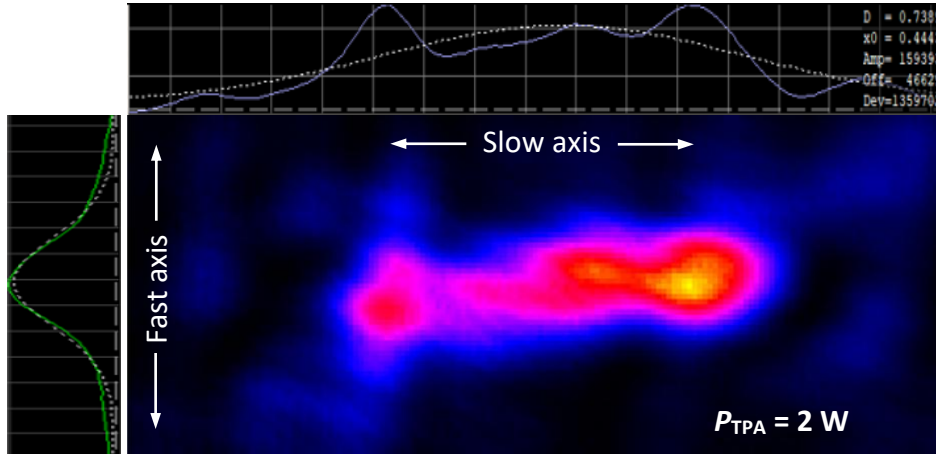


Fig. 6. Farfield intensity of the TPA (sloc-1) emission at $P_{\text{TPA}} = 2$ W optical power on the CCD screen (unscaled)

5. OPERATIONAL RELIABILITY AND THERMAL ENDURANCE

Lifetime test results of TPL

To evaluate the reliability of the chip material, accelerated lifetime tests were conducted for tapered lasers (TPL) of the same processing batches as the TPA. Figure 7 shows the step-accelerated lifetime plots of optical power at step-wise constant currents, ranging from 4 A to 10 A, with operating time of aloc-2.5 TPL (a) and sloc-1 TPL (b).

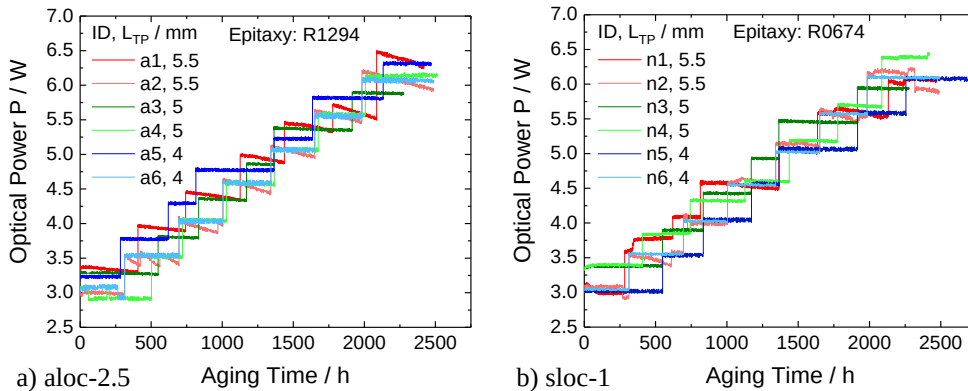


Fig. 7. Lifetime plots of optical powers at stepwise constant current (4 A to 10 A) of TPL of the aloc-2.5 design (a) and the sloc-1 design (b). The tapered lengths varied from 4 mm to 5.5 mm at constant chip length of 6 mm.

The taper length varied between $L_{TP} = 4$ mm, 5 mm and 5.5 mm with two samples per variant. All variants had the same resonator length of $L = 6$ mm. The optical power ranged from $P = 3$ W in several steps of about 0.5 W to $P = 6.5$ W after 2500 h.

There was no chip failure, which is defined as 20% power drop at operating condition (2 W), in any case – although the TPL with $L_{TP} = 5.5$ mm showed some gradual degradation, more pronounced for the aloc-2.5 TPL ($\Delta P / P \approx 15\%$) than for the sloc-1 TPL ($\Delta P / P \approx 10\%$). Anyway, there was no gradual degradation for tapered lengths smaller than 5.5 mm, i.e. for RW-lengths exceeding 0.5 mm.

In order to estimate the reliability at operating condition (2 W from the TPA) the acceleration parameters obtained previously for RWLs of the aloc-2.5 batch can be used [2]. The acceleration parameters for “scale accelerated failure time” (SAFT) including the power derating exponent n and the thermal activation energy E_A for degradation were obtained from a maximum-likelihood estimate as $n = 6.1$ and $E_A = 0.39$ eV.

Using the exponential (“random failure”) distribution for failure events the mean time to failure (MTTF) is given as $MTTF = (\text{sum of accelerated times}) / \ln(1 / \alpha)$ at zero failures and risk α . At the given step-accelerated conditions the MTTF is computed to $MTTF = 1.4 \times 10^6$ h for the aloc-2.5 TPL and $MTTF = 1.3 \times 10^6$ h for the sloc-1 TPL. Those numbers correspond to a reliability $R(t_{op}) = \exp[-t_{op} / MTTF] = 99.3\%$ for aloc-2.5 and $R(t_{op}) = 99.2\%$ for the sloc-1 TPL after $t_{op} = 10,000$ h of continuous operation at $P_{TPL} = 2$ W at risk $\alpha = 1\%$. Evaluating the TPL with taper length $L_{TP} = 4$ mm results in a $R > 99\%$ limit at higher risk ($\alpha = 40\%$) due to the small sample size of two. The results are summarized in Table 2.

Table 2: *MTTF* and reliability R in 10,000 h at risk α for both TPL variants

TPL Design	MTTF	R(10,000 h)	Risk α
aloc-2.5	1.4×10^6 h	99.3%	1%
sloc-1	1.3×10^6 h	99.2%	1%
sloc-1, $L_{TP} = 4$ mm	1.4×10^6 h	99.3%	40%

Thermal endurance of fiber collimator

As reported in the previous section, the fiber collimator was thermally damaged at $P_{loss} = 1$ W of dissipated power. The damage was located in the region where the glass tube of the collimator is filled with adhesive for attachment and strain relief, referred to as “hot spot” in Fig. 8 a. The temperature distribution in the fiber collimator, as shown in Fig. 9 b, was experimentally examined by collimating 767 nm light from a Ti:Sa laser at 50% coupling efficiency and measuring the temperature with a thermal camera. The maximum increase in temperature was $\Delta T_{max} = 74.5$ K located in the center of the hot spot region at a power loss of $P_{loss} = 0.25$ W.

The FEM-simulation was done using the 3D geometry and the physical properties (thermal conductivities) of the applied parts and materials. The temperature distribution represents the same thermal condition as in the experiment with an optical power of $P_{op} = 0.5$ W from the TPA generating a heat amount of $P_{TPA,heat} = 3.64$ W at 12% conversion efficiency (see Fig 4 b). This heat power causes a maximum temperature rise of $\Delta T_{TPA,max} = 45.6$ K in the active region of the chip. On the other side, at the collimator a heat power in the glue of $P_{glue} = 0.11$ W causes a maximum increase in temperature of $\Delta T_{FC,max} = 74.5$ K in the hot spot according to the FEM-analysis. Since the dissipated power at the FC is $P_{loss} = 0.25$ W, it follows that a fraction of $\alpha = 45\%$ of this power is absorbed in the fiber glue and converted to heat.

Table 3: Maximum temperatures for TPA powers of 0.5 W and 2 W at the chip (TPA) and at the FC for the case of uncooled and cooled FC for different coupling efficiencies η_c and fractions of absorbed power α .

TPA output P_{op} / W	Coupling efficiency η_c	Absorption α	TPA temp. $T_{TPA, max} / ^\circ\text{C}$	Uncooled FC $T_{FC, max} / ^\circ\text{C}$	FC Cooler $T_{FC, max} / ^\circ\text{C}$
0.5	50%	45%	46°C	94.5°C	
2	50%	45%	69°C	290°C	48°C
2	50%	100%	70°C	521°C	83°C
2	0	100%		804°C	

A heat spreader acting as passive cooler was designed for attachment to the fiber collimator as shown Fig. 8 d. For the simulations the thermal conductivity of Cu, 170 W / (m K) was used as material of the heat spreader. The temperature distribution computed for an operating power $P_{op} = 2$ W from the TPA is shown in Fig. 8 e. A coupling efficiency of 50% and an absorption of $\alpha = 45\%$ of the dissipated power $P_{Loss} = 1$ W in the fiber glue volume was assumed as in the case of the original (uncooled) fiber collimator. The temperature rise at the FC is reduced to $\Delta T_{FC,max} = 26$ K with the heat spreader.

In table 3 the simulated maximum temperatures at the TPA chip and at the fiber coupler (FC) are summarized for TPA output powers of 0.5 W and 2 W with heat powers depending on the coupling efficiency η_C (50% or 0) and the fraction α of absorbed power (45% or 100%). In case of an uncooled fiber collimator, the temperature rises to 290 °C at 2 W and 50% coupling efficiency. This temperature rise may cause a thermal run-away by increasing absorption and pyrolysis as outlined in the following. For example, epoxy-based adhesive starts to gradually degrade at temperatures in the range of 200 °C to 300 °C and by pyrolytic decomposition in the range of 300 °C to 450 °C, depending on the specific material [4]. This leads to the following interpretation: the absorption of scattered radiation in the glue area causes a temperature rise to about 300 °C, causing the adhesive to gradually degrade. This may cause an increasing absorption and further rise of the temperature until pyrolysis takes place. At 100% absorption, the temperature would increase to over 500 °C leading to a destruction of the fiber joint. At that point, if the coupling efficiency is totally lost, the temperature would even raise to more than 800 °C. Using a heat spreader attached to the fiber collimator will suppress the thermal run-away and limits the temperature to less than 83 °C, even in the case of 100% absorption of scattered light with 1 W power in the adhesive.

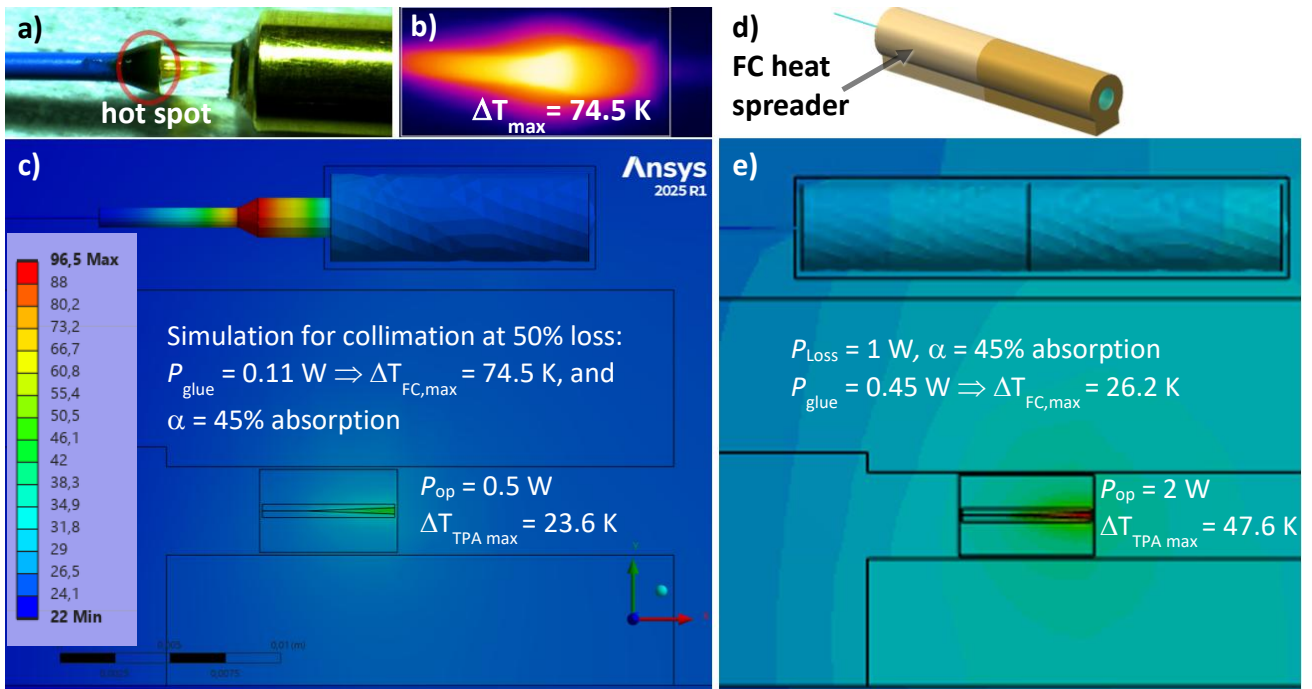


Fig. 8. Experiment (a, b), simulation (c) and new design (d, e): a) Photographic image of fiber collimator with identified hot spot, b) thermal image of fiber collimator with measured maximum temperature increase ΔT_{max} at $P_{loss} = 0.25$ W, c) simulation of experiment b) with calculated heat P_{glue} in the fiber joint glue, d) fiber collimator with heat spreader, e) simulation of ΔT_{max} at $P_{loss} = 1$ W with FC heat spreader.

6. SUMMARY, CONCLUSION AND OUTLOOK

In conclusion, we have demonstrated that a symmetrical large optical cavity design for tapered amplifiers is capable to deliver optical powers exceeding 2 W in the wavelength range from 760 nm to 780 nm. The light from a seed laser was amplified by passing through the tapered amplifier and coupled into a polarization maintained single mode fiber at 50% coupling efficiency up to an optical power of 1 W from the output port of the fiber. Absorption induced pyrolysis of the adhesive between collimator and fiber can be suppressed by using a highly heat-conducting heat spreader attached to the fiber collimator and to the housing with thermoelectric temperature control. The long-term reliability of the TPA chip material was estimated by evaluating scale-accelerated life tests over 2500 hours with step wise increasing power up to over 6 W. A reliability of $R > 99\%$ was estimated for a continuous operating time of 10,000 h at 2 W optical power from tapered lasers of the investigated material. Based on our space qualified MiLas® architecture, the technological hurdles have been overcome to deliver watt-class laser modules for space applications that are wavelength-controlled in the range of 760 nm to 780 nm.

ACKNOWLEDGEMENTS

The authors would like to thank Arnim Ginolas for assembly, Michael Ekterai and Christof Zink for measurement of chips, Gunnar Blume and David Feise for providing tapered laser samples, Maik Erbe and Johannes Glaab for performing the aging tests, Simon Kubitzka for teaching the art of fiber coupling, and Markus Weyers for reviewing this manuscript. This work was supported by the German Aerospace Center (DLR) and funded by the Federal Ministry of Research, Technology and Space (BMFTR) under the grants no. 50WM2265 (HiPoLaMo) and 50SI2662B (HYQIS-II).

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