Coherent beam combining of high power tapered (poster)

Philipp Albrodt, Marc Hanna, Frédéric Moron, J Decker, Winterfeldt M., G Blume, Paul Crump, Patrick Georges, Gaëlle Lucas-Leclin

Coherent beam combining of high-power tapered amplifiers

P. Albrodt[1*], M. Hanna[1], F. Moron[1], J. Decker [2],
M. Winterfeldt [2], G. Blume [2], P. Crump [2],
P. Georges [1] and G. Lucas-Leclin [1]

[1] Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Université Paris-Saclay, Palaiseau, France ([*]philipp.albrodt@institutoptique.fr)
[2] Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), Berlin, Germany

Abstract— **We describe the coherent beam combining of three high-power tapered laser amplifiers seeded by a DFB laser at λ = 976 nm, and demonstrate a combined power of 12.9 W in a close to diffraction-limit beam at a combining efficiency of > 65%. We use individual devices on C-mounts in a multi-arm interferometer. The phase pistons of each beam are matched by automatically controlling the ridge current of the amplifiers. Increased power per element was achieved by making use of a simplified, efficiently cooled single emitter-based optical system.**

***Index Terms*— Coherent Combining, Semiconductor Laser Amplifiers**

I. INTRODUCTION

High power diode lasers provide the energy for many laser systems and benefit from a high electrical-to-optical efficiency. Such systems are usually based on incoherent beam combining technologies [1], and recent developments of spectrally combined diode lasers led to kW class systems suitable for direct diode laser applications such as sheet metal cutting [2]. Even if the brightness of such systems has been dramatically increased within the last decade, it is still an important challenge to increase the available power close to the diffraction limit. First demonstrations of coherent beam combining (CBC) of diode lasers at comparably high power levels (~40 W) were based on very large arrays of low power amplifiers in Master Oscillator Power Amplifiers (MOPA) configuration [3].

On the one hand, arrays of amplifiers are an elegant solution to scale the number of active devices, and the phase relation between these elements is usually more stable than for individually mounted emitters as they are exposed to approximately the same fluctuations of the temperature. On the other hand, the achievable power per amplifier of such systems is significantly lower compared to the performance of individual emitters. We are therefore currently working on MOPA-CBC architectures based on a small number of individual emitters allowing to reach comparable power levels with a significantly reduced number of elements and a smaller footprint. We investigate CBC of tapered laser amplifiers because their high power and excellent beam quality is a perfect start point for power scaling [4].

II. AMPLIFIER CHARACTERIZATION

The amplifiers were grown on GaAs substrates using MOVPE, fabricated into individual, 6 mm-long devices using i-line lithography. In the studies presented here, we made use of tapered amplifiers identical to lasers described in [5], but with the internal grating section replaced by a long (2mm) ridge waveguide section. Both facets were passivated and anti-refection coated. The amplifiers are mounted p-side up on CuW heat spreaders and C-mounts, with separate electrical contacts used in order to control the drive current of ridge and tapered section independently.

Each of our amplifier elements reaches about 6.5 W at 10 A drive-current and a heat sink temperature of 20°C. The beam quality at this operating point is slightly degraded but at

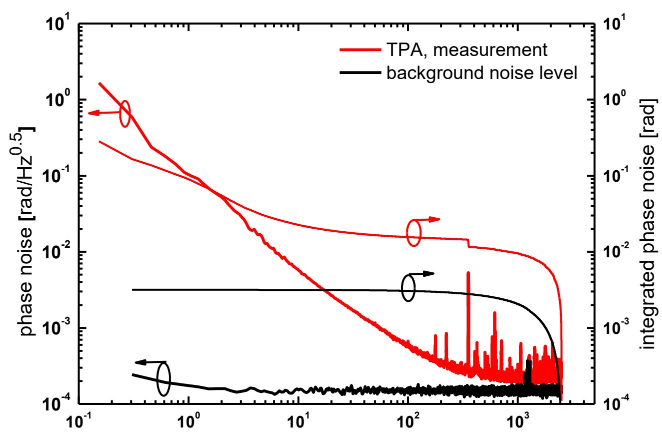

Fig 1: Measured phase noise spectrum of a tapered laser amplifier (ridge I_{rw} = 400mA, taper I_{tp} = 7A, injection P_{in} = 10 mW, heatsink T = 20°C).

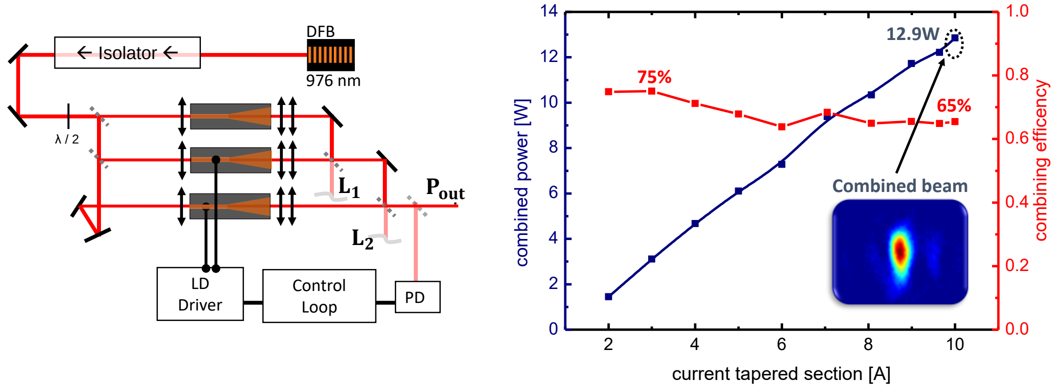

Fig. 2: Experimental setup (left), measured combined power and combining efficiency (right)

least 70% of the total power (~4.5 W) was delivered within a close to diffraction limited beam (termed the central lobe, see [4,5]). Another important property for CBC is the stability of the phase. We therefore investigated the phase noise in a Mach-Zehnder interferometer. The measured noise spectrum for a tapered laser amplifier described above is shown in figure 2. Low frequencies (f < 10 Hz) are clearly dominating the noise spectrum and are attributed to thermal fluctuations. We measured a derivation of the phase in the range of 8 rad over an observation time of 200 s. The standard deviation over one second is in the range of $\sigma(\varphi) = 0.1\,rad \approx \pi/30$, which corresponds to the integrated phase noise for f > 1 Hz at the maximum operating current. Phase fluctuations in this order of magnitude can easily be controlled by a feedback loop, so integration into a mini-array on a single heatsink is not necessary to achieve sufficient phase stability for effective coherent combination.

III. Coherent Combining in MOPA Architecture

We present MOPA-CBC of three individual amplifiers in a simple experimental setup shown in figure 2 (left), based on a multi-arm Mach-Zehnder interferometer. The MO is a narrowband distributed feedback (DFB) diode laser ($\lambda =$ 976 nm) optically isolated by Faraday isolators with a total isolation of better than 50 dB. The beam is split and recombined by standard 50:50 beam splitters in three arms.

Though the 50:50 coating is not optimal for three beams, its impact on the theoretically achievable combining efficiency is only around 3%. The phase in each arm is controlled by measuring the combined intensity with a photodiode and changing the ridge currents in the range of a few tens of mA, which has a negligible effect on the power output per amplifier. The control loop is implemented in a microcontroller and uses a sequential hill-climbing algorithm with adaptive steps. The standard deviation of the power fluctuations in the stabilized regime is below 1%.

The combined power and combining efficiency were measured for several operating points (figure 2, right). With 12.9 W coherently combined in one nearly diffraction-limited beam at the maximum current, we are able to reach higher power levels than previously demonstrated by CBC of an array of five tapered lasers [6]. The optical power was measured simultaneously at the output (combined beam, P_{out}) and the two unusable paths (combining losses, L_1 and L_2). The combining efficiency was defined as $\eta = P_{out}/(P_{out} + L_1 + L_2)$ and was 75% for low power levels and decreased to 65% at the maximum power. The relative power in the combined beam is comparable to the diffraction limited power the beam from each amplifier. The emission in the central lobe (~ 70 % of total power) has a small mismatch between beams and can efficiently combined. Emission outside the central lobe (~ 30 % of total power) shows in contrast a large mismatch between beams and leads therefore to high losses for CBC.

In summary, MOPA-CBC architectures based on individually mounted tapered laser amplifiers can deliver high power per element. The power per element is increased over that reported in our previous studies of arrays. We note however that the device design and mounting are quite different in the single emitters tested here and the arrays used in [6], making exact comparisons challenging. We note also that the single emitter based setup presented in this paper is simple and has a high potential to be integrated in small footprint modules. In future work, we will seek increased power per element via improved packaging and further improved semiconductor device design.

References

[1] T. Fan, "Laser beam combining for high-power, high-radiance sources", *IEEE J. Sel.Topics. Quantum Electron.*, vol. 11, no. 3, pp. 567-577, 2005.

[2] U. Witte, F. Schneider, C. Holly, A. Di Meo, D. Rubel, F. Boergmann, M. Traub, D. Hoffmann, S. Drovs, T. Brand and A. Unger, "kW-class direct diode laser for sheet metal cutting based on commercial pump modules", *Proc. SPIE* vol. 10086, p. 1008608-1, 2017.

[3] K. Creedon, S. Redmond, G. Smith, L. Missaggia, M. Connors, J. Kansky, T. Fan, G. Turner and A. Sanchez-Rubio, "High efficiency coherent beam combining of semiconductor optical amplifiers", *Optics Letters*, vol. 37, no. 23, p. 5006, 2012.

[4] P. Crump, J. Decker, M. Winterfeldt, J. Fricke, A. Maaßdorf, G. Erbert and G. Tränkle, "Development of high-power diode lasers with beam parameter product below 2 mm×mrad within the BRIDLE project", *Proc. SPIE* vol. 9348, p. 93480D-1, 2015.

[5] C. Fiebig, G. Blume, C. Kaspari, D. Feise, J. Fricke, M. Matalla, W. John, H. Wenzel, K. Paschke and G. Erbert, "12 W high-brightness single-frequency DBR tapered diode laser", *Electronics Letters*, vol. 44, no. 21, p. 1253, 2008.

[6] G. Schimmel, S. Janicot, M. Hanna, J. Decker, P. Crump, G. Erbert, U. Witte, M. Traub, P. Georges and G. Lucas-Leclin, "Coherent beam combining architectures for high power tapered laser arrays", *Proc. SPIE* vol. 10086, p. 100860O-1, 2017.