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Coherent beam combining of tapered amplifiers under QCW regime

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Abstract— We demonstrate the coherent beam combining of four high-brightness tapered amplifiers in quasi continuous wave operation. A maximum combined power of 22.7 W was achieved with > 64 % combining efficiency. The beam quality of the combined output was increased with regard to the individual amplifiers thanks to the inherent clean-up of the superposition, resulting in a diffraction-limited power > 20 W.

Index Terms—Semiconductor optical amplifiers, Optical interferometry, Phase measurement.

I. INTRODUCTION

COHERENT beam combining (CBC) relies on constructive interference of several beams in order to scale the power while maintaining their spatial and spectral properties. This approach has been investigated with different kind of laser sources and architectures [1]. With diode lasers, the highest combined power to date is 40 W and was achieved in a master oscillator power amplifier configuration with large arrays of single mode amplifiers [2]. Using a few high-brightness tapered amplifiers appears as a more promising approach to reduce the complexity of CBC setups and yields a higher power per element [3], [4]. Operating in pulsed, quasi continuous wave (QCW) mode results in even higher powers, as the devices are no longer limited by thermal rollover.

II. QCW OPERATION OF HIGH-BRIGHTNESS TAPERED AMPLIFIERS

The devices used in our experiment are based on the ELoD2 design, which maintains a good beam quality at high drive currents [5]. The 5-mm long amplifiers consists of a 1-mm long 4- μ m wide ridge waveguide (RW) followed by a 4-mm long tapered section (TP, 6° taper angle). The facets of the devices are passivated and anti-reflection coated ($R_1 = 0.01\%$ for RW facet and $R_2 = 0.05\%$ for TP facet). The amplifiers are individually mounted p-side up on CuW heatsinks onto C-mounts, with separate electrical contacts for the currents into the RW and TP sections. An additional CuW heat spreader is

attached to the p-side of the tapered amplifier section. The devices are fixed on individual temperature-stabilized mechanical mounts. Only the current in the tapered section of each amplifier is pulsed, with pulse lengths in the ms-range and a duty cycle of 10%, in order to limit the heat load.

The QCW output power of all four devices reaches 9 W at the operating current of 16 A, with no evidence of thermal roll-over. As typical for such tapered devices, the beam quality deteriorates at increased driving currents: the power within the central Gaussian-profile lobe is $\eta_{cl} \cong 90\%$ at $I_{tp} = 8$ A, but decreases to $\sim 75\%$ at 16 A. Furthermore, we observe a dynamic evolution of the output beam during the pulse, with a wandering astigmatism related to the heating of the device which stabilizes typically after 0.5 ms [6]. Additionally the temperature inside the amplifier rises as the current in the tapered section is turned on. Consequently the optical path length increases leading to a drift of the accumulated piston phase. The temporal evolution of the phase is nonlinear but highly reproducible and consistent between devices. It reaches 30π at 13 A during a 5 ms-long pulse (see Fig. 1).

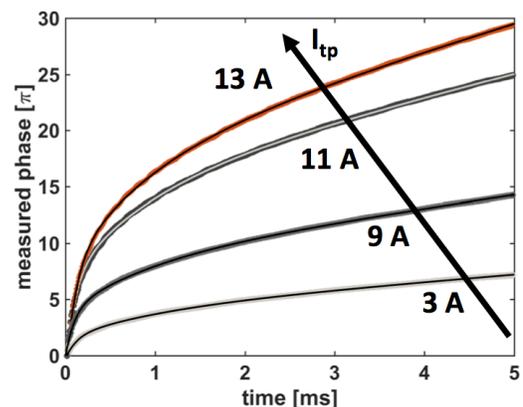


Fig. 1. Experimental piston phase drift during QCW operation of one amplifier at different currents into the tapered section.

III. COHERENT COMBINING OF FOUR TAPERED AMPLIFIERS UNDER QCW REGIME

The amplifiers are arranged in a multiarm Mach-Zehnder interferometer (Fig. 2). The seed source is a 100 mW CW narrow linewidth (< 20 MHz) DFB laser at 976 nm. After a 3-

stage Farady isolator ensuring -75 dB optical isolation, the seed beam is split using non-polarizing 50:50 beamsplitters. The power incident on each amplifier is 20 mW. The amplified beams are collimated in slow axis (SA) and fast axis (FA) individually and the astigmatism is corrected for each operating point. Identical 50:50 beamsplitters are used on the output side to recombine the beams. The combined beam is detected with a photodiode and provides the signal for phase correction (see Fig. 2).

The relative phases of the four amplified beams are corrected through a sequential hill-climbing algorithm implemented into a microcontroller. It adjusts the current into the RW of one amplifier at a time from pulse to pulse. The QCW currents into the tapered sections are manually adjusted in order to equalize the phase drifts during the pulses. Then their relative phase differences remain below $\pi/10$ during the pulse. Similarly the overlap of the amplified beams is maintained on the beamsplitters despite their time-dependent focusing. Consequently the coherent combining efficiency remains almost identical all along the pulses (see Fig. 3).

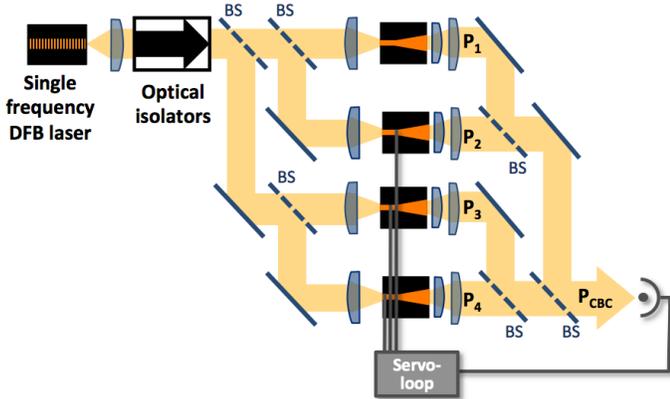


Fig. 2. Experimental setup of the CBC-interferometer with four high brightness tapered amplifiers. The amplified beams are collimated in SA and FA with a high NA aspheric lens ($f = 2.35$ mm) and a cylindrical lens ($f = 19$ mm). The phase correction is applied through the currents into the RWs.

At the maximum operating current $I_{tp} = 14.5$ A per amplifier, the QCW output power of the coherently combined output beam reaches 22.7 W (see. Fig. 3). This is the highest power reported for CBC of tapered lasers or amplifiers. The overall combining efficiency is above 70% at moderate currents and decreases to 64% at the highest driving current. It is limited by the degradation of the beam quality. The combining losses are mostly attributed to a spatial clean-up of the beam. Indeed the power content in residual high-order modes is filtered out by the coherent superposition. Then the power content in the central lobe η_{cl} of the combined beam is increased to 92%, which is significantly higher than for the individual amplifiers. The diffraction-limited power in the combined beam is thus > 20 W. Considering the central lobes only, the combining efficiency is larger than 80%. This value is limited by slight mismatches in the FA collimation and parasitic oscillations of the optical power of the amplifiers [6].

IV. CONCLUSION

We demonstrate a total power of 22.7 W from the coherent beam combining of four tapered amplifiers under QCW operation. The power in the central lobe of the combined beam is larger than 20 W. This is the highest power in a diffraction-limited beam ever reported from a single-frequency system based on tapered lasers or amplifiers. Further increase of the diffraction-limited output power seems realistic with improved semiconductor devices and good thermal management, while maintaining a comparatively simple and compact setup. This demonstrates the potential of our combining approach for demanding applications requiring excellent beam quality and spectral purity.

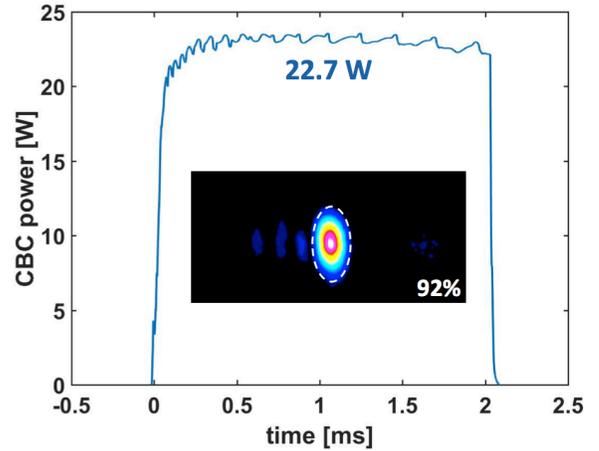


Fig. 3. Experimental pulse shape at the output of the CBC interferometer at 14.5 A in the tapered sections (average over 1 mn). (inset) Waist of the combined beam and power content in the central lobe. Bias conditions: $P_{in} = 20$ mW, $I_{rw} = 300$ -400 mA, $T = 25^\circ\text{C}$, $\Delta t_{qcw} = 2$ ms, 10 % duty cycle

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