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Scalable structure of coherent polarization beam combining based on tapered diode laser amplifiers

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HIGHLIGHTS

- A scalable multi-stage coherent polarization beam combining is introduced.
- Four amplifiers are coherent polarization beam combined using this novel method.
- An output of 6.9 W is obtained, and brightness is obtained by a factor of 3.3.

ARTICLE INFO

Keywords:
Tapered diode laser amplifier
Coherent beam combining
High brightness
Actively control phase variation

ABSTRACT

We develop a scalable multi-stage beam combining system based on the superposition of four tapered diode laser amplifiers using the coherent polarization beam combining. By employing the combination of master oscillator power amplification and active phase control of each amplifier, a stable output power of 6.9 W is obtained with a nearly diffraction-limited beam quality. The combining efficiency is 72%, and the brightness is improved by a factor of 3.3 compared to that of a single amplifier. Our system provides a new solution to obtain a high-coherence and high-brightness diode laser beam.

1. Introduction

High power diode lasers have gained a good reputation as compactness, long lifetime, and relatively low cost [1]. However, due to the low brightness and coherence, these devices are still not suitable for many applications, such as nonlinear frequency conversion, single-mode fiber coupled operation, and free-space optical communication [2–5]. The two most common approaches for scaling the brightness of the diode laser source are wavelength beam combining (WBC) and coherent beam combining (CBC). In WBC, however, all beamlets are transformed into a single beam which spatially overlaps in both the near and the far field. This approach can achieve a high spatial brightness beam at the expense of spectral purity [6]. In contrast, CBC not only combines individual beamlets to a high brightness output but also maintains a pure spectrum, which can fulfill many applications mentioned above. However, although the passive CBC of diode lasers arrays in various external cavity configurations has been demonstrated, this method can not lead to a significant increase of the brightness due to undesired sidelobes in the far field [6–8]. The active CBC usually controls the phase of several amplifiers seeded by a seed laser, which can coherently combine the beam both in the near and the far field. Impressive results for the active CBC were respectively reported in [9] and [10]. Kevin J. Creedon et al. employed a distributed feedback (DFB) diode laser to seed a 47-element array of angled-facet slab-coupled optical waveguide amplifiers, which achieved a diffraction-limited beam with an output power of 40 W. P. Albrodt et al. utilized a MOPA architecture to coherently combine three high-brightness amplifiers seeded by a single-frequency laser at λ = 976 nm, and the maximal output power of 12.9 W was obtained. In addition to the above schemes, coherent polarization beam combining (CPBC), due to its coaxially combining beamlets and scalable structure, can reduce undesired sidelobes; therefore, it becomes a promising candidate for the coherent combining. In CPBC, through the active phase and polarization control, multi-beamlets can be coherently combined by a cascaded

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combining configuration. In the past years, the proof of concept of CPBC has been successfully demonstrated in the coherent combining of fiber lasers, because the fiber laser can easily realize a single-mode output and a controllable phase at the high-power level [11]. P.F. Ma et al. have employed the CPBC system to coherently combine eight fiber lasers, which validated its potential in scaling a large number of beams [12]. Nevertheless, due to the deficiency of limited output power of single-mode diode laser and the difficulty of phase locking, only a few research groups applied CPBC in the diode laser systems [13]. Nowadays, commercially available tapered diode amplifiers (TDAs) can provide high output power with a pure spatial mode, when operating in a master oscillator power amplifier (MOPA) configuration [14,15]. We investigate CPBC based on TDAs since their high output power and near diffraction-limited beam quality are beneficial for the coherent beam combining.

In the following, we report the experimental demonstration of CPBC by combining four TDAs operating in a MOPA configuration. As a result, all beams are coaxially combined, and the brightness of the combined beam is improved by a factor of 3.3 compared with the brightness of individual TDAs. This work provides a new solution to realize the coherent beam combining of diode lasers. Although the obtained output power is lower than references [9] and [10], with the development of commercially available TPAs and the expansion of the combining scale, this technology could reach similar output power.

2. Experimental setup

The experimental setup is shown in Fig. 1. Single-passed TDAs (DILAS 0976-2000) used in the experiment consist of a 0.5 mm long ridge waveguide (RW) section and a 3.5 mm long tapered section (taper angle $\alpha_T = 4°$). Both facets are anti-reflection (AR) coated with a reflectance below 0.01%. When TDAs are injected by single-mode seed lasers, the extracted amplified optical power is around 2.4 W at a driving current of 4.0 A. Correspondingly, a beam quality of $M_{FA}^2 = 1.1$ in the fast axis (FA) and $M_{SA}^2 = 1.7$ in the slow axis (SA) is obtained, and the output brightness is 134.7 MW·cm^{-2}·sr^{-1} which is calculated by

$$B = \frac{P}{\lambda_0^2 M_{FA}^2 M_{SA}^2}, \tag{1}$$

where λ_0 is the operating wavelength of TDAs, M_{FA}^2 and M_{SA}^2 are the beam propagation parameter in FA and SA, respectively [16]. To control the operating temperature, TDAs are mounted on the specifically designed copper heatsinks attached with Peltier coolers below, which can maintain the operating temperature of TDAs at 20℃ constantly.

The seed laser source, as a master oscillator, is a commercially available narrowband ($\Delta\lambda$ = 2 MHz) DFB diode laser (λ = 976 nm) with a single-mode output power of 100 mW. An aspherical lens (f = 5 mm) is used to collimate the beam emitted from the seed laser source. An optical isolator (isolation > 50 dB) is positioned subsequently after the seed laser source to prevent the disturbance from the backward beam. Because TDAs are polarization-dependent devices, a half-wave plate (HWP) is inserted in the beam path to enable a perfect match between the polarization state of the seed laser beam and TDAs.

A diffractive optical element (DOE) is then utilized to split the seed laser beam into four beamlets. A Dammann grating, designed for splitting beam and etched on the fused silica substrate, is a one-dimensional equal-power multiple-beam splitter, whose period and angular spacing for the beam splitting are 8.15 µm and 4.7°, respectively. This Dammann grating is AR-coated, and the diffractive efficiency is approximately 80%. The power distribution of each diffractive order is measured by a slit, with 100 mW seed beam incidence, and an average optical power of 20 mW on each diffractive order is obtained. Seed beamlets are directionally controlled by reflectors and coupled into four identical TDAs by aspherical lenses with a focal length of 8 mm. The coupling efficiency is estimated to be 75%, which is sufficient for seeding each TDA. Due to the astigmatism in both the FA and the SA of TDAs, a group of FA collimators (f = 0.9 mm) and SA collimators (f = 20 mm) are applied to collimate each amplified beam. Then, a cascaded configuration of two combining stages is implemented to combine four amplified beams.

The schematic of CPBC is shown in Fig. 2. In the first stage, HWP_1 and HWP_2, whose optical axes are oriented at 45°, are inserted in $Channel_2$ and $Channel_4$ to rotate the polarization state of both TDA_2 and TDA_4 from horizontal directions to vertical directions. Then, the polarization states of paired beamlets are orthogonal to each other when being combined by polarizing beam splitters (PBS_1 and PBS_2). The principle of two beamlets polarization combining can be explained by the addition of two Jones vectors, J_a and J_b [11],

$$\begin{aligned} J = J_a + J_b &= \begin{bmatrix} a \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} \exp(i\Delta\phi) \\ &= \begin{bmatrix} a \\ b\exp(i\Delta\phi) \end{bmatrix}, \end{aligned} \tag{2}$$

where J is a polarization vector, a and b are amplitudes of laser beamlets, $\Delta\varphi$ is the relative phase between two orthogonal components. With an undefined $\Delta\varphi$, the polarization state of the combined beam is a random mixture of two orthogonal polarization states, which limits the further polarization combining. Only when $\Delta\varphi$ is well-defined and set to $n\pi$ (n is an integer), the polarization combining of these two pairs of orthogonally polarized beamlets becomes a coherent superposition, which can produce two new and pure linear-polarized laser beams. Meanwhile, the azimuth angle θ of the new laser beam, defined as the

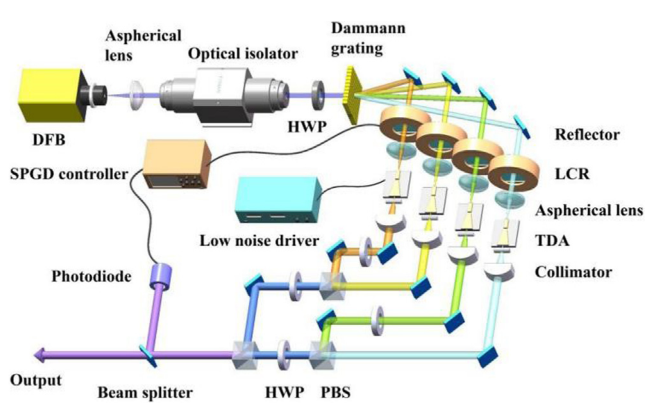

Fig. 1. Schematic diagram of CPBC experimental setup of four TDAs in a MOPA configuration.

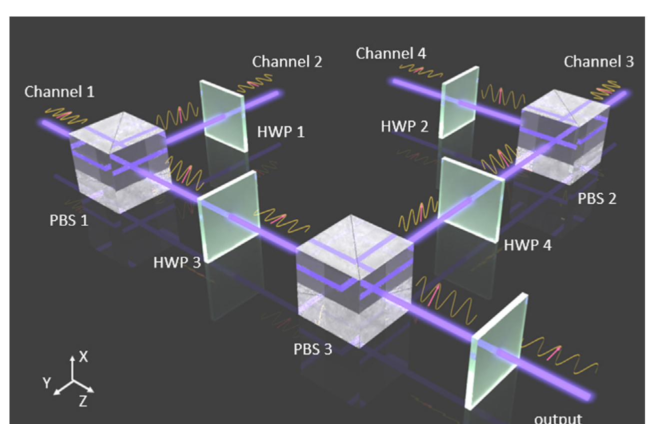

Fig. 2. Schematic drawing of two-stage CPBC mechanism. Pink arrows mean the polarization direction of laser beams. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

polarization direction relative to the x-axis, depends on the ratio of b to a, shown as follows,

$$\theta = \pm\arctan(b/a). \tag{3}$$

When lengths of J_a and J_b are equal ($a = b$), the azimuth angle θ of the combined beam is 45°. Otherwise, the azimuth angle θ will deviate from 45°, which can cause some loss in the further polarization combining.

In the second stage, these two new linear-polarized laser beams pass through HWP_3 and HWP_4, respectively oriented at 22.5° and 67.5°, and the polarization state of these two beams are then rotated to 0° and 90° relative to the x-axis, respectively. As the principle mentioned above, the two combined beams are further superposed and create a new linear-polarized laser beam when being combined by PBS_3.

In the coherent combining, the variation of optical path lengths can lead to a random phase distribution, which brings difficulties to the coherent combining of TDAs. Therefore, precise and fast control of the relative phase of each laser beam is required for coherent beam combining. In our case, we employ variable liquid crystal retarders (LCRs) to actively control the relative phase variations and lock the phase difference. When SA of LCRs is oriented at 45° relative to the polarization vector of the laser beam, by applying a voltage from 0 V to 25 V, an varying phase control in the full-wave range is realized. In order to control the phase difference $\Delta\varphi$ to $n\pi$ constantly, a small percentage ($< 1\%$) of the combined beam is split by a beam splitter and sent to a photodiode for beam detecting. The FPGA-based stochastic parallel gradient descent (SPGD) algorithm controller is used to dither the phase of each TDA by changing the voltage of LCRs. With the control loop closed, a stable far-field beam spot and a maximum output power are obtained.

3. Experimental results

We investigate the beam quality M^2 of the final output beam by increasing the current. The results are shown in Fig. 3. M^2 values are measured using the 2nd moment beam diameters [17].

At the driving current of 4 A, the M^2 factors of the output beam are ~1.15 and ~1.42 for M^2_{FA} and M^2_{SA}, respectively. As a comparison, beam shapes and intensity distributions of the seed beam and final output beam are inserted in Fig. 3 with the normalized intensity. We can see that the SA beam quality of the final output beam (driving

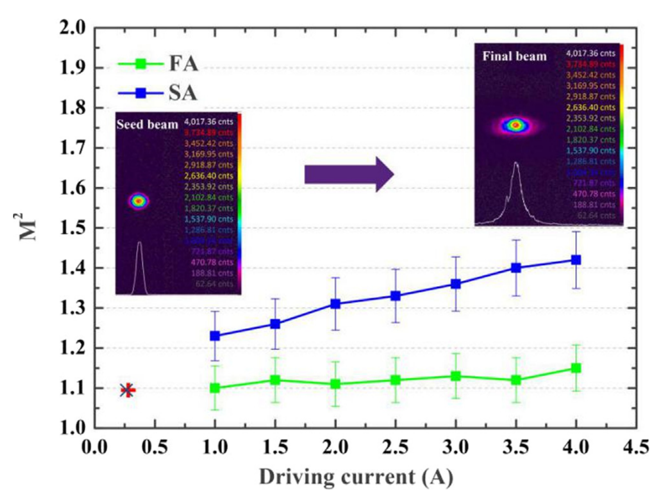

Fig. 3. M^2 of the final output beam as a function of the driving current. Insets are beam shapes and intensity distributions of the seed beam (at the maximum power) and final output beam (at the driving current of 4 A). The red plus sign and blue multiplication sign respectively means FA and SA beam quality of the seed beam. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

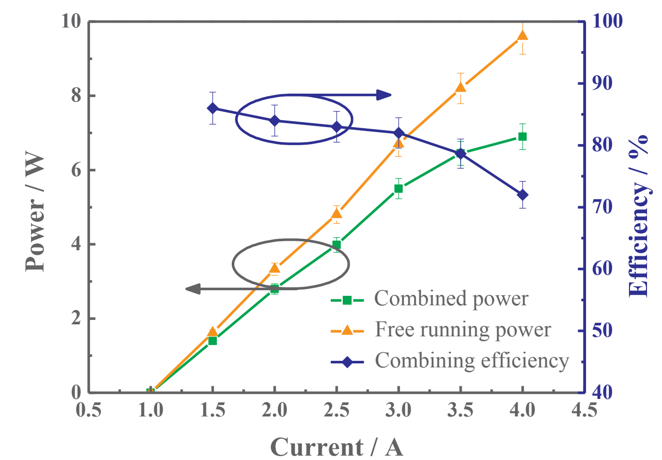

Fig. 4. Output power and combining efficiency as a function of driving current.

current ~ 4 A) is lower than that of the seed beam; while it is significantly improved compared with that of each amplified beam yielded from TDAs ($M^2_{SA} \approx 1.7$). The improvement of SA beam quality confirms the constructive interference. Thanks to the vertical waveguide structure of TDAs, FA beam quality of the final output beam maintains the eigenmode output through the whole process. It is noted that there does not exist side lobes in the inset, which proves that most of the beams are coaxially combined.

At the cooling temperature of 20 °C and CW operating mode, a final output power of 6.9 W is obtained when TDAs are injected with a driving current of 4 A. According to M^2 values measured above, the brightness is scaled to 443.6 $MW{\cdot}cm^{-2}{\cdot}sr^{-1}$ by a factor of 3.3. The corresponding combining efficiency of the whole system is approximately 72%, which is defined as

$$\eta = \frac{P_{out}}{\sum P_{TDA,i}}, \tag{4}$$

where P_{out} is the final output power of the combined beam, and $P_{TDA,i}$ is the amplified power of TDA at the driving current of 4.0 A. The P-I-V characteristics of the whole CPBC system are depicted in Fig. 4.

4. Analysis

The main loss mechanism can be explained as follows:

1. TDAs slightly produce multimode beams at the high-power range, leading to a central lobe power content of 80% at 4.0 A. However, LCRs cannot compensate for any higher order multiple modes oscillating in TDAs since it can only introduce a single phase shift, which leads to the loss at the beam combining. That is also why the power cannot increase linearly with a growing current.
2. As mentioned above, the average amplified optical power of TDAs is 2.4 W. Actually, there are some power differences between these devices, which makes the azimuth angle θ of the combined beam in the first stage deviate from 45°. It introduces the loss in the second stage combining, which can be easily explained by Eqs. (2) and (3) [11].
3. Because of the state-of-the-art coating technology, PBS has a 96% transmittance for the transmitted beam and a 99% reflectance for the reflected beam, equal to an average loss of 2.5%, which results in a total power loss of 5% in two stages of combining. This loss could be increased with more combining stages.

This CPBC system demonstrates the high stability of both the constructive interference and the output power under environmental perturbations. The observed output power is stable for hours of operation with fluctuation of less than 5%.

To prove the ability of accommodating power imbalance of individual TDAs in the CPBC structure, we intentionally enlarge the power difference between each individual TDAs randomly using separate low noise drivers. The output power of the final combined beam slightly fluctuates around 6.9 W when the power difference is set to below 200 mW. This power difference of 200 mW contains the inherent power variations of TDAs. The power loss caused by this part of power difference has been discussed before. In addition to this intrinsic power variations, the multi-channel input can offset the influence of the enlarged power difference. This result indicates that the CPBC structure is insensitive to the small power imbalance of participant laser beams.

The method of the coherent combining presented in [10,18], is simpler than our method. Because currents in RW (I_{rw}) and tapered section (I_{tp}) can be controlled independently, the phase of TDAs can be controlled by varying I_{tp} without the impact on the optical power. However, this way requires a high manufacturing technology of TDAs. Limited by the availability of the independently controlled TDAs, we use LCRs to control the phase of TDAs, and all elements are commercially available, which can increase the stabilization and decrease manufacturing costs.

5. Conclusion

We have demonstrated a CPBC structure by combining four TDAs operating in a MOPA configuration. With the active phase control of individual TDAs, four TDAs are coaxially combined in both the near and the far field. At the driving current of 4.0 A, a stable output power of 6.9 W has been extracted from this system with a combining efficiency of 72%. The brightness is significantly improved by a factor of 3.3 compared with the brightness of individual TDAs. It is worthwhile noting that this structure of CPBC is scalable, and a purely symmetric cascaded configuration with multi-stage is promising to realize a higher power and higher brightness coherent diode laser beam. However, multimode beams produced by TDAs at the high-power range is the primary limiting factor of this approach going to a higher power and higher brightness. Increasing the single-mode output of TDAs and reducing the loss caused by optical elements are important for this approach. Further demonstration of the coherent combining with more TDAs is in progress.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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