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Coherent Polarization Locking of Multimode Beams in a Diode Bar

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ABSTRACT

We demonstrate coherent polarization locking of multimode beams from four broad area emitters in a diode bar. The beams are overlapped into single output by using walk-off crystals and waveplates while their phases are locked via polarization discrimination. Coherent locking of multimode beams enabled power scaling of coherent diode output while retaining beam quality of single emitter. We obtained power of 7.2 W with M^2 of 1.5 x 11.5 from a 980 nm diode laser. This corresponds to brightness improvement of more than an order of magnitude.

Keywords: Laser beam combining, Diode laser arrays

1. INTRODUCTION

Diode lasers are important for many applications such as optical pumping, communication, medical, and military. A typical single broad area laser diode is able to generate optical power of more than 2 W. Such lasers have been used to pump high power femtosecond lasers such as Cr: and Yb: doped crystals¹⁻³. To achieve multi-Watts femtosecond output, several diode emitters are usually employed to pump the crystal simultaneously either through two sides pumping, polarization multiplexing or combination of both.

Alternatively, tens of Watts of power can be produced by single diode bar. A diode bar consists of several broad area emitters arranged side by side with pitch spacing of ~ 500 μm . However, the beam quality of diode bar in the slow axis ($M^2 > 1000$) degrades significantly compared to that of a single emitter ($M^2 \sim 15$), render it impractical to be utilized for tight pumping. Considerable efforts have been put to solve the problem, which include wavelength and coherent combining.

In wavelength combining⁴, emitters are operating at different wavelengths and then they are spatially combined by using grating. For coherent combining, emitters have to be in the same wavelength instead. Additionally, they need to be locked in phase. Maintaining the phase locking can be quite challenging since it requires sub wavelength precision. Passive coherent combining mitigates the issue by utilizing self phase-lock mechanism without the need of external control. In diode laser, self phase-lock mechanisms have been achieved by using evanescent wave coupling⁵, Talbot cavity⁶⁻⁷, and coherent polarization locking⁸.

Recently, high power multi-Watts coherent output have been demonstrated by using Talbot cavity⁷. Talbot cavity uses Talbot imaging condition to couple the phases of the emitters. However, the output lasers consist of multi-lobes profile in far field, which might not be ideal for certain applications that require single beam focus spot.

On the other hand, single beam coherent output can be achieved by coherent polarization locking. Previously, we reported coherent polarization locking of diode emitters in near-diffraction limited beam⁸. However, maximum power is limited to 1 W. In this paper, we show that the same phase locking mechanism can be applied to multimode beam by using novel combiner configuration in an imaging cavity. As the result, the coherent power is increased to more than seven times with better power stability.

2. COHERENT POLARIZATION LOCKING OF MULTIMODE BEAMS

2.1 Basic principle

Figure 1. Schematic of coherent polarization locking of two gain mediums. The polarizing beam splitter can be replaced by YVO₄ crystal for combining two orthogonally polarized lights (e-ray and o-ray for YVO₄).

Figure 1 shows the schematic of coherent polarization locking of two gain mediums. When two orthogonally polarized lights are combined, the resultant polarization will depend on their relative phase difference $\Delta\phi$. The linear polarizer placed in the cavity will introduce polarization loss discrimination of $[1 - \cos^2(\Delta\phi)]$. The cavity will therefore favor the condition when their phase difference are locked at $\Delta\phi = 0$ or $\Delta\phi = \pi$. For array of gain mediums, the role of polarizing beam splitter (PBS) as the spatial combiner can be substituted by the walk-off crystal (e.g. YVO₄).

Figure 2. Spectral characteristic of coherent polarization locking output.

Coherent superposition of two orthogonally polarized lights is possible only if they share the same wavelength. For individual cavity with length L_i , the spectrum of the laser consists of periodic peaks with free spectral range (FSR) of $c/2L_i$. When the lights with different cavity length of ΔL are combined, the common longitudinal modes shared by both

cavities will have $FSR = c/2\Delta L$. The magnitude of ΔL has to be carefully considered in order to ensure sufficient number of common longitudinal modes to be found within the laser gain bandwidth $\Delta\nu_o$, as illustrated in Figure 2.

Another requirement for coherent locking is the perfect overlap of the spatial modes of the beams. For example, a TEM_{xy} beam can only be coherently superposed with another TEM_{xy} beam. However, different emitters in single diode bar may possess different modal components in their multimode beam profile along the slow axis⁹⁻¹⁰. Yet, we show that combining of multimode beams is feasible by coherent polarization locking. We explain the combining mechanism by simultaneous superposition of several transverse modes of the same order that achieve minimum loss in the cavity. These modes will dominate and suppress other competing modes. Similar multimode combining has also been reported for diode pumped solid state laser¹¹.

2.2 Spatial combiner

The concept of coherent polarization locking is extended to four emitters in a diode bar. Figure 3 shows the design of the spatial combiner that consists of walk-off crystals and half waveplates (HWP). All walk-off crystals are 4.95 mm YVO_4 crystals with optic axis cut at 45° to obtain 500 μm walk-off displacements. The HWPs are 1 mm Quartz zero order waveplates.

Figure 3. Schematic of the spatial combiner that consists of walk-off crystals and half waveplates.

The first HWP is placed close enough to the diode entrants before the multimode beams from adjacent emitters diverge and overlap in space. From the figure, it can be traced that the relative path lengths of L_i ($i = 1, 2, 4$) with respect to L_3 (the emitter with shortest cavity length) are given by Eq. (1)-(3).

$$L_1 - L_3 = (n - 1)t. \quad (1)$$

$$L_2 - L_3 = (n - 1)t + (n_e - n_o)d. \quad (2)$$

$$L_4 - L_3 = (n_e - n_o)d. \quad (3)$$

n is the HWP refractive index (1.54), t is the thickness of HWP (1 mm), n_e is the extraordinary refractive index at 45° (2.06), n_o is the ordinary refractive index (1.96), and d is the thickness of the crystal (4.95 mm).

2.3 Resonator design

To support the multimode beam profile in the slow axis, we use an imaging cavity which consists of lenses that form an image plane at the output coupler (OC). Such arrangement is shown to be robust against cavity misalignment¹⁰. In fast axis direction, we reduced the smile effect by implementing a retro-reflection feedback configuration. As illustrated in Figure 4, the retro-feedback together with the beam collimation setup is able to reflect incoming lights back to its sources regardless of the heights from which the beams are emitted. The retro-reflector configuration consists of a focusing lens and a plane mirror located at a focal distance.

Figure 4. Illustration of smile effect compensation by using retro-reflection configuration

3. EXPERIMENT

Schematic of the experimental setup is shown in Figure 5. The diode laser is 980 nm anti-reflection (AR) coated diode bar from Jenoptik GmbH, with total of 19 emitters at a 500 μm pitch. The size of each emitter is 1 μm by 100 μm in surface area, with average M^2 of 1.5 by 13. To collimate the beam, the diode is equipped with fast axis collimator (FAC) with focal length of $f_{\text{FAC}} = 0.9$ mm and slow axis collimator (SAC) with focal length of $f_{\text{SAC}} = 1.81$ mm.

Figure 5. Diagram of the experimental setup as viewed from the top.

The cavity consists of the diode bar, series of polarization optics, two cylindrical lenses in the slow axis, one cylindrical lens in the fast axis, and the OC with transmission of 80%. Beams from the emitters are spatially combined

by the spatial combiner. The combined beam is then focused by a 100-mm cylindrical lens (slow axis) to pass through a slit that ensures single beam output. The resultant polarization will be in 45° linearly polarized if all the emitters were coherently locked. A HWP rotated at 22.5° with PBS are used to introduce the polarization selective loss that favors the coherent locking. The beam is finally focused by 100-mm lens (slow) and 50-mm lens (fast), to form the image plane at the OC and the retro-reflector configuration.

4. RESULTS

At pump current of 56 A, the total power emitted from the AR coated diode laser is 4.3 W. By coherent polarization locking, the power is increased to 7.2 W at the same pump level. The beam profile of the combined laser is similar to that of a single emitter with M^2 of 1.5×11.5 . The beam quality in the fast axis direction is slightly larger than diffraction limited beam due to the misalignment of the collimators. In the slow axis, the beam quality shows slight improvement over individual emitters. The beam characteristic in the slow axis is shown in Figure 6 (a) and (b). Without spatial combining, emission from four emitters has $M^2_{slow} = 224$. Thus, coherent polarization locking has improved the beam quality by more than 20 times.

Figure 6. Beam measurement in the slow axis at maximum power of 7.2 W. (a) Caustic measurement in the slow axis with $\omega_o = 227 \mu\text{m}$ and $M^2 = 11.5$. (b) Far field pattern of the output beam in the slow axis at the minimum waist.

The spectrum of the coherent output is shown in Figure 7. It consists of two big envelopes that contain 1 nm periodic spectral lines. The two envelopes are due to the inherent profile of the diode laser, which exhibit similar two isolated spectral peaks. The 1 nm periodic lines are caused by the relative path differences among the emitters when traversing through the walk-off crystals and HWPs. The existence of several lines for coherent polarization locking enhances the stability of the combining. At maximum output power, fluctuation of the power is observed to be less than 1.5%.

Figure 7. Output spectrum at maximum power of 7.2 W.

5. CONCLUSION

In summary, we have demonstrated coherent polarization locking of diode lasers in multimode beams. Coherent locking of multimode beams allows power scaling of the coherent output while retaining the beams quality of individual emitter. In 980 nm diode bar, we obtained 7.2 W with M^2 of 1.5 x 11.5. Our future work will continue on combining high power diode lasers to be used in applications that require high brightness coherent source.

6. ACKNOWLEDGEMENT

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