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2012

Tan, L. H., Chua, C. F., & Phua, P. B. (2012). Preserving a diffraction-limited beam in Ho:YAG laser using coherent polarization locking. *Optics Letters*, 37(22), 4621-4623.

<https://hdl.handle.net/10356/99336>

<https://doi.org/10.1364/OL.37.004621>

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Preserving a diffraction-limited beam in Ho:YAG laser using coherent polarization locking

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Received September 20, 2012; accepted October 8, 2012;
posted October 10, 2012 (Doc. ID 176537); published November 6, 2012

We overcome several thermal issues present in Ho:YAG lasers by distributing the gain over a larger volume and achieve a diffraction-limited beam using coherent polarization locking. Increased single-pass absorption, suppression of output power saturation, and improvement in beam quality were shown using the coherent polarization locking technique as compared to a conventional Ho:YAG laser cavity with the same pump and cavity configuration. Ten watts of CW Ho:YAG laser power was generated with >96% coherent combining efficiency. © 2012 Optical Society of America

OCIS codes: 140.3070, 140.3298, 140.6810.

Ho:YAG lasers are quasi-three-level systems, emitting at a wavelength of 2.09 μm . Holmium lasers have attractive medical and remote sensing applications, and they are also suitable pump sources for nonlinear frequency conversion to generate midinfrared radiation. In contrast to a four-level laser system, a quasi-three-level laser system has inherent thermal effects and its laser characteristics are strongly temperature dependent [1]. This makes its high-power operation difficult. In addition, Ho:YAG experiences reabsorption loss at the laser wavelength due to the thermally populated lower laser level. This internal power loss in the gain medium creates an additional heat load in the crystal. This leads to other common thermal degradation effects, such as thermal lensing, bifocusing, and induced birefringence. It is also known that Ho:YAG laser operation with high doping concentration can cause deleterious processes such as Ho:Ho upconversion [2], which limits the laser efficiency. Consequently, a lower doping concentration is more favorable. However, ground state depletion in low-doping crystal saturates the pump absorption under high-power pumping. Therefore, there is a strong motivation to achieve high-power laser operation with reduced thermal issues in Ho:YAG. In this Letter, we investigate the use of coherent beam combining to mitigate the thermal-related issues and upconversion loss in Ho:YAG lasers.

Coherent beam combining [3] is a promising approach for power scaling of lasers while maintaining good beam quality and preserving the coherent properties in lasers. Studies on coherent beam combining of laser diode arrays have been done for decades. Both active [4,5] and passive [6] phase locking mechanisms were demonstrated to improve the brightness of diode. Similar combining was also demonstrated for solid state lasers [7,8]. Coherent polarization locking [6,7] is one of the techniques to achieve passive coherent beam combining with near-perfect combining efficiency. Several beams in a cavity are coherently locked in phase to achieve a polarization that experiences minimal loss in the cavity. In our experiment, we use coherent polarization locking to combine several low-doping Ho:YAG lasers that are

pumped with lower powers to overcome the thermal-optics effects and upconversion loss, while achieving power scaling of the laser.

The polarization locking technique is performed on a Ho:YAG laser operating in the CW regime. The schematic of the coherent polarization locked Ho:YAG laser is shown in Fig. 1. The system is pumped by a single linearly polarized Tm: fiber laser emitting at 1.908 μm , corresponding to the peak absorption wavelength of Ho:YAG.

The fiber output is split into two separate parallel pump beams using HWP1, TFP1, and FM1. By rotating HWP1, the splitting ratio can be changed, thus manipulating the gain of each individual path. These two pump beams propagated with a spatial separation of ~ 10 mm. A 250 mm focal length lens placed before HWP1 focused both beams to a pump beam diameter of ~ 800 μm inside a single Ho:YAG slab (doping concentration of 0.75 at. %). The Ho:YAG gain medium was 10 mm in length and was cooled at 20°C. The input surface was anti-reflective (AR)-coated for the pump wavelength and highly-reflective (HR)-coated for the laser wavelength. The coherent polarization locking cavity was formed by this HR-coated surface of the gain medium and a flat output coupler with $R = 70\%$. The other surface of the gain medium was AR-coated for both pump and laser wavelengths. A dichroic mirror, highly reflective at the pump wavelength and highly transmissive at the laser wavelength, was placed after the Ho:YAG slab, allowing a double-pass pump configuration. The beams from Arm A and Arm B were spatially combined using TFP2 and FM2. TFP2 also forced the polarization of the lasing beam in Arm A and Arm B to oscillate in s polarization and p polarization, respectively. A 300 mm focal length lens was placed inside the cavity to provide a stable cavity configuration and good mode matching of the laser beam with the incident pump beam. Coherent polarization locking was achieved by HWP2 and TFP3 within the cavity. The polarization of the coherent combined beam after TFP2 was rotated by HWP2 to horizontal polarization. As shown by Phua and Lim [7], optimum combining efficiency could be achieved for any arbitrary power ratio between Arm A and Arm B by simply rotating HWP2.

Fig. 1. (Color online) Schematic setup of coherent polarization locking Ho:YAG laser. HWP, half-wave plate; TFP, thin film polarizer; FM, folding mirror; DM, dichroic mirror; OC, output coupler.

Consequently, it is possible to optimize the setup for maximum laser output power and combining efficiency by rotating both HWP1 and HWP2.

This same experimental setup also allowed laser oscillation in only one of the arms. This was achieved by having the pump power incident onto the gain medium at a single spot (a single arm) instead of splitting the pump laser into two. This allowed us to compare the laser performance and output beam profile for two different laser configurations, coherent combined laser and single arm laser with similar pump spot diameter and cavity mode diameter. Figure 2 shows the single-pass absorbed power for a single spot (single arm laser) and double spots (coherent combined laser) pump configuration with respect to pump power. Saturation in the pump absorption was observed in the single spot pump configuration when the pump power exceeded ~ 20 W, whereas the double spots pump exhibited a linear behavior. This shows that by splitting the pump source into separate beams and focusing them onto different locations in the same crystal, the total absorbed pump power increases, thus increasing the pumping efficiency and gain of the entire laser system. In essence, this duo-pumping spot configuration doubles the effective pump area, which aids in mitigating the thermal issues of increasing the power in a single pump spot area by twice the amount. Compared to a conventional end-pumping configuration, increasing the

pump mode size requires the laser mode size to increase accordingly for the same overlapping efficiency. This leads to the need for a longer cavity length. In contrast, coherent polarization locking allows the effective pump area to increase, while maintaining a compact and short laser cavity.

Figure 3 shows the output laser power from the single arm laser and coherent combined laser configuration. The curve of the single arm laser shows a rollover in the output power at our highest available pump power. The roll-off in the output power was due to the saturation of absorption coefficient and strong thermal lensing [9]. This limits the power scaling of this laser configuration. In the case of a coherent combined laser, the maximum output power produced was ~ 10 W, with no observable output power saturation even at our maximum available pump power. Slope efficiency of the coherent combined laser was close to that of the single arm laser. The pump threshold of the coherent combined laser was approximately twice that of the single arm laser due to the doubling of the pump spot area. In contrast with the single arm laser, we prevented the saturation of the laser output by the coherent polarization locking technique. Saturation of absorption coefficient was also avoided and thermal lensing was weaker in the coherent combined laser.

Using the same experimental setup, we measured the output power with respect to pump power with a pump power ratio of $\sim 1:1$. Figure 4 shows the generated output

Fig. 2. (Color online) Single-pass absorbed power for a single laser spot (Arm A alone) and coherently combined laser (Arm A and B).

Fig. 3. (Color online) Laser output power of single arm laser and coherent combined laser.

Fig. 4. (Color online) Output power [red (lower) curve] and combining efficiency [blue (upper) curve] for coherent combined laser with respect to pump power. Insert shows the output power of the independent Arm A and B, respectively.

power from the coherent combined laser. Output power for independent Arm A and B, measured with the slow axis of HWP2 rotated to 0° and 45° , respectively, is also shown in the insert in Fig. 4. When the slow axis of HWP2 rotates to 0° with respect to p polarization, Arm A oscillates, while Arm B experiences high loss on TFP3. Similarly, by rotating the slow axis of HWP2 to 45° , Arm B oscillates. The total output power generated by the independent Arm A and B was taken as a reference for incoherent combined power. This was compared with the output power from the coherent combined laser to calculate the coherent combining efficiency. We achieved combining efficiency of $>96\%$ at maximum output power.

The output beam profile of the coherently combined laser and single arm laser were taken using a Spiricon Pyrocam III beam profiler. Figure 5 shows the far-field beam profile of the output beam from the two laser configurations. An M^2 value of ~ 1.1 was achieved at maximum power for the coherent combined laser, whereas a beam quality of $M^2 > 2$ was measured for the single arm laser. Therefore, we have shown that the beam quality of the output laser is preserved to a near-diffraction-limited beam through coherent polarization locking. The improvement of the beam quality is mainly due to the reduction in the thermal effects experience in a single laser arm and the requirement to achieve coherent polarization locking. Any higher order mode in one arm needs the same higher order mode in the other arm to survive and oscillate in the coherent polarization locking configuration. This hinders the survival of higher order modes in the cavity, thus leading to the improvement of the beam quality.

We optimized the coherent combining efficiency by rotating HWP1 and HWP2, respectively, where it changed the total pump power, pump ratio, and gain of Arm A and B. With a total pump power of 30.6 W, we obtained 9.6 W of coherently combined laser power, with individual arm laser power of 6 and 3.6 W, respectively. This

Fig. 5. (Color online) Far-field beam profile of (a) coherent combined laser and (b) single arm laser at maximum output power.

corresponds to a near-perfect coherent combining efficiency. The output power of the combined laser was observed to be stable with power fluctuation of $<0.5\%$ over a period of 5 min. It should be noted that the optimum combining output achieved was not with a 1:1 power ratio, due to the imbalance in pump ratio and gain, but with an arbitrary ratio determined empirically in our experiment. This is an additional advantage of coherent polarization locking where it allows for the combination of lasers with different power outputs with near-perfect combining efficiency. In contrast, coherent combining in a Vernier-Michelson-type cavity [8] requires the individual laser output power ratio to be fixed based on the beam splitter ratio, in order to achieve near-perfect coherent combining efficiency.

In conclusion, we had preserved the diffraction-limited beam quality in CW Ho:YAG laser using the coherent polarization locking technique by overcoming the thermal issues related to Ho:YAG. The increase in single-pass absorption, suppression of laser saturation, and improvement of beam quality as compared to the output of a reference setup are strong evidence showing that the thermal-optics effects are mitigated.

The authors thank Lindy Chia and Jonathan Moh for their assistance and Teo Kien Boon and Goh Joo Thiam for their support in the work.

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