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Coherent Polarization Locking of Thermal Sensitive Ho:YAG laser

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ABSTRACT

We had demonstrated the advantage of using Coherent Polarization Locking on thermal-sensitive Ho:YAG laser cavity. We overcome several thermal issues related to Ho:YAG laser by distributing the gain over a large volume. We passively coherent locked two orthogonal polarized lasers, achieving 9.6W of output power with near perfect (>99%) combining efficiency. The resultant laser produced near diffraction-limited beam quality of $M^2 \sim 1.1$ and excellent power stability. As compared to conventional laser cavity, we had shown the increased in single-pass absorption, suppression of output power saturation and improvement in beam quality using Coherent Polarization Locking.

Keywords: Coherent locking, thermal effects, Ho:YAG lasers, quasi-three level lasers.

1. INTRODUCTION

1.1 Thermal Sensitive Ho:YAG laser

Ho:YAG laser, operating at eye-safe 2.1 μ m spectral region, has many promising applications, such as laser surgery, medicine and remote sensing. It is also a suitable pump source for ZnGeP₂ OPO, generating mid-infrared radiation. Ho:YAG laser is commonly pumped by 1.9 μ m Thulium laser, which yield high quantum efficiency, allowing efficient energy extraction. Ho:YAG laser is a quasi-three level laser system. 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. This makes its high power operation difficult.

Both the pump (1.9 μ m) and laser (2.1 μ m) wavelength of Holmium laser fall into the transition band $^5I_7 - ^5I_8$. These two levels consist of several Stark levels. The pump transition takes place from the lowest 5I_8 sublevel (ground state) to the highest 5I_7 sublevel, whereas the laser transition is from the lowest 5I_7 sublevel to highest 5I_8 sublevel. Due to the overlapping of absorption and emission spectrum, there will be significant ground state re-absorption^[1] (GSR) loss at the laser wavelength. This internal power loss in the laser medium creates additional heat load in the crystal. In such situation, the atoms are either thermally excited from the ground state to the lower laser level or from the upper laser level to the upper pump level. Both processes result in reduce of gain and hence increased laser threshold.

It is well known that the laser performance of Holmium laser is influenced by energy transfer upconversion^[2] (ETU). ETU occurs when the laser crystal doping concentration is sufficiently high for two neighbouring atoms in the upper laser level to interact. In Ho:Ho upconversion process, two Ho atoms in the 5I_7 manifold interact, leading to the excitation of one of the atoms to the next higher 5I_5 manifold and the relaxation of the other Ho atom to 5I_8 manifold. Thus ETU process degrades the laser performance due to the decrease in population inversion.

The development of high power solid state laser is often accompanied by thermo-optic effects, such as thermal lensing, bifocusing and induced birefringence. These unwanted thermo-optic effects lead to beam quality degradation and depolarization loss, hence reduce the laser performance. The common method to avoid these effects is by increasing the

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pump and mode size in the cavity. However this is not favourable because the pump power density will reduce and therefore lead to lower gain. If there is sufficiently high pump power, increasing spot size is acceptable. However, such method may not be feasible for diffraction limited operation as longer cavity and larger optical component are required.

1.2 Coherent Polarization Locking

Coherent beam combining^[3] of laser is a promising method to scale up the laser output power by combining several individual lasers, meanwhile preserving the coherent properties of the laser. In order for these lasers to be coherently combined, their phases have to be locked. Coherent beam combining can be achieved in either active^[4] or passive^[5-6] method. Coherent Polarization Locking (CPL) is one of the passive methods of locking the phases of individual laser by using their polarization properties. The phases of these lasers are self stabilized with near perfect combining efficiency. CPL does not only scale up the laser power, it also improves the beam quality. The overall brightness in a diode laser system was improved by more than 10 times^[6] using CPL. In this paper, we will focus on using CPL technique to reduce undesirable thermal effects rather than power scaling.

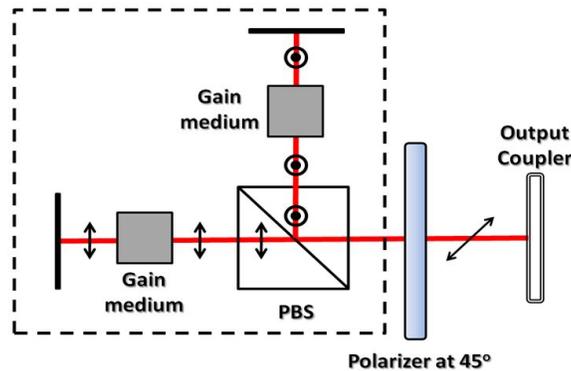


Figure 1 Illustration of coherent polarization locking of two orthogonal polarized lasers.

Figure 1 shows the basic principle of CPL of two orthogonal polarized lasers. By using a polarization beam splitter, two lasers oscillate in p-polarization and s-polarization respectively. When both lasers, emitting with same output power, are spatially overlapped, their phase difference $\Delta\phi$ is random in nature, and the combined laser is incoherent. In the case where both p-polarized and s-polarized lasers have equal magnitude of electric field, combined laser electric field will be 45° linear polarized only if both electric fields are in phase, i.e. phase difference is locked at $\Delta\phi = 0$ or $\Delta\phi = \pi$. To lock the phase of the lasers to each other, a polarizer with its transmission axis rotated to 45° is inserted in the cavity. The presence of this polarizer will cause both p-polarized and s-polarized lasers to experience polarization loss if their phase difference is not locked. Therefore, this polarizer acts as a passive mechanism to force their phase difference to lock to each other, resulting in a 45° linearly polarized laser oscillating in the common laser cavity without polarization loss.

There are several advantages of using CPL technique in Ho:YAG laser system. By splitting the available pump power to two laser crystals and coherently combine these two lasers, we can reduce those undesirable thermo-optic effects on the laser crystal. Splitting the pump power to two gain media allows us to reduce thermal lensing without the need of increasing the pump spot size, which is a better way of handling thermal effect. Concerning the energy transfer upconversion issues as mentioned, low doping concentration is preferable. However, ground state depletion in low doped crystals saturate the pump absorption under high power pumping, as all the available ground state atoms are excited to the higher level. This leads to the wastage of pump power. With the CPL technique, we can coherently combine several low doped Ho:YAG lasers, pumped with lower power, to overcome the thermal-optics effects and upconversion loss while achieving power scaling of the laser.

2. EXPERIMENTAL SETUP

Figure 2 shows the schematic setup of our experiment. The Ho:YAG laser crystal used in the experiment had a slab geometry with 10mm length, 10mm height and 20mm width and doping concentration of 0.75%. It was pumped by a linearly polarized Tm:Fiber laser, where the pump laser was split into two separate parallel pump beams with separation

of 10mm. The ratio of the split pump powers could be varied by rotating HWP1. The laser crystal was TEC cooled to 20°C. The two pump beams incident onto the laser crystal at two separate spots, thus reducing the thermal load of each spot on the gain medium. The pump spot size was focused to ~800μm in diameter. The pump input surface of the crystal was dielectric coated for high transmission at 1.9μm and high reflection at 2.1μm. Double-pass pump configuration was performed with a dichroic mirror DM after the laser crystal. The output coupler was a flat mirror with R=70% at 2.1μm. A plano-convex lens, with focal length of 300mm, was placed between the laser crystal and the output coupler. These elements formed a laser cavity with mode size matching the pump spot size.

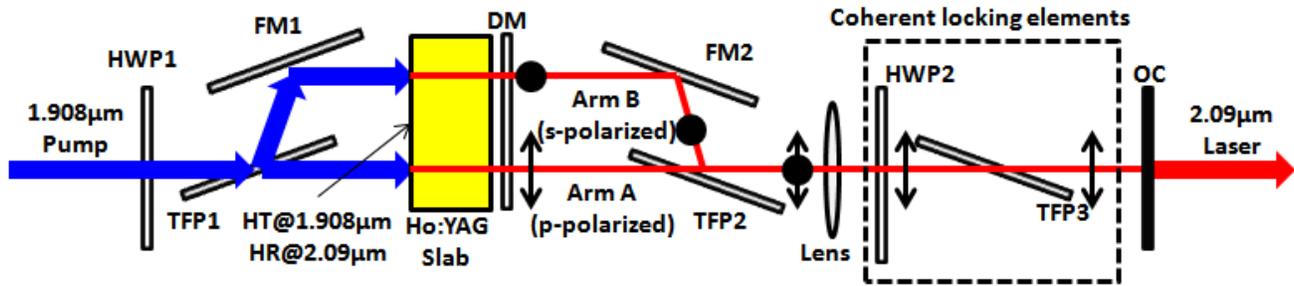


Figure 2 Experimental setup of CPL Ho:YAG laser. HWP, half-wave plate. TFP, thin film polarizer. FM, folding mirror. DM, dichroic mirror. OC, output coupler.

By using TFP2, laser Arm A and laser Arm B oscillated in p-polarization and s-polarization respectively. To coherently combine two spatially overlapped lasers emitting with equal amount of power, a 45° polarizer is used as a polarization discriminator. In the setup, HWP2, with optic axis placed at 22.5°, and TFP3 served the same purpose as a 45° polarizer: a coherent combined laser, with 45° polarization, will rotate 45° by HWP2 and pass through TFP3 without loss. In the case for two unequal power lasers, the optic axis of HWP2 could be rotated accordingly to achieve near-perfect coherent combining efficiency. The individual power of laser Arm A and laser Arm B were measured by rotating the optics axis of HWP2 to 0° and 45° respectively. At 0°, only laser Arm A can built up in the laser cavity, whereas laser Arm B will experience high loss. Similarly at 45°, laser Arm B oscillates while laser Arm A experiences loss. 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 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, single arm laser and coherent combined laser.

3. RESULTS AND DISCUSSIONS

Single-pass absorption of the pump power was measured for two pump configuration, single spot and double spots. Single spot configuration referred to all the pump power incident onto the gain medium on one position whereas the double spots configuration referred to the pump power split and incident onto the gain medium on two positions. Figure 3a shows the measured single-pass absorption. The filled square (blue) curve shows the diminishing of single pass absorbed power as the input pump power increases. This is the result from ground state depletion, where the pump power cannot be fully utilized at high pump power regime. On the other hand, the filled circle (red) curve shows that by splitting the pump power to two spots, more pump power was absorbed and hence ground state depletion was prevented. Double pump spots configuration also effectively doubled the pump area. This is equivalent to the typical method to mitigate thermal issues by increasing the single pump spot area twice. However, in end-pump configuration, increasing the pump mode size required the laser mode size to increase accordingly in order to achieve high overlapping efficiency. This leads to the need for longer cavity length. In contrast, CPL allows the effective pump area to increase, while maintaining the compact and short laser cavity.

The laser output power from the two pump configuration is shown in Figure 3b. Saturation of output power at maximum input pump power in the single arm laser configuration was observed. The saturation effect in the output power was due to the saturation of absorption coefficient and strong thermal lensing. This limits the power scaling of this laser configuration when higher pump power is available. As for the coherent combined configuration, a linear output curve

was achieved, showing the potential for further power scaling with higher pump power. This shows the advantage of using CPL in Ho:YAG laser system, where ground state depletion was prevented. The maximum output power was ~10W at highest available pump power. Slope efficiency of the coherent combined laser was closed to that of the single arm laser. Although ground state depletion and power saturation were prevented, the maximum output power for both cases gave similar output power of ~10W. CPL did not give a higher output power because of the higher pump threshold power. Figure 3b shows that the threshold of the CPL method was approximately twice of the convention method. This is because the pump area was effective double by pumping two spots. However, if a laser system is such that the unconverted pump power due to power saturation is greater than the increase in threshold power, CPL will provide a promising method for power scaling.

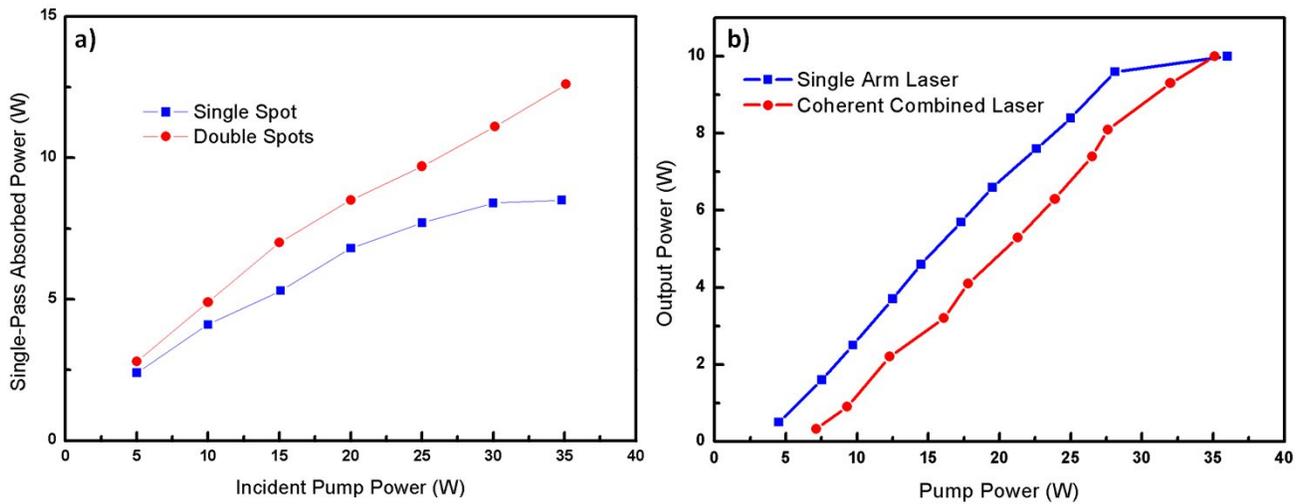


Figure 3 a) Single-pass absorption measurement. The filled square (blue) curve shows the total absorbed power for pumping all available power on the single spot, whereas the filled circle (red) curve shows the total absorbed power when pump power was split into two spots. b) Laser output power versus pump power, with the filled square (blue) and filled circle (red) corresponding to single arm laser and coherent combined laser respectively.

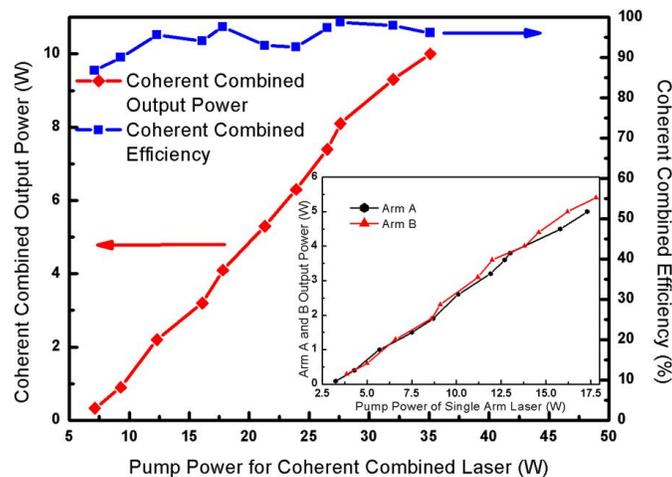


Figure 4 Laser output versus pump power. The main curve shows the output power of coherent combined laser, and the top curve shows the coherent combined efficiency. Insert shows the output power of individual arm laser A and B at different pump power.

We reported our best coherent combined result of 9.6W at total pump power of 30.6W, with individual arm laser power of 6W and 3.5W respectively. This corresponds to a near perfect coherent combining efficiency. The output power of the combined laser was very stable with power fluctuation less than 0.5%. The optimum combining output achieved was not

with a 1:1 power ratio, but with an arbitrary ratio determined experimentally. This shows the advantage of CPL where it allowed us to combine uneven individual laser output power^[5], but yet achieving near perfect combining efficiency by simply rotating HWP2 accordingly. In contrast to Michelson interferometric coherent locking^[7,8], individual laser output power ratio must be fixed according to the polarization beam splitter ratio used in the experiment. This is also one of the advantages of CPL, where it allows us to fine tune the optimum output power with another degree of freedom.

The performance of the coherent polarization locking in our Ho:YAG laser system is shown in Figure 4. The experiment was conducted by fixing the input pump power ratio to about 1:1. The laser output power of coherent combined laser and individual arm laser A and B are plotted. Fine tuning of the cavity was performed at the high pump power to achieve maximum output power and combining efficiency. No further optimization on the cavity was performed at different pump power. We achieved >85% coherent combining efficiency over the pump power range. Linear behaviour on the output power was observed, showing the potential for further power scaling when higher pump power is available.

Figure 5a and 5b shows the beam profile for the two laser configuration. This has shown a clear advantage of using CPL technique in our experiment, where it significantly improves the laser beam quality. Our result shows that by splitting the available pump power to two gain mediums, we can avoid severe thermal lensing effect which causes the beam quality to degrade. Another reason for the improved in beam quality is due to 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 reduces the probability of oscillation in higher order mode, thus leading to the improvement of the beam quality.

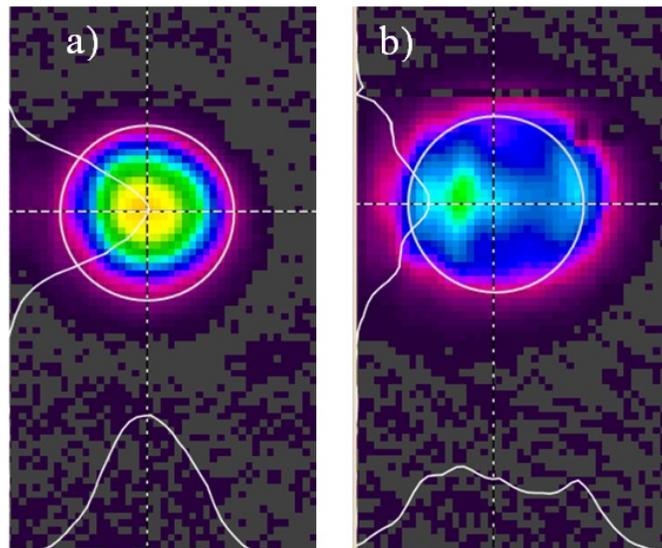


Figure 5 The laser output beam profile of a) coherent combined laser and b) single arm laser.

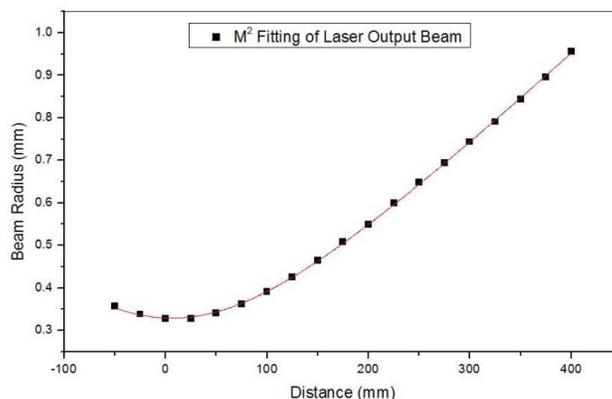


Figure 6 M^2 measurement of the combined laser output beam.

The M^2 fitting curve of the combined laser output beam at maximum output power is shown in Figure 6. The fitted curve gives $M^2 \sim 1.1$, which is close to diffraction limit beam quality. In contrast, the M^2 measurement of the single arm laser gives M_x^2 of 2.2 and M_y^2 of 1.6. In this configuration, not only the beam quality was degraded, the beam size was also jittering and the output power was not as stable as the coherent combined laser. These undesired effects are due to the thermal effect with high pump power loaded into the laser crystal.

4. CONCLUSION

In summary, we had demonstrated the main advantages of using CPL technique on thermal sensitive Ho:YAG laser. We had increased the single-pass absorption power, prevented the saturation of laser output power and improved significantly on the laser beam quality. Ground state population depletion was prevented, thus achieve higher power extraction. Thermal load were reduced on laser crystals and hence improved the beam quality. CPL also has the potential in power scaling to develop high power laser system.

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