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Coherent Polarization Locking of Q-switched Ho:YAG laser

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ABSTRACT

We had demonstrated the use of Coherent Polarization Locking (CPL) to mitigate the intra-cavity optical damage in a Q-switched Ho:YAG laser. By splitting the available pump power into two individual Ho:YAG laser rods, we had passively coherent combined two orthogonal polarized lasers with output pulse energy of 9.13mJ, pulse width of 14ns, operating at 800Hz pulse repetition rate. In contrast, when all the pump power was pumped on a single Ho:YAG laser rod built with the same cavity configuration, severe optical damage was observed. It was occurred at the surface coating of the laser rod when operating at < 2kHz pulse repetition rate, thus limiting the output pulse energy to < 5mJ. We also demonstrated, first to our knowledge, that by performing Q-switching only in one of the laser arms, it resulted in pulse operation for the entire CPL laser cavity.

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

1. INTRODUCTION

1.1 Q-switched Ho:YAG lasers

High power Holmium doped lasers operating in the 2 μ m spectral region have numerous applications varies from remote sensing, trace gas monitoring, laser surgery, medical and defense application, to scientific application. Holmium laser is also a good candidate to be the pump source of non-linear crystal to generate mid-infrared radiation via optical parametric oscillation. To achieve optical parametric oscillation with high conversion efficiency, ns pulse laser generated using q-switching method is necessary. In particular, Holmium doped lasers are attractive for Q-switching owing to the long upper laser level lifetime of $\sim 10\text{ms}$ ^[1], corresponding to an ideal Q-switch pulse repetition rate of 100Hz for maximum stored energy extraction. However, during high pulse energy operation, we are always challenged by the extremely high intra-cavity intensity generated within the laser cavity, which potentially leads to the optical damage on the thin-film coating on the optics such as mirrors, polarizers, gain mediums and the Pockel cell. High damage threshold thin-film coatings for the 2 μ m region are relatively immature in technology and not as readily available as compared to the 1 μ m thin-film coating. Thus there is a strong motivation to decrease the intra-cavity intensity of a pulse laser while maintaining its high output energy.

1.2 Coherent Polarization Locking

Coherent beam combining^[2] is a promising method to scale up the laser output power by combining several individual lasers, while preserving the coherent properties of the laser. It can be achieved using either active^[3] or passive^[4] method. Coherent Polarization Locking (CPL) is one of the passive methods to achieve coherent beam combining, where no requirement is needed for the external electronic feedback control of their phases. Instead, the phases of these lasers are self stabilized. CPL not only scales up the laser power, it also improves the beam quality. As shown in a diode laser system, the overall brightness could be improved by more than 10 times^[5]. In this paper, passive CPL technique is implemented to mitigate the intra-cavity optical damage in a high pulse energy Q-switched laser.

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In our previous work^[6], we had demonstrated the use of CPL to overcome several thermal issues in a CW Ho:YAG laser, achieving 10W output power with near diffraction limited output beam quality. In that experiment, we split the pump power to two individual laser crystals to eliminate the undesired thermal effects, and coherently combined together using CPL method, achieving > 96% combining efficiency. As for Q-switched operation, this method allows us to mitigate the potential optical damage due to the high intra-cavity intensity. In this way, two lasers share the total intra-cavity intensity within the laser cavity. Considering the case where the output pulse energy of a Q-switched laser is limited by a certain damage threshold, we can effectively scale up the output pulse energy by twice.

1.3 Thermal issues in quasi-three levels lasers

Beside the optical damage issues in the Q-switched laser, CPL also gives several advantages on CW^[6] operation. Ho:YAG laser is a quasi-three level system, unlike the Nd:YAG laser which has distinct four levels. The inherent thermal effects of the non-distinctive laser levels make the high power operation difficult. Due to the overlapping of absorption and emission spectrum, there is significant ground state re-absorption^[7] (GSR) at the laser wavelength when operating at high power. Therefore, the ground state atoms are thermally excited to populate the lower laser level and hence reducing the gain. This increases internal power loss in the laser medium leading to additional heat load.

The development of high power solid state laser is often accompanied by thermo-optic effects, such as thermally induced lensing and birefringence. These unwanted thermo-optic effects lead to the degradation of the beam quality and the de-polarization loss, hence reducing the laser performance. In most high power solid state lasers, thermal effect is one of the reasons leading to the degraded beam quality as the pump power increases. These thermal effect are even more drastic for the Ho:YAG laser due to its quasi-three level nature. Since thermal lensing is proportional to the input pump power and inversely proportional to the pump spot size, a simple way to avoid this effect is to increase the pump spot size. Most high power lasers have chosen to use a larger pump spot size and laser cavity mode size in order to generate laser output with good beam quality. However, such method may not be feasible for diffraction limited operation as longer cavity and larger optical component are essential. With the use of the CPL technique, splitting the pump power to two gain mediums allows us to reduce thermal effects without the need to increase the pump spot size.

It is also known that the laser performance of Ho:YAG laser is influenced by energy transfer upconversion^[8] (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 atoms energy upconversion process, two Ho atoms in the 5I_7 manifold interact. This interaction leads to the excitation of one of the atoms to the 5I_5 manifold and the relaxation of the other Ho atom to the 5I_8 manifold, which decreases the laser population inversion. Therefore, low doping concentration is more preferable. However, there will be saturation of pump absorption under sufficiently high pump power, as all the available ground state atoms are excited to the higher level. This effect known as ground state depletion, leads to the wastage of the pump power. With the CPL technique, we can coherently combine two low doped Holmium lasers to avoid the ground state depletion and thus achieving power scaling.

2. EXPERIMENTAL SETUP

Figure 1 shows the schematic setup of our experiment. Two identical Ho:YAG laser crystal rods were used in the experiment, with diameter of 3mm, length of 30mm, and doping concentration of 0.36%. They were pumped by a Tm:Fiber laser emitting at 1.908 μ m, which corresponds to the peak absorption of Ho:YAG crystal. The pump laser was split by a thin film polarizer (TFP1) into two separate pump beams with separation of 25mm. The ratio of the split pump powers could be varied by rotating the half wave plate HWP1. Both surfaces of the crystals were AR coated for the pump and the laser wavelength.

The pump laser beam was focused by a lens ($f=300$ mm) to a spot size of diameter ~ 1 mm on the laser crystals. Both crystals were water cooled to 20°C. Double-pass pump configuration was used with a dichroic mirror (DCM) after the laser crystals. The laser cavity was formed by two HR input couplers (IC) and a common output coupler with 40% reflection at the laser wavelength. Laser arm A and B were oscillating in orthogonal polarization by using the TFP2, with laser arm A oscillating in p-polarization while laser arm B oscillating in s-polarization.

Figure 1 Experimental setup of CPL of Q-switched Ho:YAG laser.

Considering that the laser arm A and B emitting with same power are spatially overlapped, their phase difference was random in nature, and hence the resultant combined laser is incoherent. To coherently combine two orthogonal polarized lasers, their phase difference has to be locked at $\Delta\phi=0$, and the resultant laser will be linearly polarized at 45° .

The half wave plate (HWP2, with optic axis at 22.5°) and the thin film polarizer (TFP3, p-polarization transmission) formed the passive coherent locking elements, as indicated in Figure 1. Due to the competitive nature in light amplification, the laser arm A and B were forced to be coherently combined, such that the resultant 45° polarized laser would pass through the HWP2 and TFP3 without polarization loss. In other words, the laser phases are self-locked to each other in order to oscillate within the laser cavity. The HWP2 angle could also be varied accordingly if two lasers are emitting with uneven output power.

The active Q-switching operation was performed by placing a RTP Pockel cell in the laser cavity. The Pockel cell was placed at two different positions, P1 and P2 respectively, as shown in Figure 1, for two different scenarios. At position P1, where the Pockel cell was placed after the TFP3 at the common arm, the Q-switching operation of the coherently locked laser behaved as a conventional Q-switch laser. At position P2, where the Pockel cell was placed at the laser arm A before the coherent locking mechanism was taking place, the Q-switching operation of the laser arm A induced the pulse operation of the entire laser cavity. In this scenario, we were interested in examining the pulsed operation behavior of the CPL cavity when the Q-switching was performed only at the laser arm A.

3. RESULTS AND DISCUSSIONS

3.1 Scenario 1: Common arm Q-switching operation

Repetition Rate (Hz)	Average Power (W)	Pulse Energy (mJ)	Pulse Width (ns)
5000	8.6	1.72	59
4000	8.3	2.08	47
3000	8.3	2.77	35
2000	8.3	4.15	25
1000	7.9	7.90	16
800	7.3	9.13	14

Table 1 Q-switched CPL Ho:YAG laser performance, with the Pockel cell placed at position P1.

Table 1 shows the average power, the pulse energy and the pulse width of the laser output at different pulse repetition, for the first scenario, where the Pockel cell was placed at the position P1. Total pump power of ~ 28 W was used in the experiment. CPL was performed when the output power of both laser arm A and B are approximately equal, such that each laser sharing about half of the total intra-cavity intensity. In CW operation, i.e. before Q-switched operation, the coherent combining efficiency achieved was $\sim 95\%$. The Q-switched operation was performed with different pulse repetition rate, as shown in Table 1. We achieved pulse energy of 9.13mJ with 14ns pulse width, operating at pulse repetition rate of 800Hz. The output beam is near diffraction limited, corresponding to $M^2 \sim 1.07$ achieved at the highest output pulse energy. The far field beam profile and the corresponding M^2 fitting measurement are shown in Figure 2. No intra-cavity optical damage was observed during the pulse operation at 800Hz pulse repetition rate. In addition to the lower intra-cavity intensity, good beam quality suppressed the existence of the possible hot spikes, which is another common effect that could cause damage to the optics.

Figure 2 a) Laser output far field beam profile. b) M^2 fitting measurement gives $M^2 \sim 1.07$.

For comparison, a conventional Q-switched Ho:YAG laser cavity, with the same laser cavity configuration and the gain medium, was tested. Instead of splitting the total pump power to two Ho:YAG laser crystals, all the pump power was loaded into a single laser crystal. With the same amount of pump power, the Q-switched laser performance was shown in Table 2.

Repetition Rate (Hz)	Average Power (W)	Pulse Energy (mJ)
5000	10	2.00
4000	10	2.50
3000	10	3.33
2000	X	X

Table 2 Conventional Q-switched Ho:YAG laser performance.

While the average output power for this configuration was higher compared to the CPL cavity, the highest obtainable pulse energy was limited by the catastrophic intra-cavity optical damage located at the AR thin film coating of the surfaces of the laser crystal. With the average output power of 10W, the highest output pulse energy of 5mJ was the limit that a single laser crystal can tolerate for this laser cavity configuration. Thus, the maximum output pulse energy of the conventional laser was limited to less than 5mJ. This shows the strong advantage of using CPL in pulse operation to mitigate intra-cavity optical damage. In the CPL cavity, the total intra-cavity intensity in the common arm was shared between two orthogonal polarized laser arms. The TFP2 split the intra-cavity intensity experienced by the common arm to two lower intensities for each laser arm. This mitigated the risk of intra-cavity optical damage to the optics placed along the individual arms, thus achieving higher output energy.

3.2 Scenario 2: Single arm Q-switching operation

In the second scenario, we examined the pulse operation of the CPL cavity where the Pockel cell was placed at the position P2. We showed, first to our knowledge, the Q-switching operation in one of the laser arms (laser arm A) resulting in the pulse operation within the entire laser cavity. This was verified as a result of CPL effect, by blocking the path of the laser arm B. This blocking caused the CPL laser to stop lasing due to the high polarization loss for the laser arm A experienced by the TFP3. The average power, the pulse energy and the pulse width for different pulse repetition rate are shown in Table 3.

Repetition Rate (Hz)	Average Power (W)	Pulse Energy (mJ)	Pulse Width (ns)
5000	6.4	1.28	75
4000	6.3	1.58	62
3000	6.3	2.10	47
2000	6.1	3.05	28
1000	6.0	6.00	18
800	5.6	7.00	16

Table 3 Q-switched CPL Ho:YAG laser performance, with the Pockel cell placed at position P2.

While the active Q-switching was conducted only in the laser cavity of laser arm A, the passive CPL mechanism was fast enough to autonomously phase lock two orthogonal polarized lasers during the short nanosecond time frame. Before the Q-switching operation had started, the coherent locking was achieved as usual. When the Pockel cell driver was turned on, the output laser exhibited stable pulsed operation. The corresponding pulse trains and the pulse width, at pulse repetition rate of 1kHz, are shown in Figure 3. During the “on” state (low Q-factor), both the gain mediums are building up the population inversions. And during the “off” state (high Q-factor), the “polarized gate” is open, causing both lasers to release a pulse. Since the HWP2 (optic axis oriented at 22.5°) and the TFP3 act as a coherent locking element, both lasers are forced to coherently combine such that the combined 45° linearly polarized laser pulse can transmit through the TFP3 and hence release out from the output coupler. Therefore, the coherent locking is achieved within the “off” state and both the laser arms are coherently combined to release a series of pulse trains.

Figure 3 a) Output laser pulse train and b) pulse width of the coherently locked Q-switched Ho:YAG laser, in scenario 2.

The output pulse energy for the scenario 2 was lower than that of the scenario 1. This could be due to the smaller beam size located near the laser crystal, which induced undesired thermal lensing effect on the Pockel cell crystals. We observed that the output beam distorted and the CW laser output power decreased when the Pockel cell was inserted at position P2. This caused the decreased in the spatial overlapping efficiency of the two orthogonal beams, thus achieving coherent combining efficiency of only 81%.

Despite the lower output power in this scenario, this configuration has several advantages if it is optimally designed. Considering the coating of the laser crystals are not the limitation of the output pulse energy, for example if Brewster cut laser crystals are used, one can use this configuration to mitigate the risk of damaging the AR coating of the Pockel cell. Furthermore, as shown earlier, it is possible to combine laser arms with uneven output power ratio^[4], one can make use of this advantage to mitigate the optical damage of Pockel cell even further. In our experiment, the output power ratio of the laser arm A and B was approximately 1:1, so that each laser arm experienced $\frac{1}{2}$ of the total intra-cavity intensity. If we make the output power ratio to be 1:3 for instance, the laser arm with lower output power will experience $\frac{1}{4}$ of the total intra-cavity intensity. In this way, we can further reduce the risk of damaging the AR coating of the Pockel cell, and hence achieve higher output pulse energy.

4. CONCLUSION

In conclusion, we had successfully demonstrated the advantages of using CPL method to mitigate intra-cavity optical damage in a Q-switched Ho:YAG laser. As comparison, the CPL laser cavity generated 9.13mJ output pulse energy, whereas the output pulse energy of the conventional laser cavity was limited to less than 5mJ, due to the optical damage at the AR coating of the laser crystal. We also demonstrated an alternative approach, by performing Q-switching in only one of the laser arms, the CPL mechanism was fast enough to generate stable pulse operation for the entire laser cavity. This approach allows us to further reduce the risk of damaging the AR coating of the Pockel cell.

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