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Coherent polarization locking: an approach to mitigating optical damage in a pulsed Ho:YAG laser

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Intracavity optical damage is mitigated in a pulsed Ho:YAG laser cavity using the coherent polarization locking (CPL) technique. By splitting the available pump power into two individual Ho:YAG laser rods, we passively coherently locked two orthogonal polarization lasers with 9.13 mJ output pulse energies and 14 ns pulsewidths, and operating at 800 Hz repetition rate. A conventional Ho:YAG laser cavity with the same pump and cavity configuration results in severe optical damage when operating at <2 kHz repetition rate, thus limiting the output pulse energies to <5 mJ. We also demonstrated, to the best of our knowledge, the first pulsed operation within the entire CPL Ho:YAG laser cavity by Q-switching in one of the polarization arms, producing nanosecond pulses with no sign of pulse instability. © 2013 Optical Society of America

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Ho:YAG lasers [1] 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. Q-switching operation is required to generate nanosecond pulses for pumping optical parametric oscillators with high conversion efficiency. During high pulse energy operation, one key challenge is to avoid optical damage induced by the extremely high intracavity intensity generated within the laser cavity. Typical optical damage can be easily observed on the multilayer thin-film coated optics, such as the polarizers, the gain medium, and the Pockels cell. High-damage-threshold thin-film coating for 2 μm operation is not as readily available as compared to coating for 1 μm operation. Thus, there is a strong motivation to decrease the intracavity intensity of high-energy pulse lasers while maintaining the high output energy of the laser pulses. In this Letter, we investigate the use of the coherent beam-combining technique to mitigate the intracavity optical damage in a pulsed Ho:YAG laser.

Coherent beam combining [2] 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 performed for decades. Both active [3,4] and passive [5] phase-locking mechanisms were demonstrated to improve the brightness of a diode. Similar combining was also demonstrated for solid-state lasers [6–8]. Coherent polarization locking (CPL) [5–7] 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 previous work [7], we demonstrated CPL in CW Ho:YAG, where we overcame several thermal issues related to the Ho:YAG laser, achieving 10 W of output power with near diffraction-limited output beam quality. Good beam quality prevents the existence of hot-spots in the beam profile. This reduces the possibility of

optical damage caused by the hot spikes in the beam intensity distribution. In our current experiment, we use CPL to combine two orthogonal Ho:YAG lasers in pulsed mode and investigate the advantage of using CPL to mitigate intracavity optical damage. Pulse operation is operated in two different scenarios. In the first scenario, Q-switching is performed on the common arm of the coherent combining cavity. And in the second scenario, Q-switching is performed only on one of the polarization arms, while the cavity of the other polarization arm does not have any Q-switching element. For the second scenario, it is interesting to examine the dynamics involved in Q-switching coupled with the CPL operation in the cavity.

The schematic of the CPL Q-switched Ho:YAG laser is shown in Fig. 1. The system was 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 was split into two separate parallel pump beams using HWP1, TFP1, and a folding mirror. By rotating HWP1, the splitting ratio could be changed, thus manipulating the gain of each individual path. These two pump beams propagate with a spatial separation of ~ 25 mm. The total pump power used was 28 W. A 300 mm focal length lens, placed before HWP1, focused both beams to a pump beam diameter of ~ 1 mm inside two Ho:YAG rods (doping concentration of 0.36 at. %). Both water-cooled (at 20°C) Ho:YAG rods have a diameter of 3 mm and length of 30 mm. The laser cavity was formed by two rear mirrors, one for each rod, and a common ROC 750 mm concave output coupler with $R = 60\%$ at the laser wavelength. Dichroic mirrors, highly reflective at the pump wavelength and highly transmissive at the laser wavelength, were placed after the Ho:YAG rods, allowing a double-pass pump configuration. The beams from arm A and arm B were spatially combined using TFP2 and a folding mirror. TFP2 also forced the polarization of the lasing beam in arm A and arm B to oscillate in p polarization and s polarization, respectively. CPL was achieved by HWP2 and TFP3 within the cavity.

Fig. 1. (Color online) Schematic setup of CPL Q-switched Ho:YAG laser. HWP, half-wave plate; TFP, thin-film polarizer; FM, folding mirror; DM, dichroic mirror; RM, rear mirror; OC, output coupler; PC, Pockels cell; P1, position 1 for PC; P2, position 2 for PC.

The polarization of the coherently combined beam after TFP2 was rotated by HWP2 to horizontal polarization, and transmitted through TFP3 with low reflection loss. Pulsed operation was performed using a RTP Pockels cell. The Pockels cell was placed at two different positions, P1 and P2, respectively, as shown in Fig. 1, for the two different scenarios mentioned earlier. At position P1, where the Pockels cell was placed after TFP3 at the common arm, the Q-switched operation behaved after CPL operation as a conventional laser cavity. Meanwhile, at position P2, where the Pockels cell was placed at arm A before CPL operation was performed, the Q-switched operation experienced the effects of coherent beam combining performed by the coherent locking elements. The cavity for arm B would not have any Q-switching element for pulse operation. In this scenario, we will examine the pulsed operation behavior of the CPL cavity when Q-switching was performed only at arm A.

Figure 2 shows the pulse energy and the pulsewidth of the laser output at different pulse repetition rate achieved for the first scenario, where the Pockels cell was placed at position P1. We achieved a pulse energy of 9.13 mJ with 14 ns pulsewidth, operating at pulse repetition rate of 800 Hz. We performed M^2 measurement by focusing the output beam, measuring the beam size at

several positions across the waist and curve fitting the data to the Gaussian beam propagation equation. Figure 3 shows the beam radius measured with respect to distance and the far-field beam profile captured using Spiricon Pycocam III. The output beam was near diffraction limited, with a M^2 value of ~ 1.07 achieved at the highest output pulse energy. No intracavity optical damage was observed during pulse operation at 800 Hz.

For comparison, a conventional Q-switched Ho:YAG laser cavity setup was built with the same gain medium, pump mode size, and cavity design. With the same amount of pump power, the conventional laser generated an average power of 10 W at a pulse repetition rate of 2 kHz, corresponding to pulse energy of 5 mJ. When operating below 2 kHz, intracavity optical damage was observed on the multilayer thin film coated on the surface of the Ho:YAG rod. Thus laser operation for the conventional setup was limited for pulse energies up to 5 mJ. This shows a strong advantage of using CPL in pulsed operation to mitigate intracavity optical damage. In the CPL cavity, the total intracavity intensity in the common arm was shared between the two orthogonal arms. TFP2 splits the intracavity intensity experienced by the common arm to two lower intensities for each polarization arm. This mitigates the risk of

Fig. 2. (Color online) Pulse energy/pulsewidth versus pulse repetition rate for CPL Q-switched Ho:YAG laser with the Pockels cell placed at P1.

Fig. 3. (Color online) M^2 measurement of CPL Q-switched Ho:YAG laser at the highest pulse energy. The inset shows the laser-output far-field beam profile.

intracavity optical damage to the optics placed along the individual arms, thus achieving higher output pulse energy. In addition to the lower intracavity intensity, the good beam quality of the coherent locked beam suppressed the existence of hot spikes, which was another common effect that can damage the optics. The risk of the intracavity optical damage is thus reduced.

Next, we examined the pulsed operation of the CPL cavity for the second scenario, where the Pockels cell was placed at position P2. *Q*-switching was performed only in the cavity of arm A, as there was no *Q*-switching element in the arm B cavity. Pulsed operation was successfully achieved without any observation of pulse instability, any loss of laser coherent properties, or any drastic drop in the average power compared to the output power during CW operation. A stable output pulse train generated by this setup was observed on the oscilloscope using a fast photodetector. The stable pulse train can be explained by examining the restriction imposed by the CPL technique. In a CPL cavity, coherent beam combining is achieved only when the combined gain from both arm A and arm B exceeds the total losses within the cavity. No laser oscillation is possible in an individual polarization arm without the existence of the other arm. By inserting a *Q*-switching element in one of the polarization arms, we manipulate the gain of that particular arm; however, the combined gain of the entire CPL cavity will also change dynamically according to the *Q*-switching element. This leads to stable pulsed operation without loss of the laser coherent properties and the output power. In addition, the result shows that during nanosecond pulse operation, the CPL mechanism is fast enough to respond to the dynamics introduced by the *Q*-switching element. This is, to the best of our knowledge, the first demonstration of a nanosecond pulse operation in a coherent combining cavity by only *Q*-switching in one of the orthogonal arms.

The average power, pulse energies, and pulsewidth of the laser output at different pulse repetition rate achieved for the second scenario are shown in Fig. 4. Pulse energy of 7 mJ, with 18 ns pulsewidth, operating at pulse repetition rate of 800 Hz, was achieved, with near diffraction-limited output beam quality. The decrease in the output pulse energy as compared to the first scenario was a result of the decrease in the coherent beam-combining efficiency. With the RTP Pockels cell placed at position P2, the output beam profile of arm A was slightly distorted. The cavity mode size at position P2 was smaller, which introduced undesired thermal effects on the RTP Pockels cell. This resulted in a decrease in the spatial beam overlapping efficiency of the two orthogonal arms, thus achieving a lower coherent beam-combining efficiency.

To conclude, we have successfully demonstrated pulsed operation in a CPL *Q*-switched Ho:YAG laser cavity, generating pulse energy of 9.13 mJ and a

Fig. 4. (Color online) Pulse energy/Pulsewidth versus pulse repetition rate for CPL *Q*-switched Ho:YAG laser with the Pockels cell placed at P2

pulsewidth of 14 ns, operating at 800 Hz pulse repetition rate. We have also compared the laser performance of the CPL laser cavity with a conventional laser cavity of the same pump and cavity-mode configuration. We have demonstrated that by using CPL, we have mitigated the risk of intracavity optical damage, and this allowed us to achieve higher output pulse energy. We have also demonstrated, to the best of our knowledge, the first pulsed operation of a CPL cavity with the *Q*-switching element introduced to only one of the orthogonal arms. This dynamics is possible due to the inherent fast coherent locking mechanism imposed by CPL. Stable output pulses were generated without loss of output power and laser coherent properties.

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