Generation of high energy and good beam quality pulses with a master oscillator power amplifier

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A high efficiency and high peak power laser system with short-pulse and good beam quality has been demonstrated by using a master oscillator power amplifier with two-pass amplification configuration. The master oscillator, end-pumped with a fiber-coupled laser diode array, provides low power but excellent beam quality pulses, and the amplifier boosts the pulse energy by orders without significant beam quality degradation. Short pulses of 8.5 ns with energy up to 130 mJ and approximately diffraction limited beam quality have been demonstrated.

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Scaling laser systems to high powers or high energies, while remaining good beam quality and coherence, is of great interest in many applications such as remote sensing, light detection, and micro-machining. Unfortunately, a compromise is usually made in solid-state lasers between the beam quality and the power due to heat deposition and thermal lensing[1]. In general, diode end-pumped lasers can provide an excellent beam quality as the transverse fundamental mode can be preferentially excited, but with powers limited to only tens of watts or pulse energies in the order of millijoules. On the other hand, side-pumped lasers can produce much higher output power but with much poorer mode quality.

The generation of laser pulses with both high energy and good beam quality is usually based on the combination of a master oscillator and a power amplifier[2,3]. In a master oscillator power amplifier (MOPA) system, pulse width, beam quality, and spectral width are primarily determined by the oscillator, whereas pulse energy or power is determined by the amplifier. Operating an oscillator at relatively low energy levels can reduce beam divergence and spectral width, leading to a good beam quality. Therefore, from the MOPA laser system, one can obtain a high energy and high brightness light source.

Many power amplifiers employ a configuration allowing only single-pass amplification. This may be a problem for laser systems with either high power output or low power input. Efficient energy extraction from a high power amplifier requires that the input fluence is comparable to the saturation fluence of the laser transition[4]. Therefore, the output signal from the end-pumped master oscillator, usually too small to efficiently and completely extract hundreds of millijoules energy stored in the amplifier, needs to be pre-amplified or experience a multi-pass amplification. In this paper, a two-pass amplification configuration designed for a short-pulse MOPA laser system operating at high peak power with good beam quality is presented. The master oscillator in this MOPA system was a composite Nd:YVO_4 laser end-pumped with a 30-W optical fiber coupled laser diode array[5,6], and the power amplifier used a Nd:YAG rod as the gain medium pumped by a flashlamp. With these conditions, the MOPA system produced good beam quality pulses of approximately 8.5-ns long with a typical energy of 130 mJ.

Figure 1 shows the schematic layout of the MOPA system. The composite Nd:YVO_4 was used in the master oscillator as the gain medium to effectively reduce the thermal effects and their influence on the beam quality. The oscillator was diode end-pumped with a pump beam of 0.4 mm in radius, and Q-switched with an acousto-optic (AO) Q-switch inside the resonator close to the output coupler. The laser output from the master oscillator was linearly polarized, and thus any reflection was isolated by a Faraday isolator from entering the oscillator. In this way, the Faraday isolator can also prevent parasitic oscillation from occurring between the highly reflective rear mirrors of both the oscillator and amplifier. The Faraday rotator rotates the laser polarization of the oscillator's output by 45° from the vertical direction. A pair of mirrors were then used between the oscillator and the amplifier to control the direction and position of the laser beam within the amplifier. Before entering the amplifier, the laser beam was expanded by a telescope to increase the beam size to approximate 4 mm in diameter and reduce the beam divergence. The inserted half-wave plate was used to rotate the polarization state by a further 45° so that the beam was horizontally polarized, and could transmit

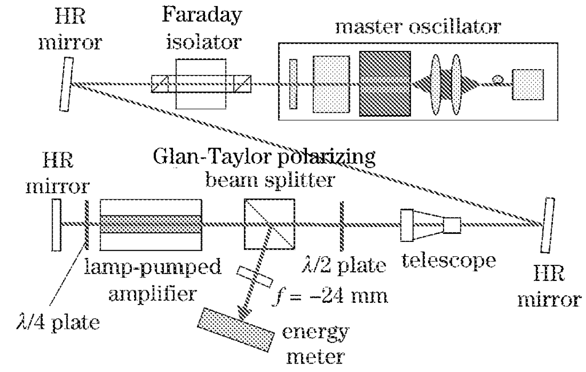

Fig. 1. Schematic layout of the two-pass amplification MOPA system.

through the following Glan-Taylor prism. A $\phi6\times110$ mm Nd:YAG laser rod in a gold-plated, single ellipse, and single flashlamp cavity was used for the amplifier, and the active length of the rod pumped by the lamp was 90 mm. On the far side of the amplifier, the light became circularly polarized after forward passing through a quarter-wave plate, then linearly and vertically polarized after being retro-reflected by the HR mirror and backward passing through the quarter-wave plate. Experiencing a second amplification through the amplifier, the laser beam was extracted efficiently by the Glan-Taylor prism.

Using the laser configuration described above, an output energy of ~130 mJ in a short pulse of 8.5 ns with good beam quality has been achieved. The initial experiments were performed at a pulse repetition frequency of 10 Hz, and a voltage of 450 V across the flashlamp to pump the amplifier. The pulse width of the flashlamp and the delay time from the lamp pulses to the oscillator pulses were both 0.5 ms. This delay allowed sufficient saturation of the population inversion in the amplifier gain medium. To characterize the laser amplification, we then investigated the dependence of amplification on both the input signal power and the amplifier's pump energy. The change of the former was made by increasing the current of the oscillator, and that of the latter by adjusting the voltage across the flashlamp.

The dependence of the amplification on the input signal from the oscillator is shown in Fig. 2. The pump pulse energy was 65 J, corresponding to a voltage of 450 V and a pulse duration of 0.5 ms. As can be seen, in the single-pass amplification, the amplifier output increased nonlinearly with the increase of the input pulse fluence, and the extraction efficiency was low as the obtained energy was smaller than 30 mJ. This can be attributed to the insufficiency of the input pulse energy. An efficient energy extraction from the amplifier can be achieved only with input pulses whose fluence is comparable to the saturation fluence of the amplifier gain medium[4]. To further elaborate this, we can describe the amplification behaviour using[2]

$$E_{\rm l} = E_{\rm s}\ln\{1+[\exp(\frac{E_{\rm i}}{E_{\rm s}})-1]\exp(g_0 l)\}, \tag{1}$$

where $E_{\rm s}$, $E_{\rm i}$ are the saturation fluence of the amplifier gain material and the input fluence to the amplifier, respectively, g_0 is the average small signal gain coefficient, l is the length of the amplifier gain material. The extraction efficiency is usually written as

$$\eta_{\rm l} = (E_{\rm l} - E_{\rm i})/g_0 l E_{\rm s}. \tag{2}$$

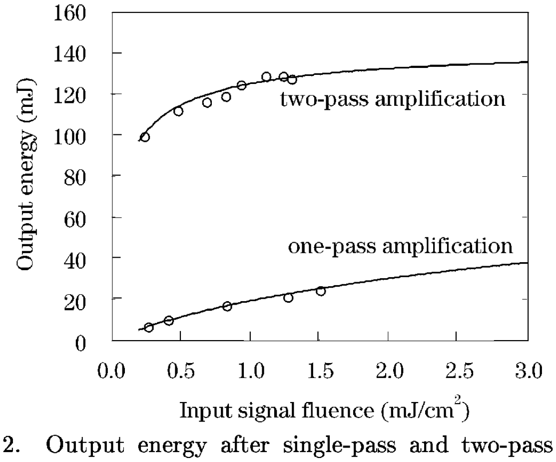

Fig. 2. Output energy after single-pass and two-pass amplification at various input pulse energies.

Equation (1) demonstrates that an approximately linear dependence of the output energy on the input energy requires $E_{\rm i} \gg E_{\rm s}$. In our case, the input signal fluence was ~1 mJ/cm^2, which is much smaller than 0.21 J/cm^2, the saturation fluence of Nd:YAG crystal used in our amplifier. As mentioned previously, there are three ways to improve the energy extraction: increasing the input energy, pre-amplification, and multi-pass amplification. Practically, an increase by orders in the pulse energy of the oscillator has been proved to be difficult without sacrificing the beam quality, whereas the MOPA configuration is aimed to achieve both high power and excellent beam quality. The pre-amplification is to boost the input signal to the sufficient level for high energy extraction. The multi-pass amplification is attractive as it avoids using multi-stage amplification in the pre-amplification. In the two-pass amplification, the first pass acts similarly to the pre-amplification by increasing the input fluence by orders higher, and the second pass extracts most of the stored energy.

The gain coefficient for the second pass g_0' is lower because the part of the stored energy has been extracted from the gain medium by the first pass,

$$g_0' = (1-\eta_{\rm l})g_0. \tag{3}$$

The output fluence E_2 from a two-pass amplifier can be calculated with[2]

$$E_2 = E_{\rm s}\ln\{1+[\exp(\frac{E_{\rm l}}{E_{\rm s}})-1]\exp(g_0' l)\}. \tag{4}$$

In the simulation, the average small signal gain coefficient g_0 was adjusted to match the output energy results of the first pass amplification. It has been found that the best fit to the experimental data can be achieved with the small signal gain coefficient g_0 being 5.3. Using the same value, the amplifier performance for the second pass amplification has also been simulated. The simulated results and experimental data are also presented in Fig. 2 for comparison. The results show that considerable improvement in output energy has been achieved after the two-pass amplification with pulse energy increasing from ~ 25 to >100 mJ. Particularly, one can get high extraction efficiency even with very small signal input energy. This is significant as excellent beam quality can be easily achieved in low power master oscillators.

Figure 3 shows the output energy of the amplifier as a function of the pump flashlamp voltage for both the single-pass and two-pass amplification configurations. The circular spots in the figure indicate the measured values, and the solid lines are the simulated results. It can be seen that the output energy increases rapidly with the increase of the incident optical pump energy, and the energy extraction efficiency of the two-pass amplification is much higher than that of the single-pass amplification. However, it was observed that at ~ 450 V voltage the increase in the two-pass output energy

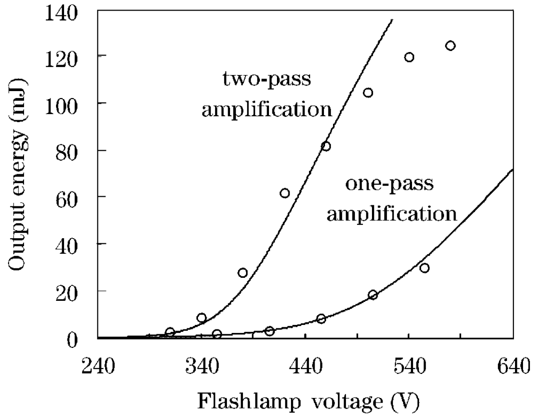

Fig. 3. Output energy of the amplifier as a function of pump voltage across the flashlamp.

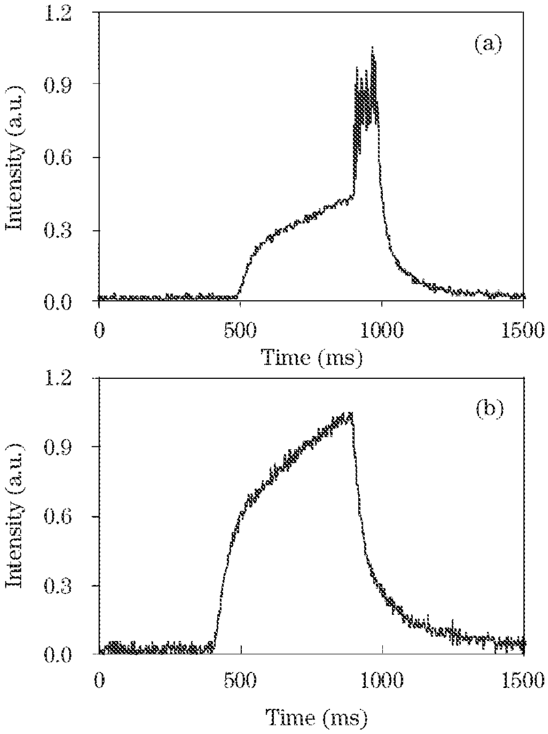

Fig. 4. Scattering radiation from the amplifier with (a) and without ASE (b).

seemed to be slowed down. Further increase in pump power did not result in significant increase in the output energy, and the limit was estimated ~130 mJ. The detailed investigation revealed that at ~450 V and above, laser action began to occur in the amplifier during the pumping phase. This is believed to result from the residual feedback of amplified spontaneous emission (ASE) from various interfaces along the optical path. The prelasing was observed by monitoring the scattered light of the amplifier with a fast photo-diode. The typical pulse shape with pre-lasing is shown in Fig. 4(a). The pre-lasing formation with a duration of ~0.1 ms and a delay time of ~0.4 ms can be seen on top of the pump pulse. Figure 4(b) shows the pulse temporal profile of the lamp without pre-lasing for comparison. The pre-lasing depleted the stored energy and thus reduced the available energy for amplification. The work to prevent ASE is under progress.

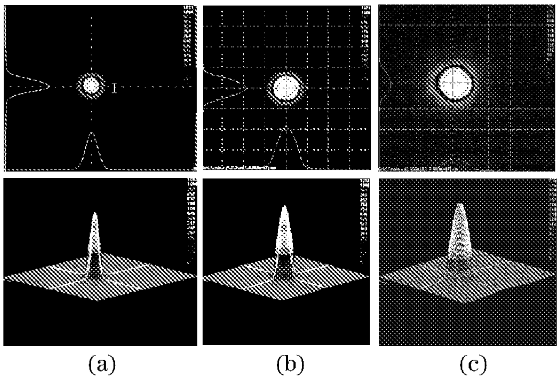

Fig. 5. The measured far-field beam profile energy distributions from the master oscillator (a), after single-pass amplification (b), and after two-pass amplification (c).

The measured far-field intensity distributions of the signal beam and the beams after single-pass and two-pass amplification are shown in Fig. 5. The graphs were taken with a Sprincon laser beam profiler. As can be seen from the beam profiles, the laser was operating at the fundamental mode with a very round symmetric beam pattern. The asymmetry was 1.07 for the master oscillator, and this became even better after single-pass and two-pass amplification to 1.05 and 1.03, respectively. The beam propagation factor M^2 was ~1.4 after two-pass amplification (It did not make much difference between single-pass amplification and two-pass amplification), which degraded slightly from ~1.3 of the oscillator.

In conclusion, a highly efficient, energetic, short-pulse, and reliable MOPA system with good beam quality has been demonstrated. The use of the two-pass amplification has significantly improved the energy extraction efficiency and simplified the system without a pre-amplification stage which is usually required for low input levels much smaller than the saturation fluence. The amplified pulses have a pulse energy of ~130 mJ, a pulse duration of 8.5 ns, and an M^2 factor of ~1.4, which degraded slightly from ~1.3 of the oscillator.

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