Energy reduction: a technique for seed-injection locking of single-axial-mode Q-switched Nd:YAG laser

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A new technique for seed-injection locking of single-axial-mode (SAM) Q-switched Nd:YAG laser is reported. The technique called energy reduction (ER) is utilized when SAM operation is locked to design its feedback scheme. This method ensures long-term 100% seed-injection locking performance and the pulsed SAM output energy can reach as high as 200 mJ. Both temporal and spatial interferometric experiments have been executed to confirm the SAM oscillation.

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The high energy pulsed Nd:YAG lasers operating in stable single-axial-mode (SAM) with Fourier transform limited bandwidth are desirable light sources for holography, lidar, nonlinear-optic studies, and high-resolution spectroscopic applications[1−4]. Among many axial mode selective techniques, seed laser injection has been proven to be a more effective and reliable method to achieve SAM oscillation due to its higher efficiency and higher damage threshold.

Seed laser injection uses a low power output laser with narrow spectral bandwidth (seed laser) to control the properties of an oscillator with much higher power (slave laser). It can be proven theoretically that the seed-injection locking threshold depends on the detuning of the seed and slave lasers. The more detuning exists, the higher seed laser power is required. Actually, the seed laser always runs in low power level to obtain perfect output light beam quality.

Usually the seed-injection Q-switched laser system requires an additional feedback scheme to achieve long-term stable SAM operation. The feedback scheme minimizes the detuning of the seed and slave lasers by detecting a typical characteristic of SAM oscillation and optimizing the cavity length of the slave resonator. To our knowledge, there are two kinds of feedback schemes sorted by the characteristic of the SAM oscillation detected: build-up time reduction (BUTR)[4] and resonator sweeping interference[5−7]. Often the commercial SAM pulsed Nd:YAG lasers are designed by BUTR, while the resonator sweeping interference technique can be applied to high noise and vibration environments like carrying laser in aeroplane.

Recently, we have developed a new seed laser injection locking technique that detects the SAM output energy reduction (ER) other than the characteristics utilized before. The reliability of the ER servo circuit benefits from the high signal-to-noise ratio (SNR) of the design. Since the ER and the BUTR have many semblances, each technique can be an alternative designing route for the other.

The seed laser injection experiments in Nd:YAG indicated that the SAM operation decreased the output energy by 15% with respect to the multi-mode oscillation. The ER phenomenon is an effect induced by inhomogeneous saturation gain broadening.

The 1064-nm transition in Nd:YAG is composed of two independent Lorentzain transitions which are independently homogeneously broadened: the principal line is centered at 1064.2 nm while the secondary emission occurs at 1064.5 nm. A further description about 1064-nm transition in Nd:YAG has been given by Danielmeyer[8]. The two components are separated by 3 cm^{-1} which is less than the approximate gain bandwidth of 5 cm^{-1}. The overlap of the two spectral lines induces inhomogeneous saturation gain broadening on a time scale of Q-switched pulse time interval in Nd:YAG.

When SAM oscillation occurs, the inhomogeneous saturation gain means not all of the inverted population contributes to the output energy. This situation decreases the output energy of SAM oscillation by 15% relative to the multi-mode operation which can detract all of the inverted population. Park *et al.* has established a model based on this situation and given numerical solutions to account for the principal effects of the 1064-nm transition during SAM operation[9−11].

Figure 1 shows the experimental results of the output energy modulated by the cavity length of the slave

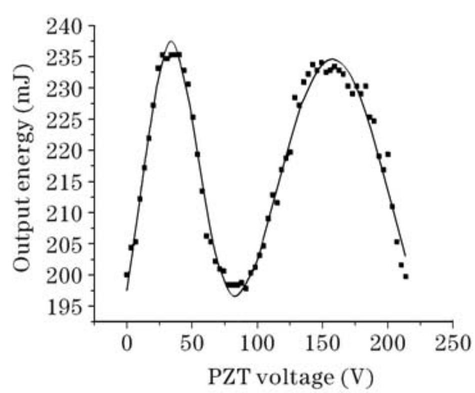

Fig. 1. Output energy modulated by the length change of the slave resonator.

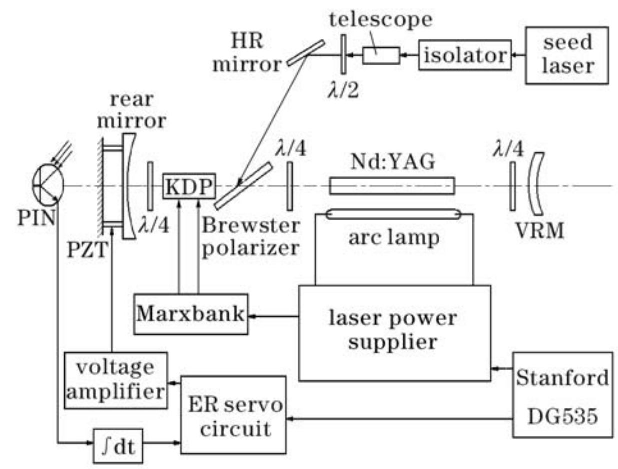

Fig. 2. Schematic of the ER experimental setup.

resonator. The longitudinal axis indicates the output energy and the unit is millijoule. The transverse axis is the voltage put upon the piezoelectric transducer (PZT) which controls the cavity length of the slave resonator approximately linearly. The modulated output energy appears to be periodically rising and falling as the PZT sweeping monotonously. The valley of the profile points to the resonance of the seed and slave lasers, hence, the minimal detuning of the two. The software of the ER servo system is negative feedback designed, which can keep the output energy near the lowest point of the profile to lock the SAM operation by adjusting the cavity length of the slave resonator.

Figure 2 is the schematic sketch of the ER experimental arrangement. An unstable Cassegrainian resonator with a variable reflectivity output mirror (VRM) was applied to the slave resonator. Since a long time constant of the system was a crucial key to the feedback loop, all the optical elements were firmly fastened to an invar framework and were mounted into dust tubes to minimize the influences of ambiance. The seed laser gave out a continuous wave (CW) TEM_{00} laser beam with 2-mW maximal output power (Lightwave Mode 101-1064-002). The pulsed laser system was 10-Hz repetitive rate. In practice, the transverse modes overlap of the seed and slave lasers was very important to seed injection technique. An adjustable telescope was used to change the seed laser beam waist to ensure their transverse modes overlap. A 50-dB optical isolator was enough to decouple the seed and slave lasers for the frequency stability and the protection of the seed laser.

The output pulses were observed using a 1.5-GHz oscilloscope (Tektronix TDS 7154) with a high-speed PIN photo detector (Thorlabs Model D400FC). Figure 3 shows no mode-beating-induced temporal modulation as seed laser injection is locked. The mode-beating-induced temporal modulation could be very serious during multi-mode operation, as shown in Fig. 4.

We experimentally confirmed the SAM operation of our ER system by etalon interferometric observations. Figures 5 and 6 were captured by an IR vidicon (MITRON MTV-1881EX) through a 27.5-MHz free-spectral-range Fabry-Perot etalon. Figure 5 shows a SAM laser shot corresponding to the waveform of Fig. 3.

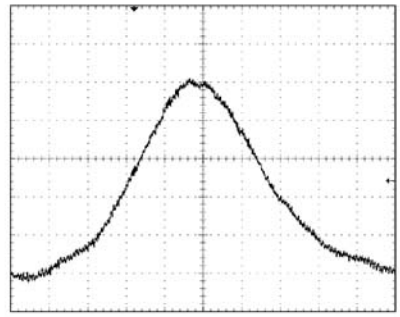

Fig. 3. Smooth oscilloscope profile of SAM operation.

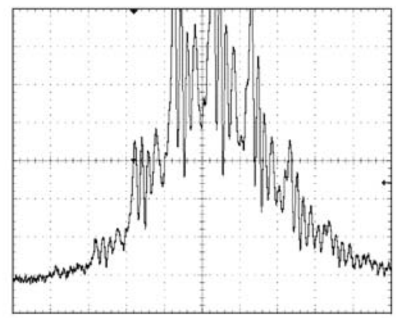

Fig. 4. Mode-beating profile of multi-mode operation.

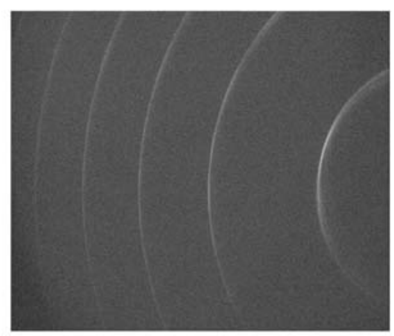

Fig. 5. Interferometric image of SAM operation.

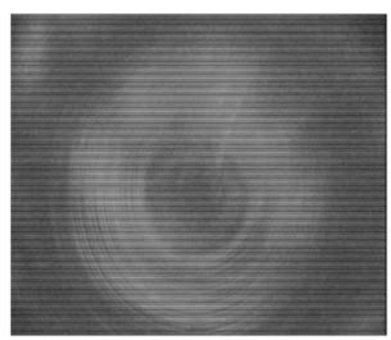

Fig. 6. Interferometric image of multi-mode operation.

It can be deduced from the image that the bandwidth of the SAM output is much narrower than the free-spectral-range of the slave resonator of 200 MHz, but close to the Fourier transform limit of the pulse width of 30 MHz. Figure 6 was captured when the seed laser was cut off, corresponding to the waveform of Fig. 4. Also it can be deduced from Fig. 6 that the bandwidth of the multi-mode oscllation is about 30 GHz.

In conclusion, the ER seed-injection-locking technique is a simple and practicable way to get stable SAM operation in the Q-switched laser system. The experimental results showed that the ER Q-switched laser system had achieved reliable long-term SAM operation within Fourier-transform-limited bandwidth. The single frequency laser pulse output could reach as high as 200 mJ, and the jitter of output was within ±1% (RMS of 300,000 shots, SAM locked). The system performed successfully in investigation of longitudinal stimulated Brillouin scattering in K9 glass and fused silica[12]. An ER SAM laser system with much higher repetition rate will soon be achievable in our laboratory when pump diodes substitute the arc lamp[1].

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