High-power monolithic unstable-resonator solid-state laser

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We report the operation of a diode-pumped monolithic Q-switched unstable-resonator solid-state laser that generates 2.15-mJ, 2-ns pulses in a single transverse mode and a single longitudinal mode. We show that the unstable resonator is effective in suppressing the spatial and the temporal instability of the laser beam in a disk-shaped laser whose transverse dimension is comparable with or larger than its longitudinal dimension.

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Monolithic solid-state lasers are promising for use as compact, rugged, and stable oscillators. In a monolithic laser resonator there are no intracavity components for transverse-mode control, frequency selection, and light modulation. These functions must be performed either by the resonators or by the laser materials. In what is believed to be the first reported diode-pumped monolithic Nd:YAG laser,[1] the transverse mode was determined by the curvature of the resonator mirrors that were formed at the end of the crystal. In monolithic microchip lasers,[2,3] the single transverse mode is defined by a thermally induced waveguide and by the gain profile created by the pump, whereas single-frequency operation is the result of a short cavity length. In monolithic Q-switched lasers light modulation, transverse-mode control, frequency selection, and polarization selection are performed by the effects of the saturable absorbers in the laser material.[4–6]

The monolithic solid-state lasers that have been reported to date were all end pumped by diode lasers. Their cavity lengths ranged from a fraction of a millimeter to several millimeters. Their output pulse energies ranged from several microjoules for a 200-μm-diameter excitation cross section[3–5] to 160 μJ for a 0.2 mm × 4 mm excitation cross section.[6] The pulse energy was proportional to the excited volume of the gain medium. To achieve higher pulse energy, one must proportionally increase the volume of the excited gain medium, and the configuration of the end mirrors must be properly chosen so that it supports a stable TEM$_{00}$ mode. To achieve 1-mJ pulse energy, one estimates the diameter of the excited gain medium to be 1 mm, resulting in a disklike resonator whose transverse dimension is comparable with or greater than its longitudinal dimension was used. A diskshaped resonator is characteristic of high-pulse-energy miniature solid-state lasers.

Standard resonator theory shows that when the cavity length is comparable with the beam waist a conventional stable resonator can no longer effectively stabilize the transverse mode. For example, to support an eigenmode with a beam waist of 1 mm in a planar–concave resonator of 5-mm cavity length, one must have a concave mirror with a radius of curvature of 6.4 km. A planar-concave resonator with such a large radius of curvature is not very different from a planar–planar cavity, and the beam characteristics of the former are susceptible to other lensing effects caused by the temperature and the gain gradients in the laser material rather than by the mirrors of the resonator. It was also reported that the laser output generated by a planar–planar laser cavity with a large beam cross section was temporally unstable and exhibited a transient evolution of the beam profile during the pulse.[6]

In this Letter we report the operation of a monolithic Q-switched unstable-resonator Cr,Nd:YAG laser whose beam waist is comparable with its cavity length. We demonstrate that the unstable resonator effectively stabilizes the spatial and the temporal characteristics of the lasing mode. Using a 5-mm-long, 6-mm-diameter monolithic cavity, we obtained pulses of 2.15-mJ pulse energy and 2-ns pulse duration in the fundamental transverse mode and a single longitudinal mode with high degrees of spatial and temporal stability. Previously, compact passively Q-switched Nd:YAG lasers yielded single-frequency pulses of 1.5-mJ pulse energy in the linear cavity and 2.1 mJ in the ring cavity with an intracavity etalon.[7] To the best of our knowledge, our experiment produced the highest-pulse-energy single-frequency laser pulse ever reported in a monolithic device.

The monolithic Cr,Nd:YAG laser shown in Fig. 1 is 5 mm long and 6 mm in diameter. Q-switched operation in this laser was induced by Cr-related saturable absorbers distributed within the gain medium. The unsaturated absorption coefficient of Cr is 0.32 cm^{-1} at 1064 nm. We polished the end surfaces of the laser rod to form a planar–convex cavity. The convex mirror has a radius of curvature of 3 m and is coated for high transmittance at 808 nm and >99.9% reflectance at 1064 nm. The planar output coupler is coated for 90% reflectance at 1064 nm. The pump laser is a stacked-bar diode-laser array operated in the quasi-cw

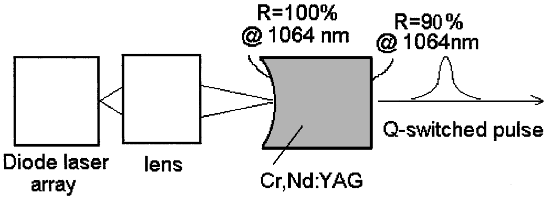

Fig. 1. Schematic of a diode-pumped monolithic Q-switched unstable-resonator Cr,Nd:YAG laser.

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mode, with a pulse duration of 250 ms at repetition rates from 1 to 25 Hz, restricted by the duty-cycle limitation of the diode laser array. The fast axis of the diode-laser output was collimated by a cylindrical lens array. The collimated beam was focused to a 6 mm × 2 mm oval-shaped spot. The threshold condition was reached when the pump power was 184 W.

Q-switched operation produced pulses with 2-ns pulse duration and 2.15-mJ pulse energy in a single frequency without pulse-to-pulse mode hopping. The peak power was 1.15 MW. The optical-to-optical energy-conversion efficiency was 4.6%, which is lower than the estimated optical-to-optical efficiency of 7.5% in passively switched external linear cavity Nd:YAG lasers.[7] The high (90%) reflectivity of the output coupler in the present device is one of the factors that affected the energy-conversion efficiency.

Figure 2 shows the beam profiles measured at the output coupler and at the virtual source. The output beam divergence was measured to be 1.8° in the vertical direction (defined by the p–i–n junction of the diode laser) and 4.8° in the horizontal direction. The asymmetry in the beam divergence is related to the oval-shaped virtual source. The virtual source is located at 5.6 cm behind the curved mirror, in agreement with the calculated distance of 5.8 cm. The dimensions of the virtual source are 90 μm × 18 μm. No astigmatism was observed. The depression at the center of the beam profile is reminiscent of that observed in unstable-resonator semiconductor lasers[8] and can be attributed to a wave front that deviates from a cylindrical shape in the presence of a loss gradient in the horizontal direction.[7]

The beam profile remained unchanged for repetition rates from 1 to 25 Hz, indicating that the thermal-lensing effect was not an important factor under our experimental conditions. The temperature increase during the pump pulse was less than 0.12 °C. The calculated effective focal length of the thermally induced refractive-index gradient, $\sim 1 \times 10^{-6}$ over a 3-mm distance, was 1 km, which caused insignificant beam shaping in the presence of a convex mirror of 1.5-m focal length.

We carried out a time-resolved beam-profile measurement to study the temporal stability of the laser output. The waveforms of the pulses at various positions in the laser beam were recorded by use of an avalanche photodiode in conjunction with a digital oscilloscope. The recorded temporal waveforms at various positions were then translated into a series of intensity distributions of the laser beam at various times during the pulse. The results are shown in Fig. 3. The general feature of the beam profile was established from the beginning of the pulse and remained nearly unchanged during the pulse. In contrast, the time-resolved beam profiles of the output beam generated by the monolithic Q-switched laser with the planar–planar resonator exhibited temporal variation throughout the entire pulse, as shown in Fig. 4. The planar–planar resonator laser was formed by a Cr,Nd:YAG crystal of identical composition and dimensions with 100% and 95% reflectance on the end mirrors.

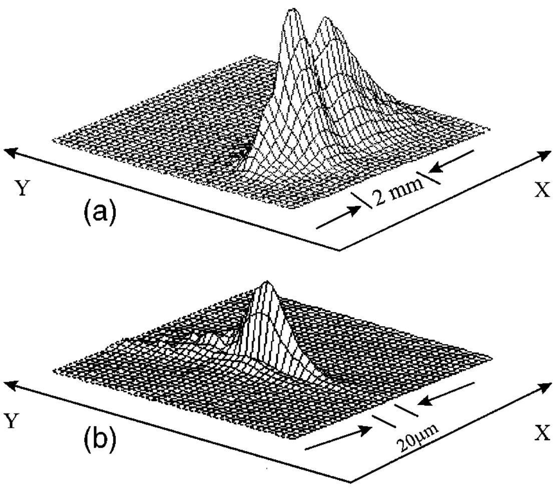

Fig. 2. Beam profiles of the laser beam at (a) the output coupler and (b) the virtual source.

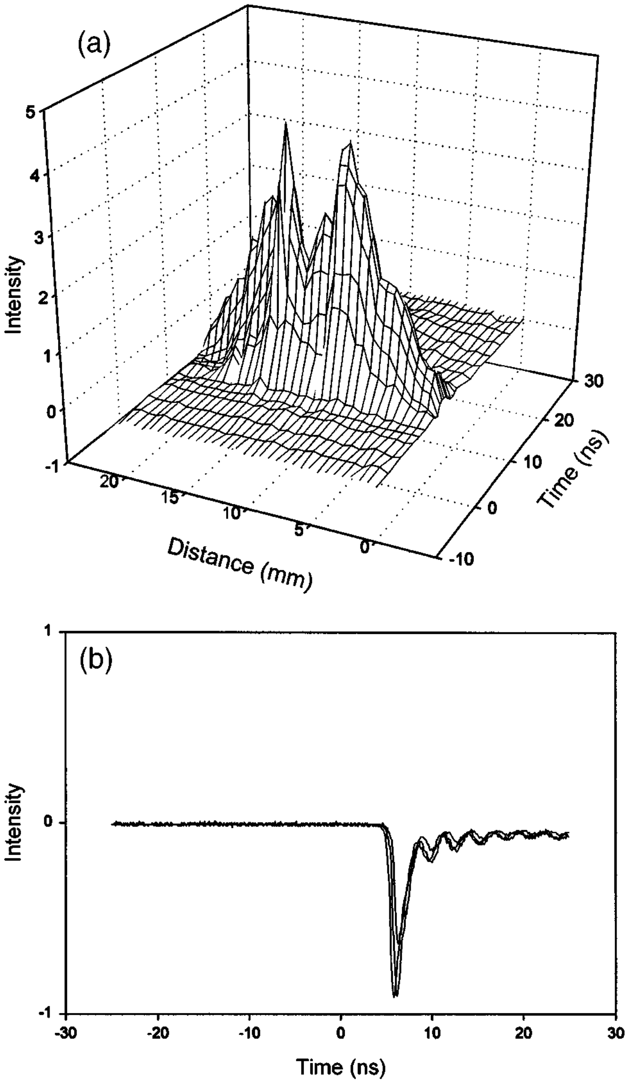

Fig. 3. (a) Time-resolved beam profiles of the output of the unstable-resonator laser and (b) pulse shapes taken at various transverse positions of the laser beam.

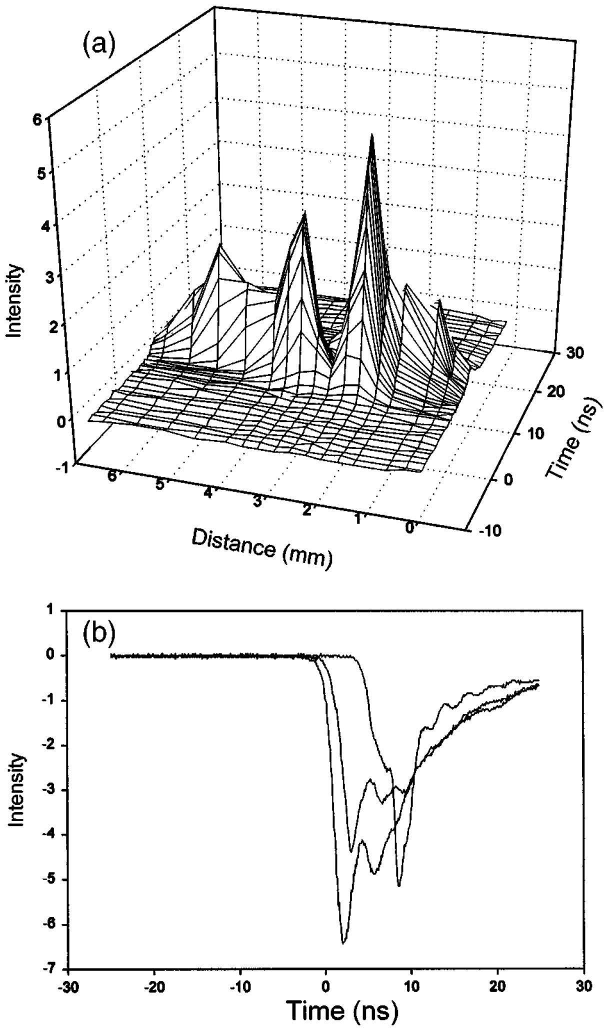

Fig. 4. (a) Time-resolved beam profiles of the output of the planar–planar resonator laser and (b) pulse shapes taken at various transverse positions of the laser beam.

The present study shows that an unstable resonator considerably accelerates the development of a stable spatial profile of the laser beam. One can estimate the time needed to develop a stable laser beam in a flat–flat cavity without a strong beam-shaping mechanism by unfolding the laser cavity and considering the propagation of a laser beam in a homogeneous medium. For an initial electric field of arbitrary spatial distribution in amplitude and phase, a steady-state beam profile that corresponds to that in the far field can be developed only after the beam propagates a distance z that is much larger than the Rayleigh distance, or $z \gg d = n\omega^2\pi/\lambda$, where ω is the beam width, $n = 1.8$ is the index of refraction of yttrium aluminum garnet, and λ is the wavelength. For a laser beam of 2-mm radius, $z \gg 2000$ cm, which corresponds to a propagation time $t \gg d/c = 75$ ns, which is longer than the pulse duration. Thus the Q-switched laser pulses generated by the planar–planar resonator exhibit transient evolution in the beam profile during the pulse. It is well known that a lens or a spherical mirror can bring a steady-state pattern that would be formed in the far field at $z \gg d$ closer to the focal point. In the present unstable-resonator laser the laser beam traveling inside the cavity undergoes periodic reimaging between the two virtual sources. The transition from the near field at the virtual source to the far field at the output coupler takes place over a 6-cm distance, which explains the fast establishment of a stable laser beam.

In conclusion, the use of an unstable resonator considerably accelerates the formation of a stable laser beam in a Q-switched laser whose transverse dimension is comparable with its longitudinal dimension. With an unstable-resonator configuration, a monolithic Q-switched laser, 5 mm in length and 6 mm in diameter, generated 2.15-mJ, 2-ns pulses in a single transverse mode and a single longitudinal mode with high degrees of spatial and temporal stability.

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