Self-stabilized single-longitudinal-mode operation in a self-Q-switched Cr,Nd:YAG laser

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It is shown, both theoretically and experimentally, that stable single-longitudinal-mode operation, with transform-limited spectral linewidth and without pulse-to-pulse mode competition, can be obtained in a monolithic self-Q-switched Cr,Nd:YAG solid-state laser with a distributed saturable absorber. In this system, the lasing mode establishes a loss grating and thereby stabilizes itself.

Single-longitudinal-mode operation in a homogeneously broadened solid-state laser is often impeded by spatial hole burning. To maintain a single longitudinal mode, it is necessary to eliminate spatial hole burning, for example, by introducing quarter-wave plates at both ends of the gain medium[1] or by using a ring cavity.[2] In a standing-wave resonator, an additional wavelength-selective element, such as an étalon[3,4] or a mirror,[5] can also lead to single-longitudinal-mode operation. Active techniques such as seeding[6,7] and the prelase method[8] have also been reported. The use of a microchip cavity is also effective.[9]

Whereas spatial hole burning in the gain medium tends to promote multilongitudinal-mode operation, the same hole-burning effect combined with distributed saturable absorbers can stabilize the single-longitudinal-mode operation. This is because the lasing mode can bleach a loss grating in the saturable absorber and create a low-loss window to enhance itself. To illustrate this effect, we consider a monolithic cavity with a uniformly distributed saturable absorber. The power density of the standing waves has a sinusoidal spatial distribution given by

$$P(\lambda, z) = P_0 \sin^2(2\pi n z/\lambda), \qquad (1)$$

where P_0 is the amplitude of the standing waves, λ is the wavelength of the longitudinal mode, and n is the refractive index. The spatial distribution of the absorption coefficient along the cavity axis established by the standing waves at wavelength λ can be expressed as

$$\alpha(\lambda, z) = \alpha_0/[1 + P(\lambda, z)/P_{\mathrm{sat}}], \qquad (2)$$

where α_0 is the unsaturated absorption coefficient and P_{sat} is the saturation power density. In the presence of a dominant lasing mode of wavelength λ_0, the effective absorption coefficient of the axial mode at wavelength λ can be calculated by

$$\alpha(\lambda) = \int \alpha(\lambda_0, z)P(\lambda, z)\mathrm{d}z \bigg/ \int P(\lambda, z)\mathrm{d}z\,. \qquad (3)$$

The calculated absorption coefficients for the axial modes of various orders in the presence of a center mode, defined as order 0, at various power densities are plotted in Fig. 1. The lasing mode establishes a narrow low-loss window that suppresses the adjacent modes. Moreover, in a monolithic cavity the spectral width of the low-loss window is always narrower than the free spectral range of the cavity. This effectively removes the restriction on the maximum cavity length for single-longitudinal-mode operation.

Using a monolithic Nd:YAG laser codoped with saturable absorbers, we demonstrated, for the first time to our knowledge, stable single-axial-mode operation, without pulse-to-pulse mode competition, in a solid-state laser that with a free spectral range of less than 1/10 of the gain bandwidth would normally operate in multilongitudinal modes. The structure

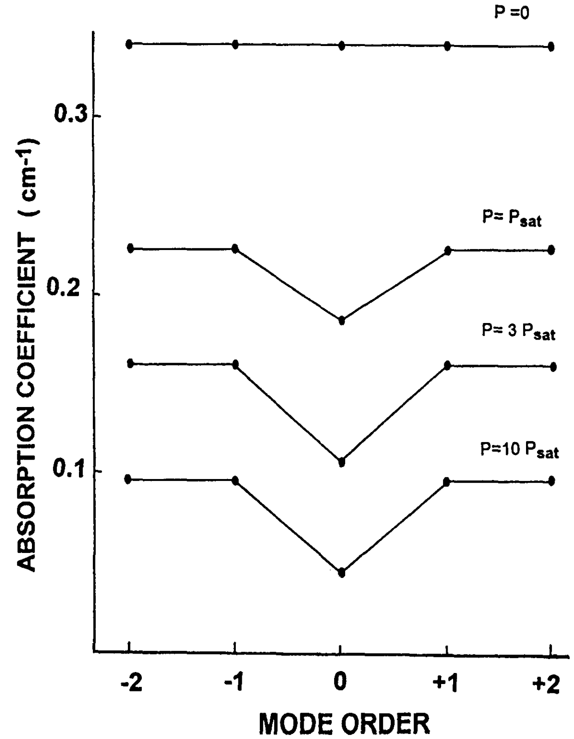

Fig. 1. Calculated loss spectrum of the lasing mode (order 0) and adjacent longitudinal modes (orders ±1, ±2) in the presence of a lasing mode (order 0) at various power densities.

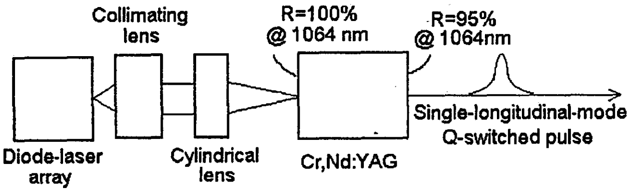

Fig. 2. Schematic of the self-Q-switched laser.

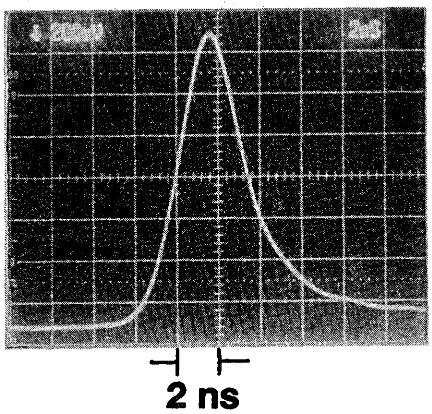

Fig. 3. Waveform of the Q-switching pulses. The trace is a superposition of 200 pulses.

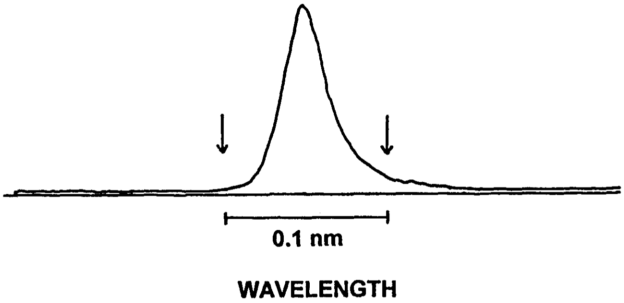

Fig. 4. Measured lasing spectrum of the self-Q-switching pulses. The width of the laser line reflects the resolution of the grating spectrometer. The arrows indicate the positions of adjacent longitudinal modes.

of the monolithic laser device is shown in Fig. 2. The cavity consists of a 5-mm-long Cr,Nd:YAG crystal with 1 wt. % Nd^{3+}. The cavity mirrors have 100% and 95% reflectivity. The pump source is an AlInGaAs/GaAs strained-quantum-well diode-laser array emitting at an 808-nm wavelength. The diode-laser output, after beam shaping, is focused onto a 100-μm-diameter area at the gain medium. The diameter of the pump beam varies by <30% within the cavity. Approximately 80% of the pump energy is absorbed in the gain medium. The absorption coefficient at 1064 nm is 0.32 cm^{-1} at low power. The saturable absorber is believed to be associated with Cr^{4+}.[10–12] The saturation power density at 1064 nm is measured to be 3.6 MW/cm^2.[13] With proper alignment, the laser generates Q-switched pulses in the TEM_{00} mode with 3.5-ns FWHM pulse duration. With a pump energy of 250 μJ, the pulse energy is 10 μJ. The net optical energy conversion efficiency is 5%. To extend the lifetime of the diode laser, all measurements reported herein were carried out with 250-μs square pulses at repetition rates of <100 Hz, corresponding to a 2.5% duty cycle. For longer pump pulse durations, multiple Q-switched pulses have been observed. During operation in a low duty cycle, the transverse mode is confined mainly by the imaginary part of the refractive-index step that is due to the high absorption loss outside the pumped region. Figure 3 shows the superposition of the waveforms of ~200 Q-switched pulses. The pulse-to-pulse intensity fluctuation is <0.1%. There are also no detectable pulse-shape variations.

Figure 4 shows the lasing spectrum of the Q-switched pulses measured by a grating spectrometer. The laser stably operates in single longitudinal mode without pulse-to-pulse mode competition over a 2-h testing period. In contrast, a monolithic Nd:YAG laser with 5-mm cavity length operates in single mode only for powers of <1.2 mW.[12] The spectral linewidth measured with a high-finesse Fabry–Perot interferometer is 120 MHz. With the instrument resolution of 20 MHz, the 3.5-ns-long pulses are nearly transform limited.

With the self-stabilization mechanism, there is no restriction on the cavity length of the monolithic device as in the microchip lasers. It is thus possible to achieve higher pulse energy by using a longer gain medium. A monolithic structure is simple, compact, stable, and suitable for power scaling in a two-dimensional array. Potential applications of such devices include remote sensing, nonlinear frequency generation, and injection seeding for high-power laser amplifiers.

In conclusion, we have shown that the loss grating established by the lasing mode in a monolithic cavity with a distributed saturable absorber leads to single-longitudinal-mode Q-switched operation with transform-limited pulses without pulse-to-pulse mode hopping.

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