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 or by using a ring cavity. In a standing-wave resonator, an additional wavelength-selective element, such as an étalon or a mirror, can also lead to single-longitudinal-mode operation. Active techniques such as seeding and the prelase method have also been reported. The use of a microchip cavity is also effective.

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

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

where $P_0$ is the amplitude of the standing waves, $\lambda$ 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 $\lambda$ can be expressed as

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

where $\alpha_0$ is the unsaturated absorption coefficient and $P_{\text{sat}}$ is the saturation power density. In the presence of a dominant lasing mode of wavelength $\lambda_0$, the effective absorption coefficient of the axial mode at wavelength $\lambda$ can be calculated by

$$\alpha(\lambda) = \int \alpha(\lambda_0, z) P(\lambda, z) dz / \int P(\lambda, z) dz.$$ 

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.
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. % Nd³⁺. 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 Cr⁴⁺.10-12 The saturation power density at 1064 nm is measured to be 3.6 MW/cm².13 With proper alignment, the laser generates Q-switched pulses in the TEM₀₀ 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.

References