Analysing the pulse formation of *Q*-switched Nd:YAG laser with super-Gaussian mirror resonator

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A numerical model is presented to predict the time-resolved evolution of the spatial intensity distribution of the laser pulses in the super-Gaussian mirror resonator, taking into account diffraction and stored energy depletion. The beam-quality factor M^2 is calculated during the pulse evolution. Simulation results show that gain saturation affects the beam quality of the Q-switched solid-state lasers, the corresponding values of the M^2 parameter increase during the pulse evolution. The spatial distribution of laser pulse first starts on the resonator axis with a Gaussian-shaped spot, then expands very quickly and forms a donut-shaped profile towards the end of the pulse.

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In some applications such as material processing, optical spectroscopy, and nonlinear frequency conversion where the temporal and the spatial shapes of the laser intensity distribution are of importance, the spatio-temporal characteristics of the laser pulses should be certainly considered. Caprara[1] and Anstett *et al.*[2] reports on an experimental investigation of the spatio-temporal pulse evolution from a flashlamp-pumped, Q-switched Nd:YAG lasers with Gaussian mirror (GM) resonators. Using GM, as a soft-edge diaphragm, the intensity distributions of output laser are improved. Gaussian reflectivity profiles, however, do not allow an efficient exploitation of the active material, because Gaussian mode spreads to a considerable distance from the resonator axis. Thus, to avoid beam perturbations originating from diffraction at the edge of the active material, the spot size has to be significantly smaller than the active material cross section. Super-Gaussian mirror (SGM) is a development of GM[3,4]. Due to better filling of the active material, SGM allow energies higher than those generated by GM to be obtained, yet preserving superior beam qualities. This paper we present the results of a numerical simulation of the spatio temporal characteristics of the laser pulses from an unstable resonator with SGM.

Ours numerical model takes the laser amplification, gain saturation, stored energy depletion, and diffraction of the laser beam into account. The calculation in the laser cavity and inside the laser crystal is divided into several steps controlled by an adaptive step-size control, as described in Fig. 1. Diffraction in the laser crystal and during free-space propagation is calculated using fast Fourier transform (FFT) method according to the angle spectrum theory of diffraction:

$$U(x,y,z) = F^{-1}\left\{ F\left[U_0(x_0,y_0,0)\right] \times \exp\left(j\frac{2\pi}{\lambda} z\sqrt{1-(\lambda f_x)^2-(\lambda f_y)^2}\right)\right\}, \quad (1)$$

where f_x and f_y are corresponding the frequency domain coordinates of the coordinates x, y of special domain, λ is wavelength. F and F^{-1} are the Fourier transform and invert Fourier transform, respectively. $U(x,y,z)$ is the complex electromagnetic amplitude. Reflection from a mirror (refraction in a transmitting mirror) can be represented by the multiplication of the complex wave amplitude by the transfer function of resonator mirror,

$$T(x,y) = R(x,y)\exp\left(-j\frac{2\pi}{\lambda}\frac{x^2+y^2}{2f}\right), \quad (2)$$

where f is the focal length of mirror, $R(x,y)$ is the reflectivity function of mirror. For total reflector, $R(x,y)=1$; For SGM, $R(x,y)$ is expressed by

$$R(r) = R_0\exp\left[-2\left(\frac{r}{w_m}\right)^n\right], \quad (3)$$

where R_0 is the peak (or central) reflectivity, w_m is the $1/e^2$ radius of the radial coating profile, n is the super-Gaussian mode order.

Gain saturation and depletion of the stored energy are described by

$$g_{k+1}(x,y,z) = g_k(x,y,z) - \frac{J'_k(x,y,z) - J_k(x,y,z)}{J_s}, \quad (4)$$

where $g_k(x,y,z)$ is the small-signal gain for pass number k, $J_k(x,y,z)$ is the fluence of pass number k, $J'_k(x,y,z)$ is the corresponding amplified fluence, and J_s is the saturation fluence of the laser medium. We suppose that there is no gain recovery during the full formation of the

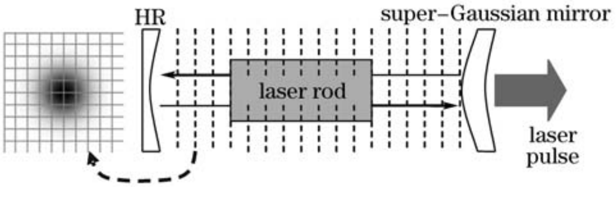

Fig. 1. Super-Gaussian mirror resonator layout.

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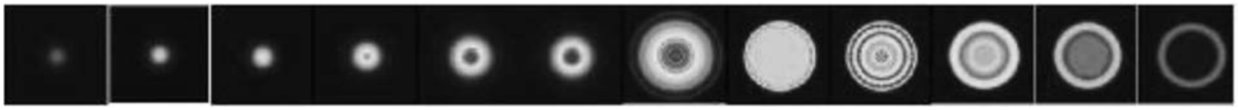

Fig. 2. Numerical results of Q-switched laser spatio-temporal pulse evolution.

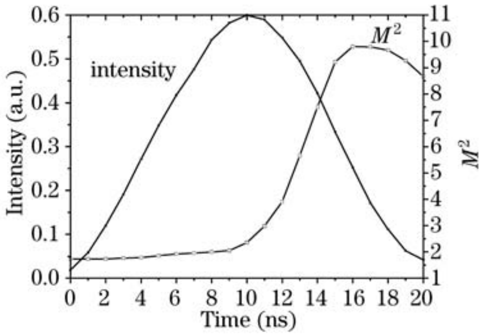

Fig. 3. Calculated temporal pulse shape and temporal development of the M^2 values.

laser pulse. According to the Frantz-Nodvik equation

$$J_k'(x,y,z) = J_s \ln\big(G_k(x,y,z) \times \Big\{\exp\left[J_k(x,y,z)/J_s\right]^{-1}\Big\} + 1\big), \quad (5)$$

where $G_k(x,y,z) = \exp[g_k(x,y,z)]$.

The beam quality represented by the factor M^2 value was calculated by using the first and second moments of the complex fields in the spatial and spatial-frequency domains as presented in Ref. [5].

The parameters used in the numerical calculations are as follows. The laser medium was a 1% doped Nd:YAG with a length of 12 cm and a diameter of 8 mm. The initial inversion was assumed to be spatially homogeneous at a value of 10^{18} cm^{-3}. The resonator length is 0.50 m, the rear mirror radius of curvature is -3.25 m, the SGM with super-Gaussian order of 4, super-Gaussian $1/e^2$ radius of 2.7 mm, peak reflectivity of 0.4, and radius of curvature of 4.25 m.

Figure 2 displays the calculated time-resolved evolution of the spatial intensity distribution of the laser pulses. The laser pulse first starts on the resonator axis with a Gaussian-shaped spot, then the spatial distribution expands very quickly and the intensity distribution is strongly non-Gaussian, and then forms a donut-shaped profile towards the end of the pulse.

Figure 3 shows the calculated temporal pulse shape and the temporal evolution of the M^2 values. The temporal distribution is close to Gaussian shape. The M^2 values start at a value close to 1.6 but during the pulse evolution M^2 increase very rapidly to almost 10 in the decreasing slope of the pulse. The increase of M^2 is understood by considering the gain saturation and inhomogeneous depletion of the laser inversion.

In conclusion, the temporal and spacial beam properties of the Q-switched laser pulse is analyzed from a positive-branch unstable resonator with a super-Gaussian coupling mirror. An important result is that gain saturation affects the beam quality of the Q-switched solid-state lasers and that the effect is larger for higher energy pulses. Simulation results show that the laser pulse starts with a Gaussian intensity distribution, but becomes rapidly non-Gaussian. The corresponding values of beam quality M^2 factor is seen to vary approximately from 1.6 at the beginning of the formation of the pulse to almost 10 in the tail of the pulse.

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