Spatial and temporal distribution of Q-switched laser pulses in multimode regimes

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The spatial and temporal distribution of Q-switched diode-pumped solid-state laser (DPSSL) pulses is investigated in multimode regimes. A theory model of spatial and temporal distribution of multimode Q-switched DPSSL pulses is established. The influences of position, initial population inversion density, and mode ratio on pulse width are studied. The results show that the pulse expands in the position wherein two or more mode intensities are equivalent, and the pulse building time difference of the modes are less than one mode pulse width. These results can be applied in pulse compression and mode composition. OCIS codes: 140.0140, 140.3480, 140.3538.

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Q-switched diode-pumped solid-state lasers (DPSSLs) are a hot topic in research[1−4] because of their wide variety of applications, such as material processing, nonlinear optics, remote sensing, medical applications, and laser ranging[5−8]. Much attention has been paid to pulse width research[9−11] because most existing applications depend on the operation pulse width[12−14]. The pulse width of Q-switched lasers is calculated under a top-hat pump beam distribution[9]. The pulse width of miniature passively Q-switched lasers are calculated accounting for thermalization and relaxation processes[10]. The pulse shape of Q-switched lasers has been described in detail in multimode regimes[11]. However, research on the spatial and temporal distribution of Q-switched DPSSL pulses has not been reported. The spatial distribution of pulse width in Q-switched DPSSLs in a single mode has been studied recently[15,16]. For multimode lasers, the spatial and temporal distribution of Q-switched DPSSL pulses should be investigated in multimode regimes.

In this letter, an acousto-optic (AO) Q-switched DPSSL is built. The spatial and temporal distribution of multimode Q-switched DPSSL pulses is measured. A theory model of the spatial and temporal distribution of multimode Q-switched DPSSL pulses is established. The influences of position, initial population inversion density, and mode ratio on pulse width are investigated in multimode regimes. The pulse expands in the position wherein two or more mode intensities are equivalent and the pulse building time difference of the modes is less than one mode pulse width. These results can be used in pulse compression and mode composition in Q-switched DPSSLs.

The experimental setup is shown in Fig. 1. The resonator is formed by two plane mirrors (M1 and M2). Plane mirror M1 is coated for high reflection at 1064 nm. The output coupler M2 is a plane mirror with 10% transmission at 1064 nm. The optical pump source consists of three laser-diode bars. The pump lights are placed in the laser rod from three symmetrical directions. The laser medium is 0.6 at.% Nd-doped Nd:YAG crystal with dimensions of 64×65 (mm). This crystal is coated for antireflection at 1064 nm on its two end faces to decrease the loss of the laser cavity. The crystal is then cooled by flowing water at a temperature of 20 °C. The AO Q-switch with high diffraction loss at 1064 nm is placed inside the cavity, and its repetition rate is tuned continuously from 0.5 to 50 kHz. In this letter, we choose 3 kHz for the experiment. The cavity length is 250 mm. The temporal shape of the output laser pulse is recorded by a photodiode detector (rise time of less than 15 ns) with a small hole fixed on the motorized stage and a fast digital oscilloscope (Tektronix DPO4032, 350-MHz bandwidth, 3.5-GS/s sampling rate). The laser reflected by an optical wedge is measured to protect the detector.

The intensity distributions of a laser beam with pump currents of 12 and 13 A are shown in Figs. 2(a) and (b), respectively. The position value represents the distance between the center of the beam cross section and the measurement position. The experimental intensity values are fitted by the Gaussian function. The beam radii with pump currents of 12 and 13 A are 1.309 and 1.556 mm, respectively. Fig. 1. Schematic of the experimental setup.
As shown in Fig. 2(c), when the pump current is 0.7 to 1.0 mm, the increment of the pulse width is 63.9 ns. When the position increases from 0 to 0.7 mm, the increment of the pulse width is only 7.9 ns. When the position increases from 0.7 to 1.0 mm, the increment of the pulse width increases with increasing position for a given pump current. The influence of position on pulse width is relatively large at the edge of the beam cross section. The pulse width increases with increasing position for a given pump current. The influence of position on pulse width is relatively small in the center of the beam cross section and relatively large at the edge of the beam cross section. The case of 12 A is taken as an example. When the position increases from 0 to 0.7 mm, the increment of the pulse width is large. When the position increases from 0.7 to 1.0 mm, the increment of the pulse width is 63.9 ns. As shown in Fig. 2(c), when the pump current is small, the pulse width is large.

Figure 3 presents the spatial and temporal distribution of the Q-switched DPSSL pulse shown in Fig. 2(b). Based on Fig. 3, the distribution is asymmetrical in the temporal domain and symmetrical in the spatial domain. The rate equations with the spatial distribution of population inversion density and photon density are given as

\[
\int_a^b \frac{\partial \phi(r, \theta, t)}{\partial t} dV = \\
\int_a^b \left[ \phi(r, \theta, t) \cos \pi(r, \theta, t) \frac{l^p}{L} - \frac{\phi(r, \theta, t) \xi}{t_r} \right] dV, \\
\frac{dn(r, \theta, t)}{dt} = G(r, \theta) - \frac{n(r, \theta, t)}{t_f} - \gamma n(r, \theta, t) \phi(r, \theta, t) \sigma c,
\]

where \(\phi(r, \theta, t)\) is the photon density, \(n(r, \theta, t)\) is the population inversion density, \(G(r, \theta)\) is the pumping rate per unit volume, \(c\) is the speed of light in vacuum, \(\sigma\) is the stimulated emission cross section, \(l^p\) is the length of the active material, \(L\) is the optical length of the resonator, \(\xi\) is the loss per round trip, \(t_r\) is the round-trip time, \(\gamma\) is the inversion reduction factor, and \(t_f\) is the upper state lifetime. In Eq. (1), the integral is calculated over the entire volume of the cavity. The loss per round trip can be represented as

\[
\xi = - \ln R + \delta,
\]

where the first term represents the output coupling losses determined by mirror reflectivity \(R\), and \(\delta\) contains all incidental losses such as scattering, diffraction, and absorption.

In all cases of interest, the Q-switched pulse duration is extremely short, such that we can neglect spontaneous emission and optical pumping in writing Eq. (2). Hence,

\[
\frac{dn(r, \theta, t)}{dt} = -\gamma n(r, \theta, t) \phi(r, \theta, t) \sigma c.
\]

In a multimode case, the rate equations can be written from Eqs. (1) and (4) as

\[
\int_a^b \frac{\partial \phi_{pl}(r, \theta, t)}{\partial t} dV = \\
\int_a^b \left[ \phi_{pl}(r, \theta, t) \cos \pi(r, \theta, t) \frac{l^p}{L} - \frac{\phi_{pl}(r, \theta, t) \xi}{t_r} \right] dV, \\
\frac{dn(r, \theta, t)}{dt} = -\gamma n(r, \theta, t) \sum_{p=0}^{l} \sum_{l=0}^{l} \phi_{pl}(r, \theta, t) \sigma c,
\]

where \(\phi_{pl}(r, \theta, t)\) is the photon density of the TEM_{pl} mode. The integers \(p\) and \(l\) represent the number of nodes with zero intensity that are transverse to the beam axis in radial and angular directions.

In cylindrical coordinates, the photon density spatial distribution of different modes is given by

\[
\phi_{pl}(r, \theta) = \rho^l |L^p_l(\rho)|^2 \cos^l(\theta) \exp(-\rho),
\]

with \(\rho = 2r^2/\omega_0^2\), where \(r\) and \(\theta\) are the polar coordinates in a plane that is transverse to the beam direction, and
Table 1. Parameter Values Used in the Calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>$3 \times 10^8$ m/s</td>
<td>$\delta_{00}$</td>
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</tr>
<tr>
<td>$\sigma$</td>
<td>$2.8 \times 10^{-19}$ cm$^2$</td>
<td>$\delta_{01}$</td>
<td>0.0482</td>
</tr>
<tr>
<td>$l$</td>
<td>0.065 m</td>
<td>$\delta_{10}$</td>
<td>0.0232</td>
</tr>
<tr>
<td>$L$</td>
<td>0.25 m</td>
<td>$\delta_{02}$</td>
<td>0.0593</td>
</tr>
<tr>
<td>$R$</td>
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<td>$\delta_{20}$</td>
<td>0.0418</td>
</tr>
<tr>
<td>$\tau_r$</td>
<td>$2.022 \times 10^{-9}$ s</td>
<td>$\gamma$</td>
<td>1</td>
</tr>
</tbody>
</table>

$L_p$ is the generalized Laguerre polynomial of order $p$ and index $l$.

Based on Eqs. (3), (5), and (6), the pulse shape of the fundamental mode can be calculated simply for different initial population inversion densities $n_0$, as shown in Fig. 4(a). Different modes correspond to different $\delta$ values, and the pulse shape of different modes can be calculated for the same initial population inversion density $n_0$, as shown in Fig. 4(b). The parameter values used in the calculation are shown in Table 1. $\delta_p$ is the loss per round trip of the TEM$_{pl}$ mode.

As shown in Fig. 4, pulse building time and pulse width decrease with increasing initial population inversion density for a single mode. For different modes, the oscillation threshold of the lower loss mode is smaller than that of the higher loss mode. Hence, the pulse building time of the lower loss mode is shorter than that of the higher loss mode for the same initial population inversion density. The pulse width is mainly determined by the ratio of the initial population inversion density to the threshold. The threshold of the lower loss mode is smaller than that of the higher loss mode, and the ratio of the initial population inversion density to the threshold of the lower loss mode is larger than that of the higher loss mode for the same initial population inversion density. Thus, the pulse width of the lower loss mode is smaller than that of the higher loss mode. The loss of the fundamental mode is smaller than that of the higher-order modes, and thus, the pulse building time of the fundamental mode is shorter than those of the higher-order modes. The pulse width of the fundamental mode is also smaller than those of the higher-order modes for the same initial population inversion density.

Figure 5 shows the spatial and temporal distribution of the Q-switched DPSSL pulse in the fundamental mode for the initial population inversion density $n_0 = 0.8 \times 10^{23}$.

Figure 6 shows the spatial and temporal distribution of the Q-switched DPSSL pulse in multimode regimes for the initial population inversion density $n_0 = 1.695 \times 10^{23}$ and the mode ratio TEM$_{00}$:TEM$_{01}$ = 55:45.

As shown in Figs. 5 and 6, the intensities of the TEM$_{00}$ and the TEM$_{01}$ modes are equivalent at the edge of the beam, and the pulse building times of the two modes are different. Hence, the pulse at the edge of the beam cross section is “thicker” than that in the center.

Figure 7 shows the variation of the pulse width as a function of the position within the beam cross section for different initial population inversion densities $n_0$ and mode ratios TEM$_{00}$:TEM$_{01}$. The pulse width does not change with increasing position in the fundamental mode, as predicted in Ref. [16], whereas it changes with increasing position for a given initial population inversion density $n_0$. The variations of the pulse width as a function of the position within the beam cross section for different initial population inversion densities $n_0$ and mode ratios TEM$_{00}$:TEM$_{01}$ are shown in Fig. 7. The pulse width does not change with increasing position in the fundamental mode, as predicted in Ref. [16], whereas it changes with increasing position for a given initial population inversion density $n_0$. The variations of the pulse width as a function of the position within the beam cross section for different initial population inversion densities $n_0$ and mode ratios TEM$_{00}$:TEM$_{01}$ are shown in Fig. 7.
the center and the edge of the beam cross section initially increases and then decreases with increasing initial population inversion density $n_0$ for a given mode ratio TEM$_{00}$:TEM$_{01}$. The pulse building time differences between the TEM$_{00}$ and the TEM$_{01}$ modes are 67, 102, 79, 57, and 45 ns for $n_0 = 1.4 \times 10^{23}, 1.5 \times 10^{23}, 1.7 \times 10^{23}, 1.8 \times 10^{23}$, respectively. When the pulse building time difference between the TEM$_{00}$ and the TEM$_{01}$ modes is large, then the pulse width difference between the center and the edge of the beam cross section is also large. Therefore, the pulse width difference between the center and the edge of the beam cross section, and the pulse building time difference between the TEM$_{00}$ and the TEM$_{01}$ modes exhibit the same trend.

Figure 9 shows the variation of pulse width as a function of the position within the beam cross section for different mode ratios of TEM$_{00}$ and TEM$_{01}$ and the initial population inversion density $n_0 = 1.534 \times 10^{23}$. The pulse width difference between the center and the edge of the beam cross section initially decreases and then increases with the increasing mode ratio of TEM$_{00}$ and TEM$_{01}$ for a given initial population inversion density $n_0$. This scenario is caused by the pulse building time of the TEM$_{01}$ mode being initially shorter than, then the same as, and finally, lasting longer than the pulse building time of the TEM$_{00}$ mode with the increasing mode ratio of TEM$_{00}$ and TEM$_{01}$ for a given initial population inversion density $n_0$.
In conclusion, the spatial and temporal distribution of \(Q\)-switched DPSSL pulses is investigated experimentally and theoretically in multimode regimes. The results show that pulse width does not change with increasing position in a single mode, but changes with increasing position for a given initial population inversion density \(n_0\) in multimode regimes. The pulse width difference between the center and the edge of the beam cross section initially increases and then decreases with increasing initial population inversion density for a given mode ratio. The pulse width difference between the center and the edge of the beam cross section initially decreases and then increases with increasing fundamental mode ratio for a given initial population inversion density. The pulse expands in the position wherein two or more modes intensities are equivalent and the pulse building time difference of the modes are less than one mode pulse width. The results of this study can be used in pulse compression and mode composition in \(Q\)-switched DPSSLs.

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References