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Dynamics of transverse mode in self-Q-switched solid-state lasers

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Abstract

In a "gain-guided" self-Q-switched laser with a large cross section, the time required for the development of a steady-state modal profile is longer than the pulse duration, resulting in transient profiles that considerably deviate from the steady-state profile prescribed by the eigen modes of the waveguide.

Beam propagation in a high-gain medium is affected by the imaginary part of refractive index. For example, in a gain-guided stripe-geometry semiconductor laser, the modal properties in the plane of the p-n junction is mainly determined by gain guiding [1,2]. Lasers with gain guiding are characterized by curved wave front, large spontaneous emission factor, and multi-longitudinal mode operation [1,3,4]. In solid-state lasers, gain guiding has mostly been neglected because the gain coefficient is at least one order of magnitude smaller than in semiconductor lasers. However, in solid-state lasers pumped by a laser beam with a Gaussian transverse profile, gain guiding can be significant [5]. In laser materials with a large distributed loss, such as the self-Q-switched solid-state lasers [6,7] and three-level lasers [8], the absorption loss outside the pumped region creates a wave guiding effect that is equivalent to gain guiding.

Previous experimental and theoretical studies of gain guiding are concerned with the steady-state conditions prescribed by the eigen modes of the waveguide. However, the steady-state solution is not always applicable in pulsed lasers with a large transverse dimension and short pulse duration because the time it takes for establishing the steady-state profile may be longer than the pulse duration. Thus the beam characteristics for a pulsed laser with a large beam cross section can deviate considerably from the eigen modes of the waveguide. In an active waveguide, the dynamics of gain saturation and bleaching of absorbers can also affect the development of the transverse mode. The principle of diffraction in a homogeneous medium requires that, for a light source of arbitrary initial spatial distribution in field amplitude and phase, a steady-state profile can be established only after propagating through a distance that is much larger than the Rayleigh distance, $z_0 = nd^2/\lambda$, where d is the transverse dimension of the beam, n is the refractive index step, and λ is the wavelength. Thus it is of interest to explore the modal behaviors in two extreme cases, characterized by $c\tau \gg z_0$, and $c\tau \ll z_0$ where τ is pulse duration.

In this paper, we present a study of transverse-mode development in a pulsed solid-state laser with gain guiding. The study uses a diode-pumped monolithic self-Q-switched Cr,Nd:YAG laser. Recently, we have demonstrated that such devices generate short pulses with high degree of spectral purity, intensity stability, and pulse shape reproducibility [6,7]. This provides a well-controlled model for studying the dynamics of the transverse mode.

The laser device, as shown in Fig. 1a, consists of a

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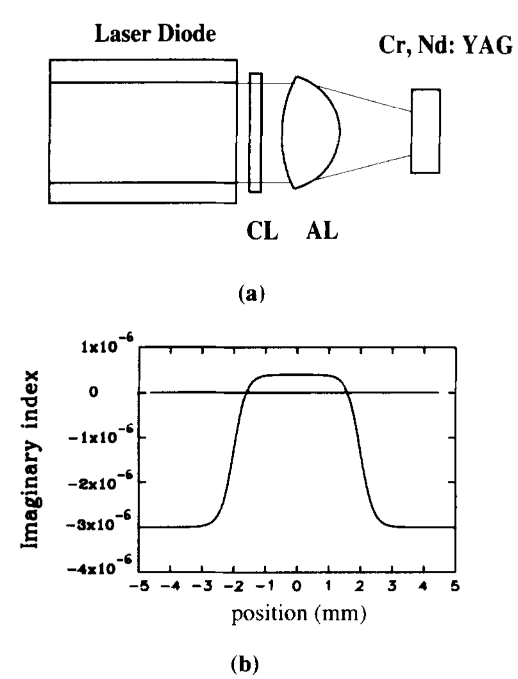

Fig. 1. (a) The schematic of the dipode-pumped monolithic self-Q-switched laser with a planar-planar cavity. The near-field profile is measured at the output coupler and the far-field profile is measured at the focal plane of a lens with 40-cm focal length. (b) Spatial profile of the unsaturated imaginary part of the refractive index of the waveguide.

1.2-mm-thick monolithic Cr,Nd:YAG etalon. The use of the short cavity is for ensuring uniform pumping over the entire length. The Cr,Nd:YAG crystal contains 1 at.% neodymium and 0.5 at.% chromium. The absorption coefficient at the lasing wavelength is 0.32 cm^{-1}. The mirror facing the pumping beam is coated for high transmission at 808 nm and 100% reflectivity at 1064 nm. The output mirror is coated with 98% reflectivity at 1064 nm. The pump laser is a diode laser bar with 1 cm stripe-width emitting at 808 nm wavelength. The laser is operated in the quasi-CW mode with 300 μs duration and 10 Hz repetition rates. A cylindrical glass rod (CL) of 2-mm diameter is used to collimate the pump beam in the vertical direction. In order to create a gain-guided laser with a large transverse dimension with the limited power of the diode laser, the pump beam is focused into an highly asymmetric 4 mm×0.2 mm spot by using an aspheric lens (AL). The self-Q-switched laser emits in a single longitudinal mode with no pulse-to-pulse mode hopping an no detectable intensity fluctuation and pulse shape variation [6,7]. With an input energy of 3.2 mJ, the output pulse energy is 160 μJ. The refractive-index profile based on the gain and loss coefficient, is shown in Fig. 1b. In the limit of low repetition rate, thermal lensing effect can be neglected.

The asymmetric cross section of the pumped region results in different modal behaviors in the two transverse directions. Along the narrow (0.2 mm) direction, the measured intensity distribution has a Gaussian-like profile, in agreement with the calculated profiles for the fundamental transverse mode. The profile also remains unchanged during the pulse. Along the long (4 mm) dimension, the beam profile deviates considerably from the bell-shape profile of the eigen mode of the waveguide. The time-integrated intensity distribution of the near-field and far-field patterns of the laser output, measured using a pyroelectric detector array, is shown in Fig. 2. Although the temporal shape and pulse duration are reproducible from pulse to pulse, the pulse shape changes with the position within the cross section of the laser beam. To further investigate the nature of

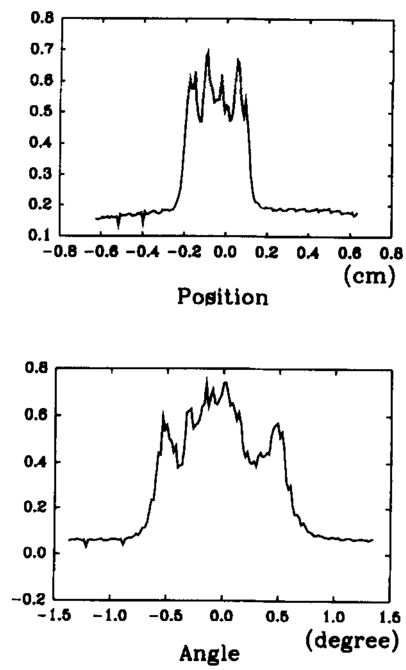

Fig. 2. Time-integrated near-field (upper) and far-field (lower) patterns.

the non-Gaussian profile and the position-dependent pulse shape, time-resolved near- and far-field measurements have been carried out. The temporal pulse shapes of the laser output at various positions in the near-field and far-field are detected by using a high-speed avalanche photo-diode and oscilloscope with a resolution of 300 ps. The oscilloscope traces are recorded using a digital camera. The recorded temporal profiles at various positions are then used to construct the spatial profiles at various times using a computer. Fig. 3 shows the constructed front and rear views of the near-field profiles at various times during the pulse. The pulses are found to start from the center in a single-lobed profile and gradually expand and evolve into a two-lobed profile at the end of the pulse. The far-field pattern undergoes a corresponding evolution as shown in Fig. 4.

The development of the transverse mode in the waveguide laser has been simulated by using the wave-propagation method in conjunction with rate equations [9]. The laser cavity is modeled as a one-dimensional gain guide between two planar mirrors separated by 1.2 mm. The laser cavity is divided into four regions of homogeneous medium. For convenience of numerical treatment, the total phase change

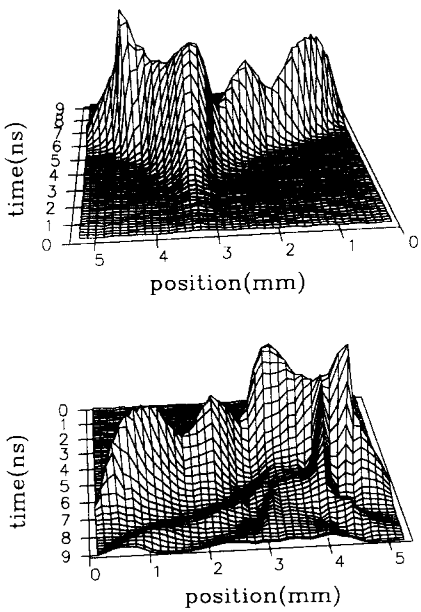

Fig. 3. Front (upper) and rear views (lower) of the time-resolved near-field patterns of the longer dimension.

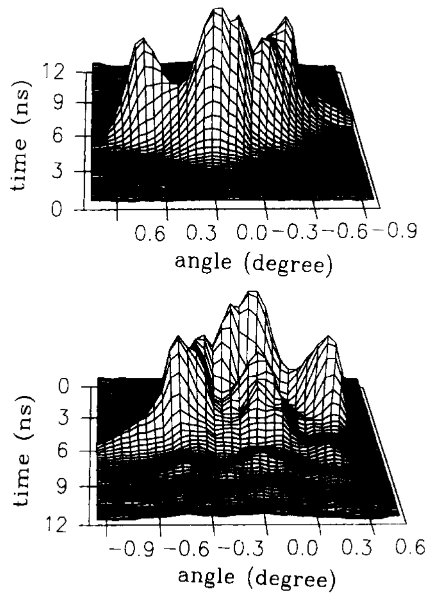

Fig. 4. Front (upper) and rear views (lower) of the time-resolved far-field pattern of the longer dimension.

in a gain region is compressed into a plane of zero thickness and inserted in the middle of each region. Fast Fourier Transform technique is used to simulate the propagation of the wave in the homogeneous medium. The interaction between gain medium and the electric field is taken into account by coupling the local rates of change in population inversion and photon number through the following equations:

$$n_{i+1}(x) = n_i(x) + \Delta n_i(x) \,, \qquad (1)$$

$$S_{i+1}(x) = S_i(x) + \Delta S_i(x) \,, \qquad (2)$$

$$S_i(x) = (\epsilon_0 \mu_r^2 V / 2h\nu_0)\, |E_i(x)|^2 \,,$$

$$\Delta n_i(x) = \left(\frac{a}{k_0 c} P(x) - \frac{\epsilon_0 a}{k_0 h \nu_0} n_i(x) S_i(x) - \frac{n_i(x)}{c\tau_e} \right) \Delta z_i \,, \qquad (4)$$

$$\Delta S_i(x) = [k_0 n_i(x) - \alpha(x)] S_i(x) \Delta z_i \,, \qquad (5)$$

where $n_i(x)$ and $S_i(x)$ are imaginary part of refractive index and density of the photon number in the ith gain region, α is the cavity loss, ϵ_0 is the permittivity constant, c is the speed of light, a is the gain cross section, τ_e is the spontaneous decay time, ν_0 is the frequency of lasing mode, μ_r is the real part of refractive index, V is the gain volume, $P(x)$ is the pumping term representing the rate of change of population-inversion density caused by optical pumping, and $E(x)$ is the electric field. Eqs. (1)–(5) are basically the laser rate equations of a local region of thickness Δz_i. The density of population inversion is represented by the imaginary part of refractive index. The cavity loss is assumed to have the following form:

$$\alpha(x)=\alpha_m+\alpha_0+\alpha_s\exp(-\Gamma/\Gamma_s)\,, \tag{6}$$

$$\Gamma=(\epsilon_0 c/8)\int_{-\infty}^{t}|E(x,t')|^2\,dt'\,, \tag{7}$$

where α_m is the mirror loss and α_0 is the residual absorption loss in the gain medium under high fluence, α_s is the saturable loss, Γ is the integrated fluence of the laser pulse, and $\Gamma_s=h\nu/2\sigma_s$ is the saturation fluence, σ_s is the cross section of the saturable absorption. The pump term, $P(x)$, is assumed to be

$$P(x)=\frac{P_0}{1+\exp[|x|/(w-d)]}\,, \tag{8}$$

where the P_0 represents the pumping level and is determined by the threshold condition, w is the half width of pumping size, and d represents the edge effect. The parameters are $a=3.5\times10^{-19}\,\mathrm{cm}^2$, $\tau_e=230$ μs, $P_0=1.2\times10^{-16}\ \mathrm{m}^{-1}$, $\alpha_m=8.4\times10^{-6}\ \mathrm{m}^{-1}$, $\alpha_0=7.0\times10^{-6}\,\mathrm{m}^{-1}$, $\alpha_s=2.8\times10^{-5}\,\mathrm{m}^{-1}$, $w=0.4$ cm, $d=0.5$ mm, $\Gamma_s=2\ \mathrm{J/cm}^2$.

The calculated near-field intensity profiles at various times are shown in Fig. 5. The calculation indeed reflects the key features of the experimental observation, including the formation of a narrow single-lobed profile at the beginning of the pulse and the two-lobed profile at the end. Furthermore, the calculated modal profile is independent of the spatial distribution of the initial input field. In contrast, the calculated modal profile for the narrow ($w=0.1$ mm) waveguide is Gaussian-like and remains stable throughout the pulse. This is also consistent with the experimental observation.

The transient dynamics can be viewed as an injection and amplification process in which the seed is provided by the initial narrow filament formed at the center. Our calculation indicates that, since the beam is developed from a common seed, the two lobes of

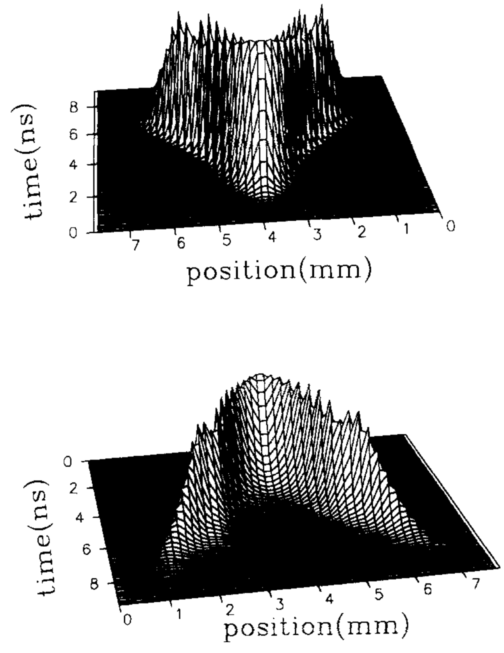

Fig. 5. Calculated near-field patterns for comparison with experimental data shown in Fig. 3.

the laser output have the same phase and, when focused by a lens, form a single-lobed spot without a dark fringe at the center. Thus the nature of two-lobed profile is different from that of the first-order mode whose two lobes have a phase difference of π and, when focused by a lens, form a dark fringe at the center. This seeding and amplification process allows the energy stored in the large gain medium to be effectively extracted in a single coherent beam in the fundamental mode without the onset of a higher order mode. This process has an important implication for the design of Q-switched lasers with a large gain volume for high pulse energy. The result may also provide useful underlining understanding of the dynamics of the transverse mode in gain-guided Fabry–Pérot lasers whose transverse dimension is larger than the cavity length, an example being the surface emitting semiconductor lasers.

In conclusion, it is shown, both experimentally and theoretically, that a self-Q-switched laser with a large transverse dimension exhibits a transient modal pattern that is considerably different from the eigen mode calculated based on the waveguide profile. The dynamics reflects the process of beam expansion and amplification initiated by a narrow filament.

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References

[1] F.R. Nash, J. Appl. Phys. Lett. 44 (1973) 4696.
[2] P.M. Asbeck, D.A. Cammach and J.J. Daniele, Appl. Phys. Lett. 33 (1978) 504.
[3] K. Peterman, IEEE J. Quantum Electron. QE-15 (1979) 566.
[4] W. Streifer, D.R. Scifers and R.D. Burnhum, Appl. Phys. Lett. 40 (1989) 305.
[5] F. Salin and J. Squier, Optics Lett. 17 (1992) 1352.
[6] S. Zhou, K.K. Lee and Y.C. Chen, Optics Lett. 18 (1993) 511.
[7] Y.C. Chen, S. Li, K.K. Lee and S. Zhou, Optics Lett. 18 (1993) 1418.
[8] T.Y. Fan, Optics Lett. 19 (1994) 554.
39] G.P. Agrawal, W.B. Joyce, R.W. Dixon and M. Lax, Appl. Phys. Lett. 43 (1983) 11.