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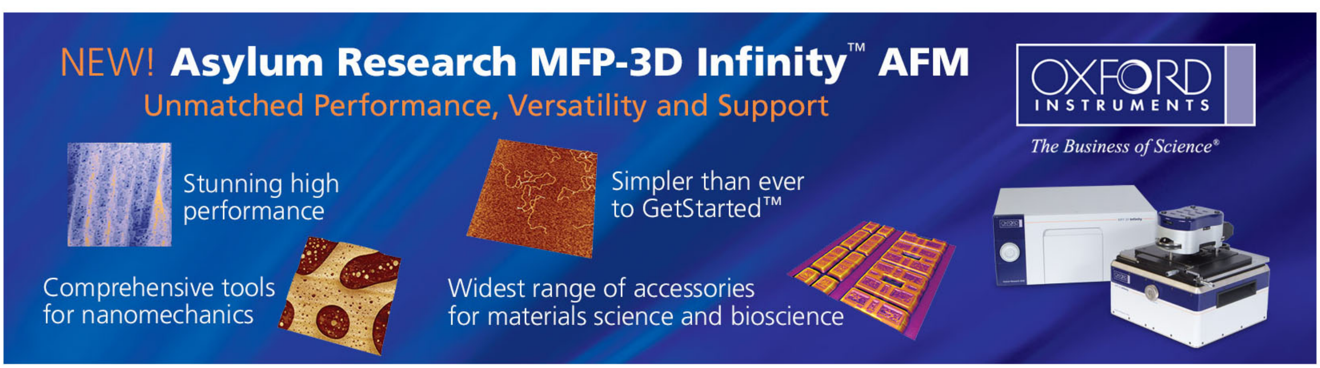

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Nonlinear dynamics in thin-slice Nd:YAG ceramic lasers: Coupled local-mode laser model

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The authors propose a coupled spatially distributed local-mode laser model for understanding self-induced high-speed modulations in Nd:YAG ceramic lasers with laser-diode end pumping, which critically depend on pump positions. In addition to complicated high-speed modulations, quasiperiodic and chaotic relaxation oscillations have been demonstrated experimentally and reproduced by numerical simulation of the model of coupled local-mode lasers. *Q*-switching-like periodic spiking pulsations have been also observed and reproduced numerically by assuming saturable absorber type of inclusions in grain boundaries. © *2006 American Institute of Physics*.
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A wide variety of materials has been studied to develop more efficient and high power microchip lasers with laser-diode (LD) pumping. In end-pumping schemes, materials with a short absorption length for the LD pump beam are most promising for highly efficient operations because of the excellent match between the mode and pump-beam profiles. Recently, new single-crystalline laser materials having increased absorption coefficients for LDs, such as $Nd:GdVO_4$ and Yb:YAG (yttrium aluminum garnet), have been reported. On the other hand, a simple sintering method led to the development of polycrystalline Nd:YAG ceramics that have transparency comparable to that of Nd:YAG single crystals.[1,2] Systematic studies of Nd:YAG ceramic lasers for different doping levels showed that if we dope Nd^{3+} ions highly, it is difficult to keep the large grain size and the number of grain boundaries will increase within the same path length accordingly.[1–7]

In this letter, we propose the model of coupled local-mode lasers for understanding instabilities in thin-slice Nd:YAG ceramic lasers with coated end mirrors reported before.[8,9] With a generalized model of coupled local-mode (i.e., filament) lasers proposed here, observed dynamic effects are shown to be explained from various aspects, without assuming a conjectured formation of "nonorthogonal transverse modes,"[8–10] although both models can explain modal-beating type of high-speed modulations.

Thin-slice Nd:YAG ceramic lasers consist of randomly distributed single-crystalline grains, whose directions of crystal axes surrounded by grain boundaries are independent, placed between closely spaced reflective end surfaces. Since the birefringence (i.e., depolarization) strongly depends on the direction of crystal axes of the grain, strong phase distortions occur over transverse directions with increasing the pump power. Due to resultant random phase disturbances distributed inside the plane-parallel cavity, Hermite-Gaussian modes cannot form and the lasing pattern is expected to split into multiple localized transverse modes, called "local modes" hereafter, having slightly different lasing frequencies resulting from slightly different optical cavity lengths, i.e., standing-wave conditions. These local modes are coupled through spatial fields overlapping across the transverse direction. An example of an etched surface indicating single-crystalline grain structures is shown in Fig. 1(a), in which a pump-beam size is depicted. Assuming the nearest neighbor coupling among spatially distributed local modes, the model equations of such coupled lasers are given as follows:

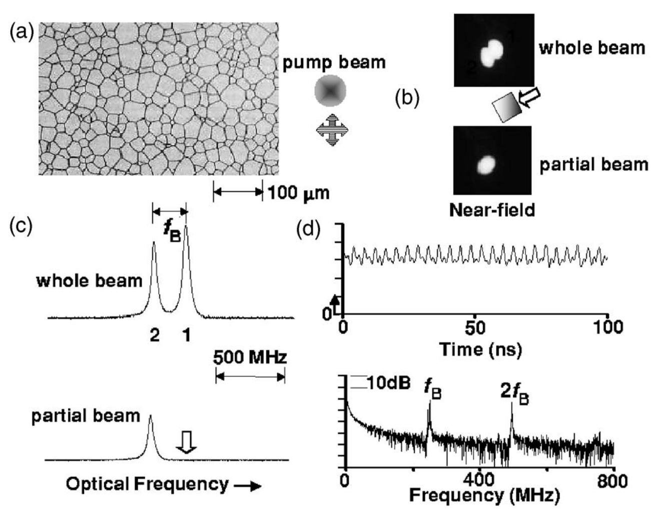

FIG. 1. (a) Etched surface indicating single-crystalline grain structures. (b) Near-field patterns with and without blocking the beam. Pump power $P=352$ mW. (c) Optical spectra corresponding to (b). (d) Intensity wave form and the corresponding power spectrum.

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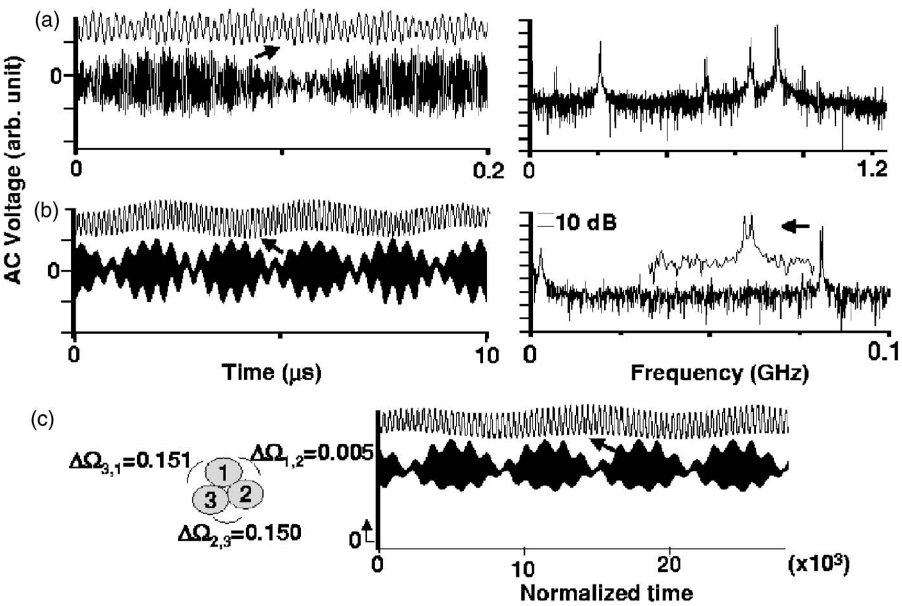

FIG. 2. High-speed modal-beat mediate modulation wave forms and power spectra. $P=455$ mW. Focusing lens: (a) NA=0.25 and (b) NA=0.4. (c) Numerical result: $w=1.05$, $K=2000$, $\eta_{1,2}=0.0004$, $\eta_{2,3}=\eta_{3,1}=0.032$.

$$dN_i/dt = \{w - 1 - N_i - [1 + 2N_i]E_i^2\}/K, \quad (1)$$

$$dE_i/dt = N_iE_i + \eta_{i,j} \sum E_j \cos \Phi_{ij}, \quad (2)$$

$$d\Phi_{i,j}/dt = \Delta\Omega_{i,j} - \eta_{i,j} \sum [(E_j/E_i) + (E_i/E_j)]\sin \Phi_{i,j}. \quad (3)$$

Here, $E_i=(g\tau)^{1/2}E_i(t)$ is the normalized field amplitude of ith local mode and $N_i=gN_{\rm th}\tau_p(N_i(t)/N_{\rm th}-1)$ is the normalized excess population inversion of ith local mode where $N_{\rm th}$ is the threshold population inversion. g is the differential gain coefficient, where gain is defined as $G=G_{\rm th}+g(N_i(t)-N_{\rm th})$.[11] $w=P/P_{\rm th}$ is the relative pump power normalized by the threshold, $K=\kappa\tau$ is the fluorescence lifetime normalized by the damping rate of the optical cavity, κ, $\Phi_{i,j}$ is the phase difference between ith local mode field and adjacent jth local mode field, and $\Delta\Omega_{i,j}=(\omega_j-\omega_i)/\kappa$ is the normalized frequency difference between ith local mode field and adjacent jth local mode field. $\eta_{i,j}$ is the coupling coefficient between adjacent local mode fields, and t is the time normalized by the damping rate of the optical cavity. In a weak coupling regime, $\Delta\Omega_{i,j}>\eta_{i,j}$, phase locking between local modes fails and beating modulations at $\Delta\Omega_{i,j}$ take place.

The experiment was carried out using Nd:YAG ceramic lasers purchased from a different supplier (Polytechno Corp.) to clarify the generic nature of self-induced instabilities in Nd:YAG ceramic lasers independently of sintering procedures. The experimental setup is the same as before.[9] A collimated elliptical-shape pump beam from the LD was passed through a pair of anamorphic prisms to transform the elliptical shape into a circular one, and then it was focused onto the surface of Nd:YAG ceramic lasers by microscope objective lenses with different magnifications, i.e., $M=10\times$ [numerical aperture (NA)=0.25] and $20\times$ (NA=0.4). All the samples were 5 mm in diameter and 1 mm in thickness, and end surfaces were coated by the same dielectric mirrors M_1 (99.9% reflection at 1064 nm and high transmission at 808 nm) and M_2 (98% reflection at 1064 nm).

In order to identify expected splits into spatially distributed local modes, we measured near-field patterns, corresponding optical spectra, and output wave forms. Here, a single-longitudinal-mode operation in the entire pump-power region was confirmed by a multiwavelength meter. Examples of results are shown in Figs. 1(b)–1(d), in which a scanning Fabry-Pérot interferometer of 6.6 MHz resolution was used to measure detailed optical spectra. A knife edge placed close to the laser was used to block a part of the lasing beam. Near-field patterns for the whole and partial beams and their optical spectra are shown in Figs. 1(b) and 1(c). In this case, two local modes separated by 250 MHz are oscillating at their own frequencies. A high-speed intensity modulation at 250 MHz was observed as shown in a wave form and the corresponding power spectrum in Fig. 1(d) exhibiting peaks at 250 MHz and its harmonic of 500 MHz.

Various modulation patterns featuring periodic and breathing-type wave forms at beating frequencies of adjacent local modes were observed by slight changes, e.g., several tens of microns, in pump positions similarly to the previous results observed in Baikowski samples.[9] Examples of high-frequency modulation wave forms and corresponding power spectra observed for different pump-beam (i.e., lasing beam) diameters observed in a 3.6 at. % doped sample are shown in Fig. 2, in which the threshold pump power was 92 mW and the slope efficiency was 20%. With increasing lasing beam diameter by the use of smaller magnification lenses, the number of grain boundaries across the lasing beam increases. As a result, the number of interacting local modes, i.e., beat frequencies, increases accordingly, yielding complicated modulation wave forms.

Quasiperiodic and chaotic modulation wave forms at the relaxation oscillation frequency were observed as shown in Figs. 3(a) and 3(b) at the same pump power as Fig. 2, where the pump beam was tightly focused using the $20\times$ (NA=0.4) magnification lens. The simultaneous measurement of optical spectra revealed that these instabilities were confirmed to take place when a beat frequency among coupled local modes approached the relaxation oscillation frequency.[10] With the provided averaged grain size shown in Fig. 1(a), a slight change of pump position could result in a change in the spatial arrangement of local modes within the lasing beam. Numerical high-speed modulation and quasiperiodic and chaotic relaxation oscillation wave forms, ΣE_i^2, corresponding to Fig. 2(b) and Figs. 3(a) and 3(b), reproduced by the simulation of the proposed model [Eqs. (1)–(3)]

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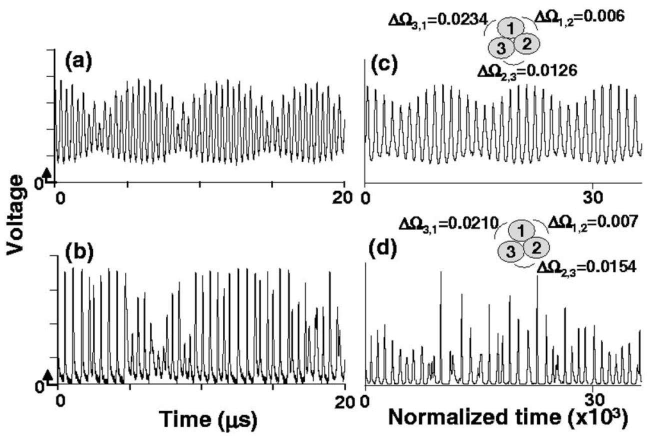

FIG. 3. [(a) and (b)] Quasiperiodic and chaotic relaxation oscillations observed when modal-beat frequencies approached relaxation oscillation frequencies. Objective lens: NA=0.4. P=455 mW. (c) Numerical quasiperiodic oscillation. $w=1.05$, $K=2000$, $\eta_{1,2}=\eta_{2,3}=\eta_{3,1}=0.001$. (d) Numerical chaotic oscillation. $w=1.05$, $K=2000$, $\eta_{1,2}=0.001$, $\eta_{2,3}=\eta_{3,1}=0.002$.

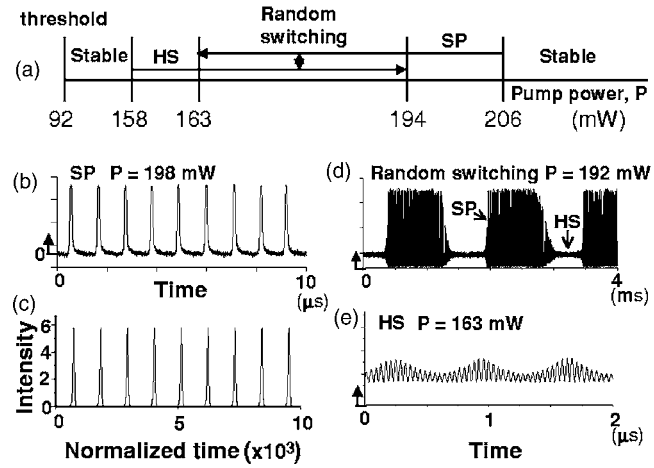

FIG. 4. Q-switching-type spiking pulsation. (a) Bifurcation diagram. (b) Periodic spiking. (c) Numerical result, where $w=1.05$ ($w_a=1$, $w_l=2.1$) and $\alpha=2.5$. (d) Random switching between spiking and high-speed modulation wave forms. (e) High-speed modulation.

are shown in Fig. 2(c) and Figs. 3(c) and 3(d) respectively. Here, three coupled localized modes, with frequency differences $\Delta\Omega_{i,j}$ depicted in figures, are assumed.

Finally, let us briefly discuss periodic spiking operations observed with a precise tuning of the pump position. Q-switching-type periodic spiking oscillations, which appeared even in the single-mode region near the lasing threshold, are shown to be brought about by a different dynamic origin from modal-beating mediate intensity modulations shown in Fig. 2. Examples of a bifurcation diagram and typical wave forms obtained at a fixed pump position are shown in Fig. 4. The periodic spiking oscillation in the single-mode region PS (b) tended to coexist with high-speed beating modulations in two-mode region, featuring random switching between two dynamic states RS (d), and finally high-speed modulation dominated spiking oscillations as the pump power approached the threshold pump power in region HS (e). Note that the spiking oscillation frequency decreased with decreasing the pump power.

Observed periodic spiking oscillations were well reproduced by the standard single-mode laser rate equation including saturable absorbers:[12] $dn_l/dt=(w_l-n_l-n_ls_l)/K$, $dn_a/dt=(w_a-n_a-\alpha n_as)/K$, and $ds/dt=2(n_l-n_a-1)s$, where n_l and n_a are normalized population densities for the laser and saturable absorber, respectively, s is the photon density, w_l and w_a are normalized pump rates, and α is the saturation parameter. Observed periodic spiking oscillations which appeared near the lasing threshold $w=P/P_{\rm th}=w_l/(w_a+1)<2$ have been well explained by the linear stability analysis. An example of the numerical result is shown in Fig. 4(c). It was found theoretically that the periodic spiking oscillation starts to appear just above the threshold pump power, i.e., $w=1$, and the pulsation frequency increases as the pump power increases. In the real experiment, however, such a pulsation sometimes coexists with beating-type high-speed modulations as shown in Fig. 4(d). Observed spiking oscillations and theoretical reproductions strongly suggest the possible inclusion of saturable absorber-type defects into grain boundaries in highly doped Nd:YAG ceramics. Detailed theoretical results will be published elsewhere.

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