Self-induced high-speed modulation in microchip solid-state lasers with asymmetric end pumping

Kenju Otsuka

Department of Human and Information Science, Tokai University, 1117 Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan

Tsong-Shin Lim

Department of Physics, National Cheng Kung University, Tainan 70101, Taiwan

Jing-Yuan Ko and Hironori Makino

Department of Human and Information Science, Tokai University, 1117 Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan

Received April 3, 2002

We applied laser-diode sheetlike end pumping to a multimode Nd:YVO$_4$ laser and observed high-speed (>400-MHz) modulation of the intensity of chaotic pulsation near 1 MHz. The frequencies of modulation were the beat frequencies for pairs of closely spaced lasing modes. Asymmetric optical confinement and the resultant modal interference are shown to lead to oval-hollow-mode operation in which modal beat notes induce high-speed modulation, the frequency range of which is 2 orders of magnitude higher than the intrinsic relaxation oscillation frequency. Good numerical reproduction of the observed chaotic pulsations and their high-speed modulation was obtained with model equations in which such effects as nonlinear gain coupling among modes and field interference between pairs of modes were included. High-speed pulsations in nonchaotic lasers were also demonstrated. © 2002 Optical Society of America

OCIS codes: 190.3100, 140.3480, 140.3580.

In a class-B laser, the polarization lifetime is much shorter than either the population lifetime or the photon lifetime. Polarization dynamics are thus adiabatically eliminated. Consequently, no dynamic instability arises, even in ranges that have multi-longitudinal and multitransverse modes without additional degrees of freedom, such as modulation, light injection, or optical feedback. However, if we introduce the nonlinear interaction among modes that is inherent in lasers of a certain kind, such as a nonlinear modal gain coupling in Nd:YVO$_4$ lasers, forms of dynamic instability that lead to chaos are observable in multimode operation. We report here on the formation of patterns of emission in an oval hollow mode (OMH) and associated forms of dynamic instability in a multimode Nd:YVO$_4$ laser that is pumped at one end by sheetlike emission from a laser diode (LD).

The experimental setup is shown in Fig. 1(a). A 3-mm-square 1%-doped Nd:YVO$_4$ laser (Casix DPO3104) with a 1-mm-thick resonator in a plane-parallel Fabry–Perot configuration was used. One surface of the crystal was coated to be transmissive at the LD pump wavelength of 808 nm (85% transmission) and to be highly reflective (99.9%) at the lasing wavelength of 1064 nm. The other surface was coated to be 2% transmissive in the range of the latter wavelength. The LD that we used to pump the Nd:YVO$_4$ laser had a 1-W maximum level of output power and was supplied by Opto-Power Corporation. The thickness of the LD’s active layer in the vertical or $y$ direction was 1 $\mu$m, and the width of emission in the horizontal or $x$ direction was 100 $\mu$m, where the LD pump light was linearly polarized along the $x$ axis. The diffraction effect at the facet led to a highly elliptical far-field pattern for the beam from the LD. We passed this beam through a collimator followed by a microscope objective lens of 10× magnification to focus it directly onto the Nd:YVO$_4$ crystal surface. The mode profile of the focused LD beam on the input mirror of the crystal was 20 $\mu$m × 2 $\mu$m; i.e., the aspect ratio was 10. The absorption length for the light from the LD was ~1 mm, which produced thermal effects that led to a graded distribution of refractive index, in turn producing the tapered-horn pattern of optical confinement of the lasing fields that is shown in Fig. 1(b). After many round trips within the cavity bounded by the two end mirrors, this pattern yielded an OMH of laser emission. Global oscillation

0146-9592/02/191696-03$15.00/0 © 2002 Optical Society of America
spectra were observed by a multiwavelength meter (Agilent Technologies 86120B; 700–1650 nm; resolution, 20 GHz). The detailed structure of the lasing modes was measured by a scanning Fabry–Perot interferometer (Burleigh SA-91; free-spectral range, 2 GHz; resolution, 6 MHz). An InGaAs photodetector (New Focus 1611; bandwidth, 1 GHz) converted the output for display on a digital oscilloscope (Tektronix TDS3052; bandwidth, 500 MHz).

Let us now look at some typical near- and far-field patterns of an OHM. The near-field pattern was observed by a PbS sensor, whereas the far-field pattern was measured by a CCD sensor followed by a personal computer. The near-field pattern and the three-dimensional far-field pattern thus observed are shown in Fig. 1(c). In this experiment the direction of polarization of the Nd:YVO₄ laser light was set perpendicular to the direction of polarization (i.e., the x axis) of the LD light. The dark spot within the beam pattern and the uniform line emission in the far field connected to the near field through a Fourier transformation⁵ indicate operation in an OHM. The observed near- and far-field patterns are totally different, and this rules out the possibility of superposition of typical orthogonal Hermite–Gaussian modes as an explanation for OHM operation.

The spectra across the full range of oscillation indicate that single-mode oscillation occurs only in the vicinity of the threshold level of pump power, whereas two-mode oscillation with a wavelength separation given by the free spectral range Δλ = λ²/2nL = 0.248 nm (wavelength, λ = 1064 nm; refractive index, n = 2, cavity length, L = 1 mm) appears over a wide range of higher pump-power levels. Three-mode oscillation appears with further increases in the level of pump power. An example of an oscillation spectrum that features two-mode oscillation is given in the left-hand half of Fig. 2(a). Chaotic pulsation, which appeared in the two-mode regime, is shown in Fig. 2(b); the time scale of the pulsations, which are produced by the nonlinear modal gain coupling effect in the Nd:YVO₄ laser,²⁴ is determined by the relaxation oscillations near f₀ = 1 MHz. Figure 2(c) shows the corresponding power spectrum. In the whole experiment the entire output beam was focused onto the detector.

Now let us focus on fast modulation of the chaotic pulsation. In the fine structure of the optical spectrum, which is given as the right-hand half of Fig. 2(a), a weak mode (2) is seen to oscillate at f₂ = 463 MHz apart from the strong mode (1). In short, what appears as a single mode in the overall spectrum consists of closely spaced modes 1 and 2. The free spectral range of the scanning Fabry–Perot interferometer of 2 GHz is much smaller than the frequency separation of 75 GHz (0.248 nm) between two strong longitudinal modes, which is seen in the left-hand half of Fig. 2(a). As a result, mode 3 in the right-hand half appeared through a different transmission peak of the interferometer, and the frequency separation between the two strong modes (1, 3) is meaningless, whereas modes 1 and 2 are within the free spectral range. Indeed, some of the pulses in the chaotic pattern of pulsation shown in Fig. 2(b) were found to be amplitude modulated at f₃ = 463 MHz. Magnified views of the spectrum, the waveform, and the corresponding power spectrum for this pattern are shown in Fig. 3, which includes as an inset a more-detailed view of the waveform. The frequency of modulation seen here coincides with the beat frequency f₄(≫ f₀) for modes 1 and 2, which is the most prominent feature of the power spectrum. Note that high-speed modulation is not superimposed upon all the chaotic pulses. When the level of pump power was decreased, the weak mode disappeared, to leave chaotic pulsations that were not subject to fast modulation.

In conventional orthogonal Hermite–Gaussian laser modes obtained with symmetric pumping, beat notes between transverse modes were absent, and no instability occurred. In the system we are considering here, closely spaced OHMs that belong to the same longitudinal mode may violate mode orthogonality such that transverse modal beating is produced by interference among transverse fields $E_m$ and $\bar{E}_n$. Such an interference effect is expected to introduce a significant gain (i.e., stimulated emission) modulation at the beat frequency to the laser in the form of $N_0B \int \int E_m E_n^* dxdy + c.c.$, where $B$ is the stimulated emission coefficient and $N_0$ is the population inversion density.

The model equation, which includes such effects as nonlinear gain²–⁴ and modal interference within a nonorthogonal mode pair, is

![Fig. 2](image-url)

![Fig. 3](image-url)
Fig. 4. Numerical results. (a) Chaotic pulsation, (b) corresponding power spectrum; (c) high-speed-modulated waveform, (d) corresponding power spectrum. Total intensities are shown for both cases. The following parameters were adopted: $w_{1,3} = 1.05, w_2 = 1.02, \beta = 0.06, \eta = 0.079, g_1 = g_2 = 0.3$, $\Delta \Omega = 2$.

Fig. 5. High-speed pulsation in a nonchaotic laser with symmetric contact. (a) Experimental result for a 5-mm-thick Nd:YAG laser; pump power, 88 mW (threshold, 67 mW). (b) Numerical result for $\eta = 0, g_1 = g_2 = 0.04$, and $\Delta \Omega = 0.2$. Other parameters are the same as for Fig. 4.

$$\frac{dN_i}{dt} = \left[ w_i - 1 - N_i - (1 + 2N_i) \times \left( E_i^2 + \sum_{j \neq i} \beta E_j^2 \right) \right] / K,$$

$$= \left( \sum_{j \neq i} \eta E_j^2 \right) + g_i E_1 E_2 \cos \Delta \Omega t,$$

where $i$ is the modal index, i.e., 1, 2, or 3, and $g_i = 0$ for $i = 3$. Here $N_i$ is the normalized excess population-inversion density; $E_i$ is the normalized field amplitude; $w_i$ is the relative pump power normalized against the threshold level for the first ($i = 1$) mode; $\beta$ is the cross-saturation parameter; $\eta$ is the nonlinear gain coefficient; $K$ is the lifetime ratio, i.e., the ratio of fluorescence lifetime $\tau$ to photon lifetime $\tau_p$; $g_i$ is the interference parameter; $\Delta \Omega = \Delta \omega / \tau_p$ is the normalized difference between the frequencies of lasing in the first mode ($i = 1$) and in the second mode ($i = 2$), where $\Delta \omega$ is the difference between the frequencies of lasing modes; and $t$ is normalized by the photon lifetime. The numerically produced chaotic intensity waveforms, $I = \sum E_i^2$, shown in Fig. 4 feature high-speed modal-beat-mediated modulations that correspond to the waveforms of Figs. 2(b) and 3. High-speed pulsation occurs only when the pulsating modal chaotic light fields overlap in time, and this condition parallels the results of experimental observation. The interference-induced pulsations shown above were reproduced in a wide domain of parameters such as $g_i, \eta$, and $\Delta \omega$.

Finally, it should be mentioned that such high-frequency modulation through interference between transverse mode fields is achievable in nonchaotic solid-state lasers in which there is no nonlinear gain coupling, i.e., $\eta = 0$. Indeed, we have observed stable continuous high-speed modulation in nonchaotic Nd:YAG and LiNdP$_2$O$_4$ lasers that are asymmetrically end pumped by a LD. Experimental and numerical results for a 5-mm-thick Nd:YAG laser are shown in Fig. 5.

The basic idea of sheetlike pumping is general and is thus applicable to achieving high-speed modulation that is not restricted by the intrinsic frequency of relaxation oscillation for a wide range of microchip lasers. Bottom-emitting vertical-cavity surface-emitting lasers with noncircular contact would be promising candidates for demonstrating modal-interference-induced high-speed modulation over 100 GHz because transverse mode orthogonality in the eigenvectors of those lasers with conventional circular contact is expected to be violated as a result of the deformed thermal lens effect.

T.-S. Lim was supported by the National Science Council, Taiwan, under project NSC90-2112-M-006-018. K. Otsuka's e-mail address is ootsuka@keyaki.cc.u-tokai.ac.jp.

References