Q switching by self-focusing

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A novel passive technique for obtaining short-laser-pulse emission is presented. A cell with a high-second-order refractive-index liquid is included in an unstable laser cavity. The external self-focusing introduced by the cell at higher optical intensities reduces the diffraction losses, producing modulation of the gain and Q switching of the cavity. Compared with saturable absorbers, this method provides better mode quality, avoids filamentary emission, and is not restricted in wavelength. Experimental results are presented that are in good agreement with the numerical model developed.

The generation of short and high-power laser pulses by passive methods has been of great importance in recent years. Many organic dyes with absorption peaks at the laser wavelength and short relaxation times have been used as saturable absorbers for passive Q switching of solid-state lasers.[1–4] The main advantages of such passive methods are simplicity and the low cost of the equipment. Nevertheless, this modulation technique has the important drawback of absorber degradation, which changes the initial conditions with use, so that the dyes become unreliable when they are used for long periods of time. Other disadvantages are that the dye to be used must have an absorbing peak tuned with the laser wavelength and that the bleaching process may favor filamentary emission of the laser.

In this Letter, we present a novel technique to obtain short pulses by passive modulation of the gain. This new method has the traditional advantages of the passive technique without the drawbacks mentioned above. The new system makes use of the self-focusing effect in a liquid with a high-second-order refractive index n_2. A cell containing such a liquid is introduced into an unstable laser cavity, and the self-focusing introduced at higher intensities then reduces the diffraction losses by changing the optical configuration of the resonator. Other authors have used similar nonlinear media in order to compress Q-switched pulses by self-induced ellipse rotation and self-focusing.[5–7] In these cases the Q switching was provided by external elements (rotating prism and electro-optic modulator). Mode locking has been obtained[8,9] by using nonlinear devices that exhibit a large optical Kerr effect, but in both cases elliptical rotation in a nonlinear medium was used.

The cell in our laser, when in contact with one of the spherical mirrors of the cavity, acts as a positive lens with a focal length variable with the field intensity. We assume that the cell length is much smaller than the cavity length and that only phase distortion occurs in the cell, with no change in the amplitude profile. Hence the cell changes the mirror's effective radius, and the resonator configuration becomes intensity dependent.

In the aberrationless approximation, the focal length induced by the external self-focusing can be calculated by[10]

$$Z_f = a^2/(2n_2dE^2), \tag{1}$$

where a is the spot size, d is the cell length, n_2 is the second-order refractive index, and E is the field amplitude. Following Siegman,[11] we can compute the behavior of a given laser cavity by using two parameters that determine the evolution of a field distribution inside the passive resonator. These are the distance X of a beam to the cavity axis and the ray angle X'. For a given resonant cavity it is possible to write a matrix equation that relates the initial amplitude profile defined by X_0 and X_0' with the profile one round trip later, defined by X and X':

$$\begin{bmatrix} X \\ X' \end{bmatrix} = \mathbf{M} \begin{bmatrix} X_0 \\ X_0' \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} X_0 \\ X_0' \end{bmatrix}, \tag{2}$$

where $\mathbf{M}$ is the round-trip magnification matrix, which can be calculated from the geometric configuration of the cavity.[12]

Equation (2) has two eigenvalues for positive- and negative-branch resonators:

$$M_{1,2} = g \pm (g^2 - 1)^{1/2}, \tag{3}$$

with the parameter g defined by

$$g = (A + D)/2. \tag{4}$$

With the magnification M it is possible to obtain the round-trip power transmission $T = 1/M^2$ and the diffraction-loss coefficient $W = -\ln T$. In this approach we neglect diffraction losses in the stable resonator, for which $W = 0$ is assumed.

We consider the unstable-resonator configuration shown in Fig. 1. If the focusing cell is in contact with a mirror of radius R_2, the effective power of the mirror is

$$1/R_2 = 1/R + 1/Z_f, \tag{5}$$

where R is the fixed mirror's radius. Replacing z_f by expression (1) then gives

$$\frac{1}{R_2} = \frac{1}{R} + \frac{2n_2E^2d}{a^2} = \frac{1}{R} + \gamma\alpha I, \tag{6}$$

where $\alpha = 2d/a^2$ and (see Ref. 13) $\gamma I = n_2E^2$. The parameter γ takes into account the nonlinear charac-

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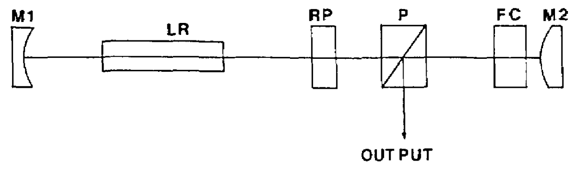


Fig. 1. Experimental setup. M1 is a 100% reflecting mirror $r = 2$ m, M2 is a 100% reflecting mirror $r = -1$ m in contact with the focusing cell. FC is the focusing cell, P is a polarizing prism, RP is a quarter-wave plate, and LR is a Nd:glass laser rod.

teristics of the product and α the geometry of the resonator and the focusing cell.

By substituting Eq. (5) into Eq. (4), the intensity dependence of the parameter g is obtained, which defines the stability characteristics of the resonator and the loss coefficient W:

$$g = g_0 - \beta I, \tag{7}$$

with

$$\begin{aligned} g_0 &= 1 - 2L_c/R - 2L_c/R_1 + 2L_c{}^2/RR_1, \\ \beta &= 2L_c \gamma \alpha g_1, \\ g_1 &= 1 - L_c/R_1, \end{aligned} \tag{8}$$

where L_c is the cavity length. The parameter β completely defines the nonlinear characteristics of the focusing cell.

The equations presented above allow us to compute the diffraction losses introduced by the unstable configuration in each round trip. By making use of rate equations for the photon density and the amplification coefficient G it is possible to evaluate the temporal evolution of the field intensity in the laser cavity. The curves in Fig. 2 show a numerical simulation of the system from which the intensity evolution can be visualized. The rate equations used in the simulation are

$$\begin{aligned} \frac{\partial \phi}{\partial t} &= (G - W - \Gamma)\phi/T_{\text{cav}}, \\ \frac{\partial G}{\partial t} &= (G - G_0)/T_a - \phi \sigma_a G + P, \end{aligned} \tag{9}$$

where G_0 is the unsaturated amplification coefficient, Γ is the linear loss (absorption, scattering, etc), T_{cav} is the round-trip time, T_a and σ_a are the decay time and the amplification cross section of the amplification medium, respectively, and P is the pump rate. The quantity W was defined above and is the diffraction-loss coefficient. The parameters used in this simulation were $G_0 = 1.5$, $W = 0.35$, $\Gamma = 1.145$, $T_{\text{cav}} = 6$ nsec, $T_a = 550$ μsec, $P = 10^{-4}$ sec^{-1}, and $\sigma_a = 4 \times 10^{-20}$ cm^2, typical values for a Nd:glass laser system.

Figure 2 shows a change in the slope of the curve when ϕ achieves a critical value of $\phi_c = 10^{25}$ cm^{-2} sec^{-1}. For this critical value, the equivalent focal length of the focusing cell compensates for the divergence introduced by the mirror, and a stable configuration is achieved. In the focal-length calculation we assume that parameter a has a stationary value corresponding to $\phi = \phi_c$. Exact computations have been done changing the value of the beam size for each value of Z_f, and the results are essentially the same.

For different values of the parameter β, which defines the intensity dependence of g and W, the Q-switching effect shown in the numerical simulations is similar.

If the field intensity is further increased the cavity configuration becomes unstable again if the parameter g is less than -1. Hence there is a limitation on the maximum power obtainable in the laser emission, and this limit depends on the initial configuration of the unstable resonator. Figure 3 shows the dependence of the losses per transit L and the parameter g versus the field intensity for the resonator configuration that we consider here.

The system should be designed so that the gain saturates after a stable configuration is reached in order

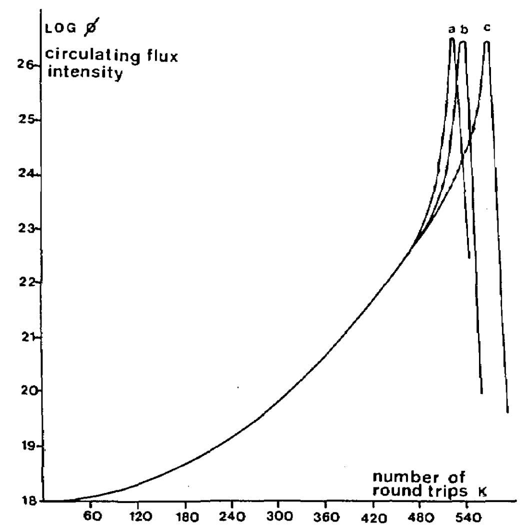


Fig. 2. Numerical simulation of the temporal flux intensity evolution ϕ versus the number of round trips $K = t/T_{\text{cav}}$ for different values of the parameter β: a, $\beta = 10^{-7}$ cm^2/W; b, $\beta = 5 \times 10^{-8}$ cm^2/W; c, $\beta = 10^{-8}$ cm^2/W.

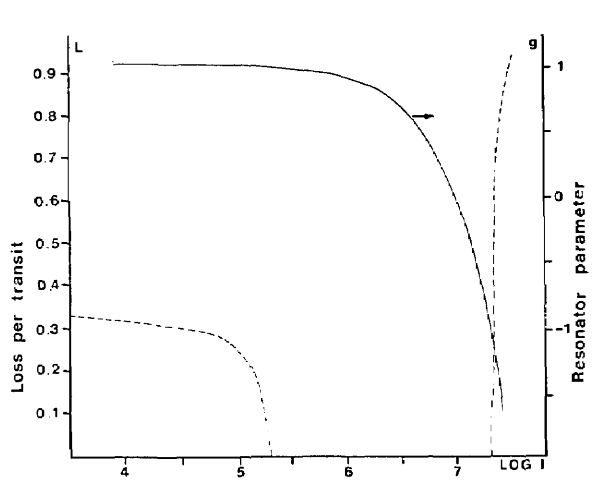
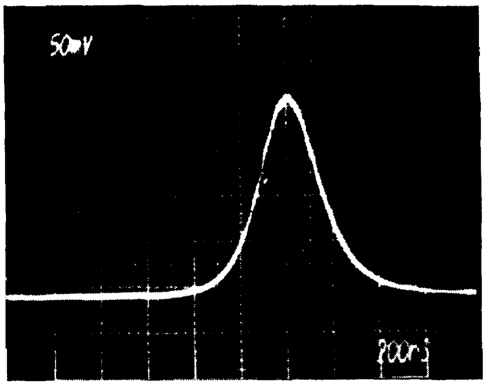
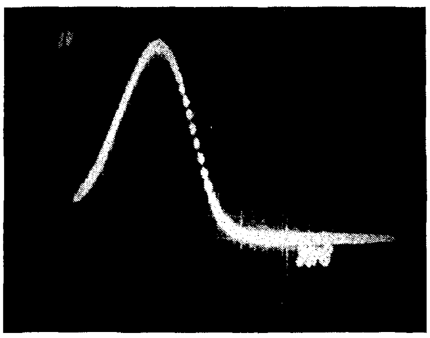


Fig. 3. Cavity losses per transit $L = 1 - T$ and resonator parameter g as a function of the intensity in the cavity in watts per square centimeter for the configuration considered here. For a stable resonator ($-1 < g < 1$), $L = 0$ is considered.



(a)



(b)

Fig. 4. Oscilloscope trace of the laser output. (a) Free-running emission without the focusing cell showing one of the multiple spikes that appear with a FWHM duration of about 300 nsec. Horizontal scale 200 nsec/division; vertical scale, 50 mV/division. (b) Single Q-switch pulse obtained with the focusing cell in the cavity. Horizontal scale, 20 nsec/division; vertical scale, 2 V/division.

to achieve Q switching before it becomes unstable again. A single pulse with most of the stored energy is obtained in this case.

The experimental setup used is shown in Fig. 1. The cavity length is fixed to give an initial diffraction loss per round trip of 30%, and a 4-cm focusing cell was filled with phenyl salicylate (SALOL)[14] supercooled at 25°C. In this case, the relaxation time for the second-order index is less than the round-trip time,[15] so it is possible to use the approximation

$$\delta n = n_2 |E(t)|^2. \tag{10}$$

The output coupling, and hence the linear loss, was varied with a quarter-wave plate and a polarizing cube. The laser rod was a Kigre phosphate Q-88 Nd:glass, and the detection system had an overall response time of 0.8 nsec.

Figure 4(a) shows an oscilloscope trace for one of the multiple spikes in the conventional configuration cavity without the focusing cell. In this case normal emission is obtained with many spikes of a typical duration of 300 nsec. Figure 4(b) shows typical emission when the focusing cell is included in the laser cavity. Only one pulse appears, with 40-nsec FWHM duration and an average power of 500 kW. In this case the peak intensity is about 50 times larger than in the former case.

The average power obtained in this case is limited, as we mentioned above, by the switch to a new unstable configuration when g becomes less than -1. The values obtained experimentally agree well with those obtained in the numeric simulations.

Further experiments are being carried out with different unstable configurations to obtain a better emission characteristics. The system is controlled by four parameters, i.e., Γ (linear losses), g_0 (resonator parameter), β (nonlinear coefficient), and P (pumping power). The initial gain G_0 depends on Γ and g_0. At present, work is in progress to find an expression for the second-threshold condition (defined by New and O'Hare[16]). This second threshold defines the range for β for which Q switching takes place. Such a range will depend on the other parameters, and further work will be carried out to define the optimum values for such parameters.

Studies concerning the mode shape that is obtained with this configuration also are in progress using the Kirchhoff–Fresnel integrals to compare the stable modes of the cavity with Gaussian beams that are only a first aberrationless approach for a cavity with a nonlinear phase term.

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