Self-mode locking of solid-state lasers without apertures

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Numerical simulations that take into account propagation, self-focusing, and gain saturation in solid-state lasers reveal that self-mode locking can take place in such lasers even in the absence of apertures. The combination of self-focusing and gain saturation produces a differential gain that favors the growth of short pulses and eliminates cw oscillations. Nonsymmetrical cavities can provide a substantial differential gain when they are operated near a stability limit.

The observation of self-mode locking in Ti:sapphire lasers, first reported by Spence *et al.*[1] and then confirmed at many laboratories,[2–10] has clearly established that this mode-locking scheme is a powerful method for the generation of femtosecond optical pulses. The method can also be used with other solid-state laser materials.[11,12] The physical origin of the self-mode-locking regime is generally attributed to self-focusing,[13–17] although the understanding is far from complete. Some experiments[3,4,6] have shown that the insertion of apertures at selected places in the laser cavity leads to stable mode locking (the so-called Kerr-lens mode-locking scheme). However, other results[1,2] have clearly established that self-mode locking is stable even in the absence of apertures. The objective of this Letter is to show that the combination of self-focusing in the laser rod and gain saturation can create conditions favorable to the onset of mode locking and to the suppression of multimode (cw) oscillations.

Self-mode locking is a stable regime of emission only when the short pulse circulating in the laser cavity experiences a higher gain per round trip than do cw signals. In solid-state lasers, this higher gain can result from self-focusing's taking place in the gain material; an effective loss modulation is generated by introducing apertures into the cavity. When properly positioned, apertures can lead to a higher transmission of the more intense beams, produced by short pulses, whose size and divergence have been modified by self-focusing. The active medium can play the role of an aperture when its gain coefficient varies spatially, a situation common to optically pumped solid-state lasers. To describe the effect of gain properly, one must take saturation into account, since the gain profile is not a static parameter but rather depends on the field distribution of the incident beam. Owing to self-focusing, the beam shape associated with a short pulse is different from that of cw signals; hence the two beams saturate the gain differently.

We have developed a numerical code to simulate the evolution of the beam profile in typical Z-type four-mirror laser cavities used in self-mode-locked solid-state lasers. A schematic representation of the laser cavity is shown in Fig. 1. The active medium of length L is cut at Brewster's angle and placed between two converging mirrors (M_1, M_2) of the same radii of curvature R. The output coupler M_3 has a transmittance T_3. We have made no assumption about the shape of the beam circulating in the cavity; we have used a numerical algorithm[18] (the so-called beam-propagation method) to calculate how the beam profile evolves in the active medium. We have considered a homogeneously broadened active medium pumped by a Gaussian beam; for the sake of simplicity, we have assumed that the gain profile is uniform along the axis of propagation (e.g., the gain coefficient and the waist of the pump beam are kept constant throughout the active medium). The single-pass saturated gain factor $G(x)$ at transverse position x is hence given by

$$G(x) = \exp\left[\frac{g_0 \exp(-2x^2/W_p{}^2)}{1 + \langle I^+(x)\rangle + \langle I^-(x)\rangle}\right], \tag{1}$$

where g_0 is the single-pass unsaturated gain coefficient at the beam center and W_p is the waist of the pump beam; $\langle I^+(x)\rangle$ and $\langle I^-(x)\rangle$ represent the time-averaged intensity of the counterpropagating beams at position x (all intensities have been normalized with respect to saturation intensity I_s). The active medium is also assumed to have a nonlinear index of refraction n_2, which produces a nonlinear phase shift proportional to the local value of intensity. The spatial variation of this phase shift gives rise to self-focusing. We have found it convenient to define a dimensionless parameter K representing the strength

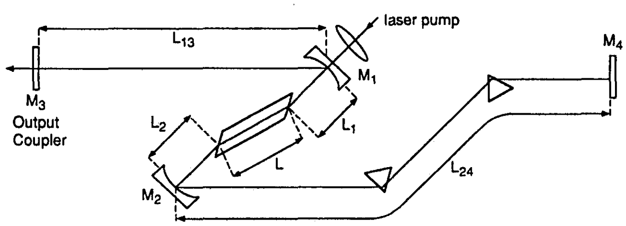

Fig. 1. Z-type four-mirror cavity under consideration.

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of the Kerr nonlinearity as $K = (2\pi/\lambda)n_2 2L(t_r/t_p)I_s$, where λ is the laser wavelength, t_r is the duration of a round trip in the cavity, and t_p is the pulse duration. Configurations with the same value of K are equivalent; hence, one can use this definition to study the effect of a Kerr nonlinearity for a broad set of laser parameters.

The calculations proceeded as follows. The active medium was divided into N thin sheets (with N as high as 21). At each sheet a correction to the beam amplitude and phase profiles was made to account for amplification and Kerr nonlinearity. The propagation from one sheet to next was made with fast Fourier transforms, according to the beam-propagation-method algorithm.[18] The calculations showed that steady state was reached after a few hundred round trips in the cavity when the field distributions on consecutive round trips n and $n + 1$ verified that $E_{n+1}(x) = \exp(i\psi)E_n(x)$. The phase shift ψ is the sum of a linear component θ evaluated with $K = 0$, which represents an axial phase shift (the Guoy effect), and of a nonlinear contribution ϕ that is due to the Kerr nonlinearity. The parameter ϕ represents the nonlinear phase retardation, or self-phase modulation (SPM), experienced by the entire beam. The residual gain per round trip g_{cw} of cw oscillations was also evaluated with the saturated gain profile computed for a short pulse ($K > 0$). The numerical parameters used for the simulations were the following (unless otherwise specified): $R = 15$ cm, $L = 1.5$ cm, $L_{12} = L_1 + L_2 + L = 16.4$ cm, $L_1 = L_2$, $T_3 = 10\%$, $g_0 = 15\%$, and $W_p = 30$ μm. The calculations were made independently for sagittal and tangential directions; this approximation is justified by the fact the beam waists along the two orthogonal directions are quite different in the laser material; hence coupling between sagittal and tangential beams should be small. Mirrors M_1 and M_2 were tilted by 18.5 deg so as to compensate for astigmatism[19] (the index of refraction of the active material was assumed to be 1.75). With such parameters, the laser was operated at twice the laser threshold and delivered 410 mW of output power, assuming that $I_s = 400$ kW/cm^2.

The results shown in Fig. 2 are typical of many resonator configurations that were studied. Figure 2 indicates that the output power increases as a function of nonlinearity (or inversely with pulse duration) up to a point where the power drops abruptly. Figure 2 also shows the residual gain for cw oscillations as a function of nonlinearity. It is seen that the cw oscillations experience a net loss per round trip that should lead to their suppression; that loss can exceed 1% if the contributions along the sagittal and tangential directions are added. Hence a short pulse benefits from a differential gain proportional to its nonlinearity K; mode locking could then be achieved even in the absence of apertures. It is also seen that the cw oscillations remain below threshold even at values of nonlinearity (near $K = 3\pi$) for which the power has dropped below its value in the cw regime. This may explain partly why the observed output power in the self-mode-locked regime is sometimes higher or lower than in the cw regime.

The spatial profiles shown in Fig. 3 reveal that the laser beam narrows as the nonlinearity increases, leading to a better overlap with the gain profile. As a result, the gain is more depleted at center by short pulses than by cw oscillations; such a process discriminates against cw oscillations, which require a higher gain at the center to reach threshold. At large nonlinearities, where the power drops (see Fig. 2), the beam becomes very narrow, and small wings appear (curve 3 of Fig. 3); the net result is a poorer extraction efficiency, while discrimination is maintained against cw oscillations.

Information about minimum pulse durations can be extracted from Fig. 2. Since self-mode locking should be stable up to $K = 3\pi$, the corresponding pulse duration can be calculated from the definition of K; using $\lambda = 800$ nm, $n_2 = 3 \times 10^{-16}$ W/cm^2, $I_s = 400$ kW/cm^2, $t_r = 11$ ns, and $L = 1.5$ cm, one finds that $t_p = 39$ fs. If thinner gain materials are used ($L = 0.8$ and 0.4 cm), then one finds that $t_p = 21$ and 11 fs, respectively. These numbers correspond closely to the minimum pulse durations measured experimentally.[7–10] To achieve such pulse durations, one needs to compensate for second- and third-order dispersion terms; when this is done, our simple result predicts that there is a limit to pulse narrowing beyond which the short pulse is unstable because its differential gain is insufficient to discriminate against cw oscillations.

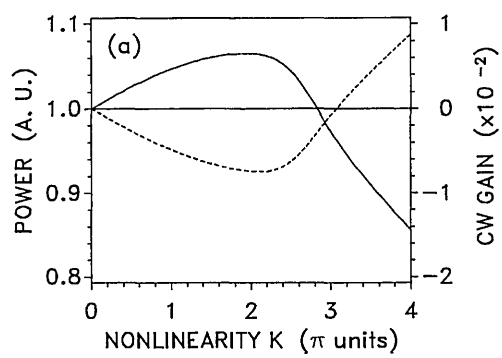

Fig. 2. Normalized output power (solid curve) and residual cw gain (dashed curve) as a function of nonlinearity K for the sagittal component of a symmetrical cavity with $L_{13} = L_{24} = 75$ cm.

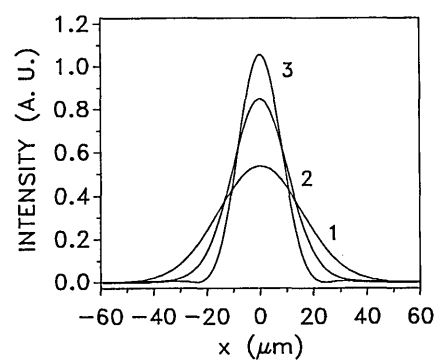

Fig. 3. Beam profile at the center of the laser rod, for a beam traveling from M_1 to M_2, for the same parameters as in Fig. 2. Curve 1 is obtained in the cw regime ($K = 0$), curve 2 corresponds to $K = 2\pi$, and curve 3 corresponds to $K = 3\pi$.

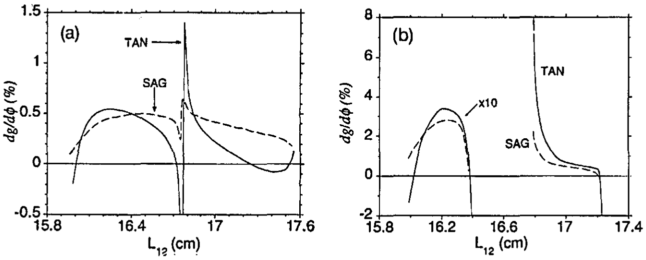

Fig. 4. Differential gain per unit of SPM as a function of the distance L_{12} between mirrors M_1 and M_2 (a) for a symmetrical cavity with $L_{13} = L_{24} = 75$ cm and (b) for a nonsymmetrical cavity with $L_{13} = 75$ cm and $L_{24} = 125$ cm. SAG, sagittal component; TAN, tangential component.

We have studied how the discrimination against cw oscillations is sensitive to the resonator geometry by calculating $dg/d\phi$, the differential gain of the nonlinear beam ($g = -g_{cw}$) per unit of SPM. For the symmetric resonator of Fig. 4(a), $dg/d\phi$ is positive for almost every value of the distance L_{12} between the two focusing mirrors where a stable mode exists; $dg/d\phi$ exceeds 0.4% over a large fraction of the stability range. This means that such cavities can provide a weak differential gain that discriminates against cw oscillations; however, this gain is small compared with SPM; hence the differential gain is insufficient for it to have significant effects on the pulse duration, which is determined by the equilibrium between dispersion and SPM.

Halfway through the stability zone (near $L_{crit} = L_{12} = 16.77$ cm), the curves show a discontinuous behavior. It can be shown that, at such a value of L_{12}, the cavity is equivalent to a standard two-mirror confocal cavity that stands at the limit of geometrical instability. Self-focusing has the effect of pushing the cavity into the unstable zone when $L_{12} < L_{crit}$, while it pushes the cavity well into the stable zone for $L_{12} > L_{crit}$. Enhancement of this type of response can be effected by use of a nonsymmetrical cavity, as shown in Fig. 4(b). Two stability zones are predicted for such cavities. In the first zone, where the mirror separation is small, the behavior resembles that of a symmetrical cavity; the beam then has a minimum spot size in the active medium, just as in Fig. 4(a). However, for the second zone, with a larger mirror separation, the differential gain increases abruptly near the edge of instability. At that position, the beam has a very small minimum spot size outside the active medium; owing to its divergence in the active medium, such a beam has a poor overlap with the gain profile. The presence of self-focusing pushes the cavity well into the stability zone, producing a beam of smaller size in the gain medium. Such a beam leads to a higher saturation of the gain, which in turn becomes insufficient to sustain cw oscillations. One can also obtain large values of $dg/d\phi$ at the short limit of the first stability zone (near $L_{12} \approx 16.0$ cm) by moving the active medium toward a focusing mirror. Again, self-focusing has the effect of compensating for beam divergence in the gain medium. However, at the other limits of the stability zones ($L_{12} \approx 16.4$ and 17.2 cm), self-focusing pushes the cavity into the unstable zone, and no significant enhancement of $dg/d\phi$ has been noticed.

In summary, we have shown that self-focusing and gain saturation can create conditions leading to self-mode locking and to the elimination of cw oscillations. In general, the differential gain experienced by the short pulse is small, except at the limit of geometrical instability in nonsymmetrical cavities. Under such circumstances, mode locking should be much easier to initiate and should be more stable.

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