Self-starting Kerr-lens mode locking of a Ti:sapphire laser

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It is shown that Kerr-lens mode locking of a Ti:sapphire laser, with no intracavity elements except the laser rod and the dispersion-compensating prisms, can be made to be completely self-starting. We achieve this result by carefully designing the resonator to maximize the nonlinear mode variations and dynamic loss modulation.

Kerr-lens mode locking (KLM) is a well-established technique for ultrashort-pulse generation based on the self-focusing effect occurring in an intracavity Kerr medium.[1,2] This effect modifies the mode profile so that the losses caused by a suitable aperture decrease as the power increases.[3,4] A drawback of KLM lies in the fact that it does not spontaneously start from the cw regime but requires an external initiating action. For a solution to this problem several starting devices have been proposed.[3–7] Recently self-starting of a KLM Ti:sapphire laser was achieved with a unidirectional ring resonator[8] and with a linear cavity containing a second pair of folding mirrors with a highly nonlinear material inside.[9]

Until now it was believed that KLM of Ti:sapphire lasers with a linear cavity could not start without a suitable initiating device because of the too-low nonlinear loss modulation delivered by the KLM mechanism. In this Letter we show that KLM Ti:sapphire lasers, with no intracavity elements except the laser rod and the dispersion-compensating prisms, can be made to be completely self-starting. This feature can be achieved by a careful resonator design that maximizes the nonlinear mode variation and dynamic loss modulation. The optimum resonator parameters are derived with the help of a theoretical analysis based on a nonlinear *ABCD* matrix formalism previously introduced by the authors.[10,11]

In KLM lasers the cavity losses L are given, to the first order, by

$$L = L_0 - kP, \qquad (1)$$

where L_0 are the total linear losses, k is the nonlinear loss coefficient, and P is the intracavity instantaneous power. For the mode-locking process to be self-starting, the coefficient k must exceed a suitable value.[12,13] Consider the typical astigmatically compensated resonator shown in Fig. 1 in which slit S_1 is placed in front of mirror M_1 to sustain KLM. Assuming that the self-consistent mode is a TEM_{00} beam (possibly elliptic) not appreciably disturbed by the slit, one can estimate the coefficient k by calculating the fractional transmission through the slit. This calculation yields

$$k = -2\sqrt{2/\pi}\,\exp[-2(a/w_1)^2]\,\frac{a}{w_1 P_c}\,\delta_1, \qquad (2)$$

$$\delta_1 = \left(\frac{1}{w_1}\frac{\mathrm{d}w_1}{\mathrm{d}p}\right)_{p=0}, \qquad (3)$$

where $2a$ is the width of the slit, w_1 is the Gaussian beam spot size in the direction in which the slit cuts the beam, δ_1 is the small-signal relative spot size variation,[10] P_c is the critical power for self-focusing, and $p = P/P_c$.

The parameter δ_1 can be calculated, within the framework of the aberrationless theory of self-focusing, by a nonlinear *ABCD* matrix formalism[10,11] and turns out to be a simple function of the resonator parameters. Since the intracavity peak power of a KLM Ti:sapphire laser is high, even low values of $|\delta_1|$ are usually sufficient to sustain mode locking, but a particular resonator design that maximizes $|\delta_1|$ is required for self-starting. We have shown[11] that for any resonator a limit on the maximum achievable value of $|\delta_1|$ is set by

$$|\delta_1|_{\max} = \frac{1}{4[A_0 D_0(1 - A_0 D_0)]^{1/2}}, \qquad (4)$$

where A_0 and D_0 are the elements of the one-way matrix for the propagation from mirror M_1 to mirror M_2, including the curvature of the mirrors. It should be noted that Eq. (4) does not give the value of $|\delta_1|$ as a function of the matrix elements but only sets an upper limit that is reached with suitably optimized resonators.[11] Since the resonator is stable for $0 < A_0 D_0 < 1$, Eq. (4) evidences that $|\delta_1|_{\max}$ can grow to infinity at the borders of the stability region. Self-starting operation should, therefore, in principle be achieved with a resonator working close enough

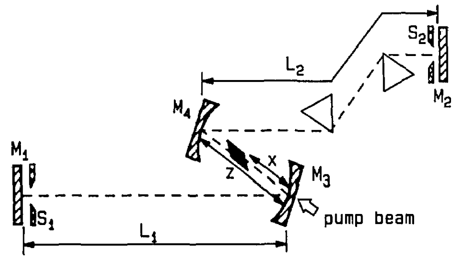

Fig. 1. Resonator configuration used for the experiments. M_3, M_4, concave folding mirrors.

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to one stability limit. Usually, as the resonator approaches a stability limit with A_0 or $D_0 \rightarrow 0$ (as in the case of asymmetric flat end mirror cavities), the laser mode tends to degenerate into a spherical wave and the laser performances dramatically worsen. The attainment of large nonlinear loss modulations seems therefore to be practically impeded. If, however, the resonator approaches the stability limit because both A_0 and D_0 simultaneously vanish, it becomes equivalent to a confocal resonator with a well-behaved transverse mode. In these conditions δ_1 can diverge without laser performance degradation. If the resonator presents astigmatism the above considerations are still approximately valid provided that they are referred to the sagittal or tangential planes separately. In particular, numerical simulations have shown that as an effect of the astigmatism $|\delta_1|$ tends to increase in the tangential plane and decrease in the sagittal plane with respect to the predictions of the *ABCD* matrix formalism. With a resonator structure such as that shown in Fig. 1 the simplest way to achieve $A_0 = D_0 = 0$ in the tangential plane consists of using a symmetric resonator ($L_1 = L_2$) with flat end mirrors and folding mirrors of radius R placed at a distance

$$z = z_m = \frac{4L_1R_t - R_t^2}{4L_1 - 2R_t} + d\left(1 - \frac{1}{n^3}\right), \quad (5)$$

where z is the physical path length between mirrors, $R_t = R\cos\theta$ is the equivalent radius of curvature in the tangential plane of the folding mirrors tilted by an angle θ, d is the length of the Brewster-cut rod, and n is its refractive index (d/n^3 is the equivalent rod length in the tangential plane).

For the experiments we set up an argon-ion-pumped Ti:sapphire laser according to the configuration of Fig. 1. The system was placed on a vibration-isolated honeycomb table, and the rod and the folding mirrors were mounted on precision translators. The power fluctuations of the argon-ion-laser (Coherent Innova 310) were measured to be less than 0.3% rms in the bandwidth of 20 Hz to 100 kHz. The Brewster-cut laser rod was 20 mm long, the intracavity SF10 prisms were at a tip-to-tip distance of 500 mm, and the output coupling was 5%. The resonator parameters were $L_1 = L_2 = 850$ mm, folding mirror radii of curvature $R = 100$ mm, and folding angle $\theta = 14.5°$. The condition $A_0 = D_0 = 0$ is reached in the tangential plane for a folding mirror distance $z_m \approx 116.1$ mm. Slit S_1 was placed in front of mirror M_1 to cut the beam in the tangential plane and was used to sustain KLM, while slit S_2, placed close to mirror M_2, was used for wavelength control. When the laser was pumped with 4.5 W of power, the typical cw output power of the Ti:sapphire laser at 800 nm was 850 mW. For KLM to be achieved the folding mirror distance z and the position x of the Ti:sapphire rod have to be carefully optimized to provide suitable negative values of δ_1. For this purpose we used a plot (Fig. 2) of the contour lines of δ_1 in the tangential plane as a function of x and z. Figure 2 also shows, denoted by the squares and triangles, the coordinate pairs (x, z) for which we could experimentally achieve KLM. Because of the resonator astigmatism, KLM could not be obtained with the slit cutting the beam in the sagittal plane. A suitable adjustment of the pump-beam focus prevented the laser from working in KLM with the slit open, as a result of gain-guiding effects. Generally we initiated mode locking by slightly tapping one of the end mirrors. The output power during KLM was 300–450 mW, and the pulse duration was 50–80 fs.

When the folding mirror distance was adjusted in a suitable range around the critical value $z_m = 116.1$ mm, the KLM became self-starting, so that initiating the pulse formation required no external perturbation. The values of x and z for which self-starting operation was readily achieved are given in Fig. 2 as triangles. Figure 3 shows the temporal behavior of the laser with a mechanical chopper inserted in the cavity: when the chopper is transmitting the laser starts oscillating cw and then spontaneously turns to mode locking. The buildup time of the mode-locking pulse train was found to be strongly dependent on the slit size, the pump power level, and the intracavity dispersion; in particular, the measured dependence of the average buildup time on the pump power is shown in Fig. 4. As evidenced in this figure, the buildup time presents wide statistical fluctuations. The self-starting regime was very stable (amplitude fluctuations on a millisecond time scale of <1%) and easily reproducible, and the laser could be operated in the self-starting mode for several days with minor day-to-day adjustments. The transverse mode profile, measured with a solid-state camera, evidences a pure TEM_{00}-mode operation, which is consistent with the fact that the resonator is nearly equivalent to a confocal one. The tolerance on the

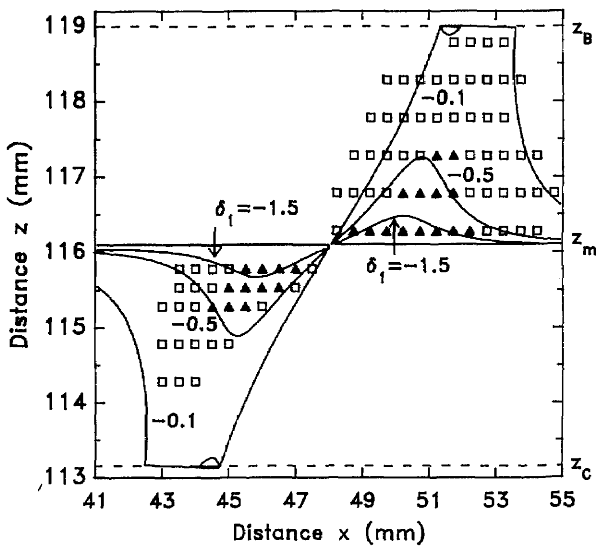

Fig. 2. Contour lines of the spot size variation δ_1 in the tangential plane for the resonator of Fig. 1 as a function of the folding distance z and of the rod position x. The squares mark the points where KLM is initiated by tapping of one of the end mirrors; the triangles correspond to the self-starting condition. For $z = z_m$ the resonator is equivalent to a confocal one ($A_0 = D_0 = 0$). z_B and z_C correspond to the stability limits.

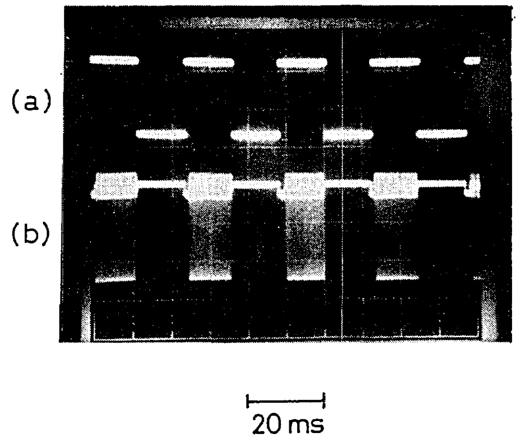

Fig. 3. Self-starting regime of KLM monitored with a fast photodiode and a mechanical chopper that periodically stops the laser action: (a) reference signal from the chopper (the lower level corresponds to a chopper blade in the path of the beam), (b) KLM pulse train.

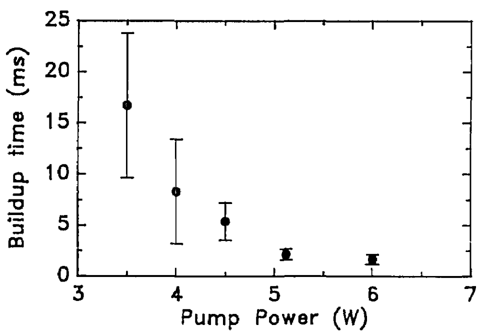

Fig. 4. Buildup time of the self-starting regime, averaged over 20 measurements, as a function of pump power. The resonator parameters are $z = 116.3$ mm and $\acute{x} = 50.5$ mm.

exact values of L_1 and L_2 was not very tight: in fact, we could vary L_1 by 50 mm and still keep the laser in the self-starting regime. As mentioned above, the symmetric plane-mirror cavity is not the only one that can satisfy the condition $A_0 = D_0 = 0$; an asymmetric cavity with $L_1 = 480$ mm, $L_2 = 850$ mm, and mirror M_1 concave with $R_1 = -500$ mm is a valid alternative. Building this cavity and working near $z \approx 118.6$ mm, we could again achieve self-starting KLM.

The theoretical analysis of the dynamics of cw lasers mode locked with a fast saturable absorber presented in Ref. 13 provides the following self-starting condition:

$$kP > T_r/[\ln(m_i)\tau_c], \tag{6}$$

where P is the average intracavity cw power, T_r is the round-trip time, τ_c is the correlation time of the axial modes, and m_i is the number of modes initially oscillating. The correlation time is related to the 3-dB full width of the first beat note of the axial modes, $\Delta\nu_{3\,\mathrm{dB}}$, by $\tau_c = 1/(\pi\Delta\nu_{3\,\mathrm{dB}})$, and $\ln(m_i)$ represents the ratio of the peak power of the most intensive fluctuation to the average intracavity power. The predicted buildup times of the mode-locking regime are of the order of τ_c. For our laser we measured with an electronic spectrum analyzer $\Delta\nu_{3\,\mathrm{dB}} \approx 3.5$ kHz, yielding a correlation time of $\tau_c \approx 100$ μs. Because the round-trip time is $T_r = 12$ ns, assuming $\ln(m_i) \approx 5-10$, we derive for the self-starting condition $kP > 1-2 \times 10^{-5}$ and a buildup time in the range 50–200 μs. The maximum value of the product kP achievable with our laser as a function of the slit width has been estimated with Eq. (2) and a rate-equation model. Assuming, according to Fig. 2, that $\delta = -2$ and $P_c = 2$ MW, for our system we derived $(kP)_{\max} \approx 3 \times 10^{-6}$, which is lower than the value required by relation (6). Accordingly, the measured average buildup times are longer than those predicted by theory. A closer agreement with the experimental results can be obtained by including in the model the effects of cavity dispersion.[14]

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