Measurements of the self-starting threshold of Kerr-lens mode-locking lasers

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We measured the self-starting threshold of passive Kerr-lens mode-locking dye lasers and Ti:sapphire lasers by varying the concentration of the intracavity dilute-dye saturable absorbers that start the mode locking. From the threshold absorber concentration, we determined the strength of the intracavity pulse-broadening effects that counteract the pulse-shortening mechanisms in the self-starting stage. Experimental results agree well with theories based on phase diffusion and mode pulling.

Recently there have been great advances in passive mode locking of solid-state lasers. The new mode-locking mechanisms utilize the optical Kerr effect to produce a fast pulse-shortening effect equivalent to that of a fast saturable absorber. In additive-pulse mode locking (coupled-cavity mode locking), pulse shortening results from the interference of pulses with different amount of self-phase modulation,[1,2] whereas in Kerr-lens mode locking, pulse shortening comes from the intracavity self-focusing effect that is biased for the laser to have a higher gain for the pulse state than for the cw state.[3–6] Because the Kerr effect is proportional to the instantaneous intensity, the mode-locking mechanism becomes stronger as the pulses shorten and the peak intensity increases. But before the pulses shorten significantly, the mode-locking mechanism is extremely weak. Therefore the laser may not be able to start the mode-locking process by itself.[7] Understanding the self-starting conditions for passive mode locking is not only scientifically interesting but also of practical value for future development of passive mode-locking lasers.

Consider a broadband laser with an effective fast saturable absorber in the cavity. If no pulse-broadening effects existed, then an infinitesimally small intensity fluctuation would grow into pulses even if the fast-saturable-absorber effect were negligibly small, and there would be no self-starting mode-locking threshold. In reality this is not the case because there are pulse-broadening effects in the cavity. Theoretical models explaining how intensity fluctuation decays or pulses broaden in laser cavities have been proposed.[8–11] These models predict the minimum strength of the pulse-shortening mechanism needed to balance the pulse-broadening effects and hence predict the threshold conditions for passive mode locking. In this Letter we report our measurements of the intracavity pulse-broadening effects and compare the results with theories.

It is known that dilute dye saturable absorber can be used to start Kerr-lens mode locking in Ti:sapphire lasers.[4,12] Recently our research group used the same method to start Kerr-lens mode locking in dye lasers.[13] Dilute dye saturable absorbers are not only effective media for initiation of passive mode locking but also have the advantage that their strength can be accurately controlled and varied continuously. By carefully varying the concentration, one can walk the laser from a non-self-starting operating point to a self-starting one, crossing the threshold region. The threshold absorber concentration thereby reveals how large the intracavity pulse-broadening effects are.

The pulse-shortening effect from the absorber, expressed in fractional pulse shortening per round trip, $\mathrm{d}\tau/\tau\mathrm{d}n$, can be estimated from the rate equations that govern the dynamics of the absorbers[4]:

$$\frac{1}{\tau}\frac{\mathrm{d}\tau}{\mathrm{d}n} = -\frac{l\sigma_a E}{2\hbar\omega A_a}\left[f\left(\frac{\tau}{T_a}\right) - h\left(\frac{\tau}{T_a}\right)\right],$$
$$f(x) = \frac{x+4}{8(x+2)^2}, \qquad h(x) = \frac{x^3+8x^2+28x+64}{32(x+2)^4}, \tag{1}$$

where σ_a is the absorption cross section, T_a is the upper-state lifetime, E is the pulse energy, A_a is the beam area in the absorber, and l is the linear loss of the absorber. The rational functions $f(x)$ and $h(x)$ result from a second-moment analysis and integration of the rate equations. In the self-starting stage the peak intensity of the initial pulse or fluctuation is low, and the Kerr-lens pulse-shortening mechanism is negligibly small compared with that of the saturable absorber. Equations (1) therefore represent the pulse-shortening effect in the cavity.

Two types of physical process have been postulated to cause pulse broadening or fluctuation decay in the initial stage of mode locking. In Ref. 8 phase dispersion of the longitudinal modes caused by spurious reflections was analyzed, and in Ref. 11 similar effects caused by spatial hole burning were considered. Both analyses point out a phase diffusion time constant that originates from the dispersion of longitudinal mode spacing (mode pulling). Phase diffusion washes away the phase correlation between the modes, thereby causing pulse broadening and fluctuation decay. The fractional pulse broadening per round trip is given by the following equation, which

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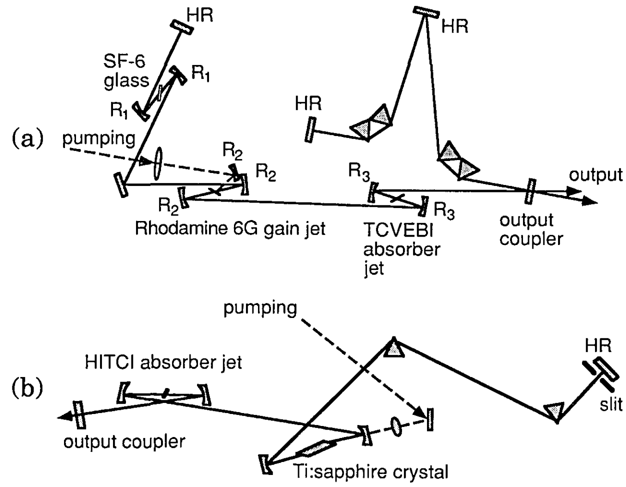

Fig. 1. Schematic diagrams of the passively Kerr-lens mode-locked (a) Rhodamine 590 dye laser and (b) Ti:sapphire laser. R's, reflectors; HR's, high reflectors.

we adapted from Eq. (3′) of Ref. 9 by changing variables from the peak intensity to the pulse width:

$$\frac{1}{\tau}\frac{\mathrm{d}\tau}{\mathrm{d}n} = \frac{T_R}{\tau_c}, \tag{2}$$

where T_R is the cavity round-trip time and τ_c is the phase diffusion time. Experimentally, the phase diffusion time constant is inversely proportional to the linewidth of the first beat note, which can be readily measured by electronic means.

Dynamic gain saturation also affects the stability of the initial pulses. The effect was considered in Ref. 10. Using a simple energy balance principle, those authors derived a necessary condition for self-starting passive mode locking:

$$\kappa/g > \beta\sigma\tau, \tag{3}$$

where κ is a proportional constant that depends on the nonlinearity, g is the saturated gain before the perturbation of the initial fluctuation, β is a numerical factor that depends on the pulse shape but is of order unity, σ is the emission cross section of the gain medium, and τ is the FWHM pulse duration. Although relation (3) was originally derived for general fast-saturable-absorber mode locking, it can also be applied to dye saturable absorbers in which the upper-state lifetime is much shorter than the duration of the initial pulses. For absorbers in which the lifetime is comparable with or longer than the pulse duration, one should replace $\kappa/(\sigma\tau)$ by the linear loss l and β by the following equation to take into account the relaxation of the upper states:

$$\beta = \left(\frac{\sigma_g/A_g}{\sigma_a/A_a}\right)\frac{\int s(t)\int s(t')\exp\left(-\frac{t-t'}{T_g}\right)\mathrm{d}t'\,\mathrm{d}t}{\int s(t)\int s(t')\exp\left(-\frac{t-t'}{T_a}\right)\mathrm{d}t'\,\mathrm{d}t}, \tag{4}$$

where σ_g and σ_a, A_g and A_a, and T_g and T_a are the cross sections, beam areas, and upper-state lifetimes of the gain medium and the absorber, respectively. Because dynamic gain saturation is proportional to the emission cross section, the effect should be much larger in dye lasers than in solid-state lasers.

In the experiments we first measure the mode-beating line width and calculate the pulse-broadening effects according to relations (2)–(4). Then we use Eqs. (1) to estimate the threshold concentration of the dye absorber needed to overcome the pulse-broadening effects and compare the predicted values with experimental results. We find that the phase diffusion (mode-pulling) theories correctly predict the intracavity pulse-broadening effect.

Figure 1 is a schematic diagram of the lasers used in our experiments. The dye laser is a Kerr-lens mode-locking Rhodamine 590 laser recently developed by our research group,[13] and the Ti:sapphire laser is built from a Clark NAJ-1 kit. In the Ti:sapphire laser the absorber is a 75-μm HITCI (T_a = 1.2 ns) jet,[14] and in the dye laser a 30-μm TCVEBI (T_a = 35 ps) jet is used.[15] The output of the lasers is monitored by a fast photodiode, a real-time autocorrelator, and an optical multichannel analyzer. The fast photodiode is used to determine the duration of the initial pulse, which in our lasers is equal to the width of the mode-beating waveform, whereas the autocorrelator and the optical multichannel analyzer are used to distinguish mode locking from mode beating. The laser is classified to be mode locked only when the autocorrelator produces stable second-harmonic autocorrelation traces and the optical multichannel analyzer shows stable broadened spectra. We determine the threshold point by slowly increasing the absorber concentration until mode locking self-starts. At that point the pulse-shortening effect from the absorber balances the pulse-broadening effects. In the experiments we find that the transition from mode beating to mode locking is sharp. The narrow, unstable, ambiguous region between mode beating and mode locking does not contribute to the uncertainty of our measurements. For both lasers measurements are done at various wavelengths within the tuning range.

Experimental results are shown in Figs. 2 and 3. To make the data presentation independent of the thickness of the absorber jets, we plot the threshold linear loss instead of the concentration as a function of the absorption cross section of the dye absorber, which varies with wavelength.[15,16] The linear loss l is related to the concentration N by $l = \exp(-N\sigma L)$, where σ is the absorption cross section and L is the jet thickness. Experimental data of the dye laser, shown in Fig. 2, fit well with the phase diffusion theories but not with the dynamic gain saturation model. According to the gain saturation model, in dye lasers gain saturation should be the dominant pulse-broadening effect, yet the experimental result agrees with the much smaller phase diffusion effect. The experimental result indicates that the gain saturation effect is overestimated. The overestimation may be due to the fact that mode locking in our laser is initiated from mode beating instead of from random intensity fluctuation. In the

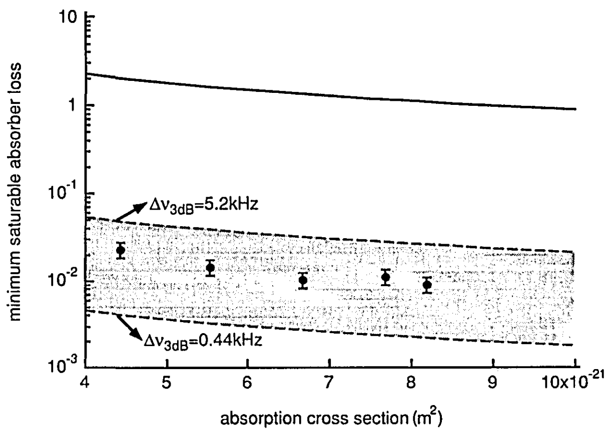

Fig. 2. Mode-locking-threshold measurements with the dye laser. Solid curve, prediction of the gain saturation model; shaded band, prediction of the phase diffusion theories. In our measurements of the beat-note linewidth the sampling time is 10 ms. The linewidth fluctuates near 1.5 kHz with a 1.8-octave standard deviation. Filled circles, experimental data.

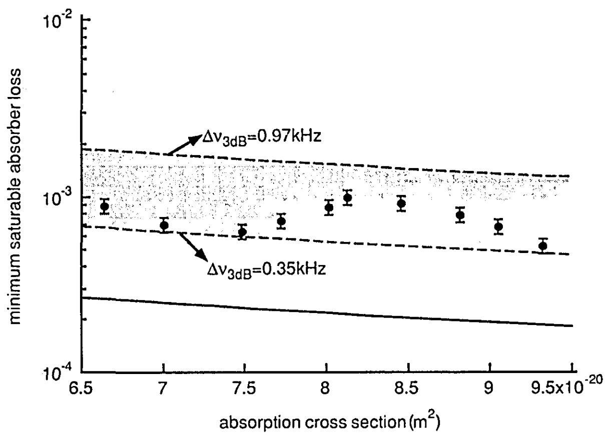

Fig. 3. Mode-locking threshold measurements with the Ti:sapphire laser. Solid curve, prediction of the gain saturation model; shaded band, prediction of the phase diffusion theories. In our measurements of the beat-note linewidth the sampling time is 20 ms. The linewidth fluctuates near 590 Hz with a 0.7-octave standard deviation. Filled circles, experimental data.

mode-beating case the gain for the beating modes is spatially partitioned because of spatial hole burning; therefore in the gain medium the amplitude of the local intensity oscillation at the beat frequency is much smaller than that in the output waveform. The notion that mode locking is initiated from mode beating is also supported by the fact that in our experiments with both lasers we can start the mode locking only when there is clear, deep mode beating.

Experimental data for the Ti:sapphire laser are shown in Fig. 3. In our Ti:sapphire laser the calculated pulse-broadening effect from phase diffusion is larger than that from gain saturation. The experimental data agree with the phase diffusion theories, as expected. It should be noted that from the discussion in the last paragraph we may expect that the gain saturation effect in the Ti:sapphire laser will also be overestimated as a result of mode beating. From our experimental data for the dye laser (Fig. 2), the overestimation may be as large as 2 orders of magnitude. Thus the real magnitude of the gain saturation effect in the Ti:sapphire laser should be much smaller than indicated in the figure. Therefore in the Ti:sapphire laser phase diffusion is also the dominant pulse-broadening effect.

In the spatial hole-burning threshold theory the mode-locking threshold also depends on the intracavity power of the laser, whereas in the spurious reflection theory the threshold is independent of power. In principle one could measure the power dependence of the mode-locking threshold to determine which theory is closer to reality. However, the power ranges in which our lasers mode lock are too small to permit us to tell the difference.

Because in unidirectional ring lasers effects the spatial hole burning and spurious reflection are insignificant, one would expect that in unidirectional passive mode-locking ring lasers the mode-locking threshold would be much lower than in linear lasers. The prediction is qualitatively confirmed by the self-starting Kerr-lens mode-locked Ti:sapphire laser described in Ref. 17. Our experiments quantitatively confirm that phase diffusion is indeed the dominant pulse-broadening effect in the self-starting stage of linear cavity Kerr-lens mode-locking lasers, whether the effect is due to spatial hole burning, spurious reflection, or both.

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