Amplitude modulation mode locking of lasers by regenerative feedback

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We analyze the performance of regenerative feedback mode locking using intracavity amplitude modulation (AM). Regenerative feedback is predicted to improve the stability of AM mode locking especially at low and moderate repetition rates and short pulse durations. We report on AM regenerative-feedback mode locking of a continuous wave Nd:glass laser. The generated train of 8 ps pulses has an excellent long-term stability and is completely free of relaxation oscillation instabilities inherent in conventional AM mode locking.

Active mode locking of lasers has been a reliable technique for the generation of coherent ultrashort light pulses.[1] Owing to spontaneous phase switches inherent in frequency modulation (FM) mode locking[2] and the achievable shorter pulse durations at moderate repetition rates,[3] active mode locking is most frequently accomplished by intracavity amplitude modulation (AM).

In actively mode-locked lasers instabilities mainly originate from a detuning $\Delta\nu = \nu - \nu_0$ between the modulation frequency ν (equal to the mode-locked pulse repetition rate) and the cavity round-trip frequency ν_0 of the free-running (unmodulated) oscillator. This deviation is caused by inevitable changes in system parameters during long-term operation.[1,4] Detuning results in a phase shift ϕ_l between the modulation and the mode-locked pulse train as shown in Fig. 1. This phase shift, in turn, leads to pulse broadening, reduction of the output power, and increased fluctuations of the pulse parameters. In addition, AM mode locking tends to excite relaxation oscillations, and may even result in regular undamped spiking (self Q switching).[5] In order to suppress these instabilities $\Delta\nu/\nu_0$ must be kept below 10^{-5} in a Nd:YAG laser delivering pulses of ~ 100 ps.[6] This tolerance goes down rapidly with decreasing pulse duration as we shall see later. Both a well-stabilized laser cavity and a highly stable signal generator are thus required for conventional AM mode locking.

The purpose of this letter is to show that the undesirable phase shift ϕ_l can be substantially reduced by the regenerative feedback technique thereby allowing highly stable AM mode locking on a long time scale without the need for an ultrastable radio frequency (rf) signal source. The basic idea dates back to the early years of mode-locked lasers and takes advantage of the fact that the driving signal for the intracavity modulator can be derived from the mode-locked laser output itself. A schematic of the system is shown in Fig. 2. A small portion of the laser output is directed onto a photodetector capable of sensing the fundamental beat note equal to ν_0 of the laser output. This signal is selectively amplified, frequency divided, phase shifted by a variable amount, and after further amplification, applied to the modulator. Under certain conditions the loop may go into regeneration and the laser may be mode locked. Such a scheme has been referred to as a regenerative feedback loop or oscillator loop. It was proposed by Hugett for FM mode locking.[7]

In this letter we analyze the performance of regenerative-feedback mode locking (RFML) and demonstrate its capability of improving the stability of AM mode-locked lasers. The stability of external drive mode locking with regard to detuning depends on the magnitude of the phase dispersion $\partial\phi_l/\partial\nu$ at $\nu = \nu_0$. A straightforward analysis of AM mode locking yields the simple expression:

$$\frac{\partial\phi_l}{\partial\nu} = \frac{\alpha}{\nu_0^3 \tau_p^2 \theta_m^2}, \tag{1}$$

where τ_p is the pulse duration and θ_m is the amplitude of the phase grating in the acousto-optic modulator also termed modulation depth.[3] α is a numerical factor of order of unity depending on the pulse shape and the type of modulation. Assuming a Gaussian pulse shape $\alpha = 2ln2/\pi$ for Raman–Nath diffraction and $\alpha = 4ln2/\pi$ for Bragg de-

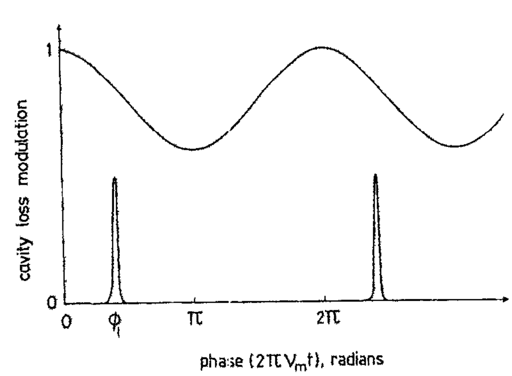

FIG. 1. Cavity round-trip loss vs phase of modulation in an AM mode-locked laser. In case of detuning the laser pulses pass through the modulator at an instant different from that of maximum transmission.

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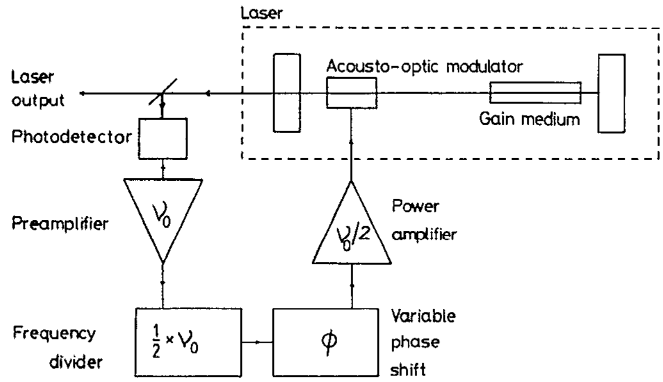

FIG. 2. Schematic diagram of a regenerative feedback loop for AM mode locking. The amplifiers perform selective amplification at ν_0 and $\nu_0/2$, respectively.

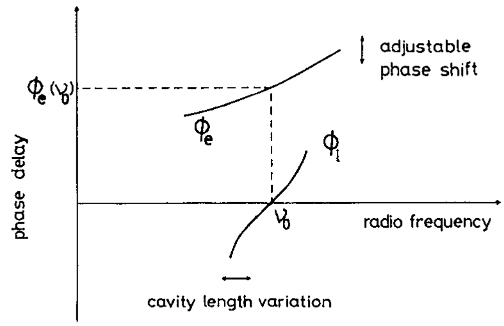

FIG. 3. Phase delay in different parts of the regenerative feedback loop as a function of the laser repetition frequency.

flection. The derivatives with respect to ν are to be taken at $\nu=\nu_0$ throughout this letter. In external drive mode locking the phase shift ϕ_l is simply given by

$$\phi_l=\frac{\partial\phi_l}{\partial\nu}\Delta\nu \tag{2}$$

Following from (1) and (2), lasers which operate at high repetition rates (several hundred MHz) and/or produce comparatively long pulses are less sensitive to detuning. For many purposes, however, lasers with moderate repetition rates ($\sim$100 MHz) are more useful because they have higher pulse energy and make single pulse selection for further amplification more convenient. If, in addition, they produce short pulses owing to a large gain bandwidth and/or by some additional passive pulse shaping,[8,9] the phase dispersion $\partial\phi_l/\partial\nu$ may become extremely large implying a very small tolerance for cavity length or drive frequency variations. For example, $\nu_0=100$ MHz, $\theta_m=1$, and $\tau_p=20$ ps, result in $\partial\phi_l/\partial\nu\approx 2\times 10^{-3}$ rad/Hz, which in turn, yields a relative frequency or cavity length tolerance $\Delta\nu/\nu_0\approx 10^{-6}$ (permitting a phase shift of $\phi_l=0.1\pi$). It is impossible to maintain such great stability without active control of cavity length or drive frequency for a long period of time.

The stability of RFML, with regard to small changes in cavity length and phase delay along the loop, depends on the phase dispersion of the different parts of the loop. The overall phase delay in the loop may be divided into two parts: ϕ_l between the modulation and the pulse train as shown in Fig. 1, and ϕ_e comprising all the phase shifts in the remaining part of the loop. ϕ_e is usually dominated by the phase delay of the electronic circuits but high-Q modulators may give a substantial contribution to $\partial\phi_e/\partial\nu$. ϕ_l and ϕ_e vs ν around ν_0 are schematically shown in Fig. 3. Whereas ϕ_e is a function of the absolute frequency, the trace of ϕ_l shifts left and right by small variations of the cavity length. ϕ_e, on the other hand, shifts up and down due to a small jitter in the electronics and the modulator. The instantaneous repetition frequency can be determined from the requirement of stationarity: $\phi_e+\phi_l=m\pi$, where m is an integer. Supposing the cavity round-trip frequency to have some initial value ν_0 in the absence of modulation and $\phi_e(\nu_0)=m\pi$, ϕ_l can be expressed in terms of cavity length variation $\Delta\nu$ and phase jitter $\Delta\phi$ as follows:

$$\phi_l=-\frac{(\partial\phi_e/\partial\nu)(\partial\phi_l/\partial\nu)}{(\partial\phi_e/\partial\nu)+(\partial\phi_l/\partial\nu)}\Delta\nu - \frac{(\partial\phi_l/\partial\nu)}{(\partial\phi_e/\partial\nu)+(\partial\phi_l/\partial\nu)}\Delta\phi. \tag{3}$$

The coefficients standing prior to $\Delta\nu$ and $\Delta\phi$ determine the stability of the mode-locked system against small fluctuations of the resonator length and the phase delay of the loop. The electrical phase dispersion $\partial\phi_e/\partial\nu$ is typically on the order of 10^{-5} rad/Hz and can be reduced even further by simple electrical compensation using a tunable resonant circuit when required. Owing to $\partial\phi_e/\partial\nu\ll\partial\phi_l/\partial\nu$ RFML is able to substantially reduce the sensitivity of conventional AM locking to fluctuations of the cavity length as revealed by a comparison of (2) and (3). $\partial\phi_e/\partial\nu$ takes over the role of $\partial\phi_l/\partial\nu$ in (2). At the same time, the coefficient of $\Delta\phi$ in (3) becomes nearly one, thus the phase jitter $\Delta\phi$ contributes with its full amplitude to the phase shift ϕ_l of the laser. However, $\Delta\phi$ may be kept well below 0.1π by careful design of the electrical circuits, hence regenerative feedback in place of an external rf source has the potential to significantly improve the stability of AM mode locking.

Experiments for the confirmation of these findings have been carried out by employing a cw Nd:glass laser.[10] Less than 1 mW from the 100 mW output of the laser was incident on a photodiode having a response time of about 1 ns. As self-starting mode locking requires a narrow-band loop amplification, the signal of the diode was amplified by 40 dB within a 50 kHz bandwidth around the first beat note frequency $\nu_0\approx 80$ MHz of the laser. In contrast to FM regenerative feedback,[7] a frequency division by a factor of two must be performed in the implementation of RFML with AM locking, because the modulation frequency of an amplitude modulator is twice its drive frequency. Careful design of the frequency divider was necessary to keep the phase jitter as low as possible. After frequency division, a phase shift by a variable amount followed to meet the condition for self-sustaining operation, $\phi_e+\phi_l=m\pi$. Finally, the signal was further amplified by 10 dB and applied to the modulator. Intracavity loss modulation was performed by a recently developed high-efficiency $LiNbO_3$ acousto-

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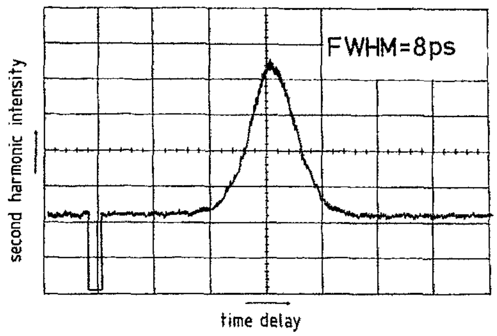

FIG. 4. Collinear autocorrelation trace of the output of the cw AM mode-locked Nd:glass laser using the regenerative feedback technique. One small division on the oscilloscope corresponds to 2 ms real time.

optic modulator.[3,11] The modulator having a length of 14 mm and an aperture of 3×4 mm^2 produced a modulation depth of $\theta_m\approx3$ at $\lambda=1.054$ μm, when driven at a power of about 200 mW. Under these conditions $\partial\phi_l/\partial\nu\approx2\times10^{-3}$ rad/Hz, and $\partial\phi_e/\partial\nu\approx10^{-4}$ rad/Hz dominated by the dispersion of the high-Q modulator in our case.

When the phase shift in the loop was properly adjusted, the laser immediately became mode locked, i.e., mode locking built up automatically from the initial free-running laser oscillation. Figure 4 shows the autocorrelation trace of the laser output. The curve fits well to the autocorrelation function of a sech^2-type pulse with a duration of $\tau_p=8$ ps. The detection system of the autocorrelator had a bandwidth greater than 100 kHz, therefore the real-time autocorrelation trace in Fig. 4 provides information about the short-term (ms) stability of the laser at the same time. The peaks of the subsequent autocorrelation traces during a somewhat longer period of time are shown in Fig. 5. These measurements reveal an excellent short-term stability of the laser with second-harmonic fluctuations of less than 1.5% rms deviation. The suppression of relaxation oscillation instabilities is mirrored also by the inset in Fig. 5 showing the difference between noise spectra of the fundamental laser output with feedback and external drive, respectively.

A really dramatic improvement in mode-locking stability was achieved on a long time scale. Whereas external drive mode locking could be kept stably for a few minutes at best, RFML operated for hours without any noticeable change in pulse parameters. The output was free of relaxation oscillation instabilities and self-Q switching during the whole period of time. The great difference between the long-term operations of the two systems can be understood by comparing the tolerances for cavity length variations. In fact, RFML tolerated changes in cavity length of ±30 μm over an order of magnitude more than external drive mode locking in good agreement with the prediction of the presented analysis.

In conclusion, we have shown theoretically and have demonstrated experimentally that regenerative feedback in place of an external frequency synthesizer greatly improves the long-term stability of AM mode-locked lasers. Regenerative-feedback mode locking is able to prevent relaxation oscillations and repetitive Q switching from occurring and keep the pulse parameters constant for a long period of time. The variation of the phase delay along the feedback loop with respect to mode-locking frequency has been found to be a key parameter for the stability of such a system. The technique is the most powerful at low and moderate repetition rates and short pulse durations, where it is most difficult to realize stable long-term operation by the conventional external drive technique. Last but not least, the improved performance can be achieved with cost-effective apparatus. These features open up attractive prospects for the use of this technique in active and hybrid mode locking of lasers.

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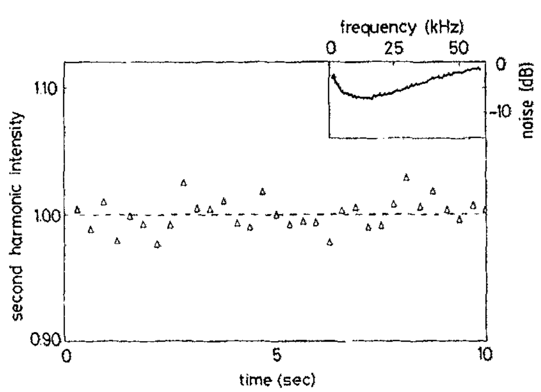

FIG. 5. Peaks of subsequent SHG autocorrelation traces taken by the scanning autocorrelator. The inset shows the reduction of noise of the laser output by the regenerative feedback technique with respect to external drive mode locking.

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