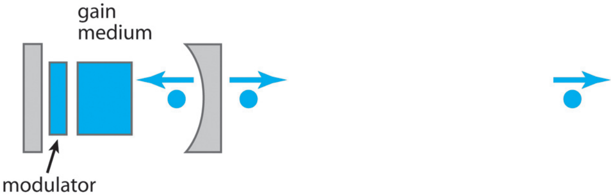
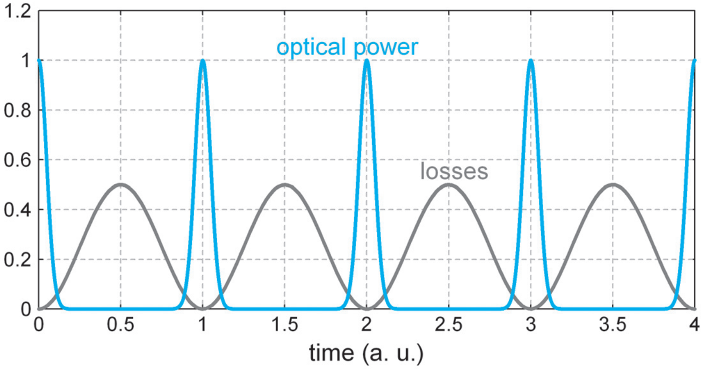
Active Mode Locking

In an **actively mode-locked laser**, as shown below, mode locking is achieved with a modulator (for example, electro-optic type), which modulates the resonator losses in exact synchronism with the resonator round-trips. The modulator is often placed near an end of the resonator.



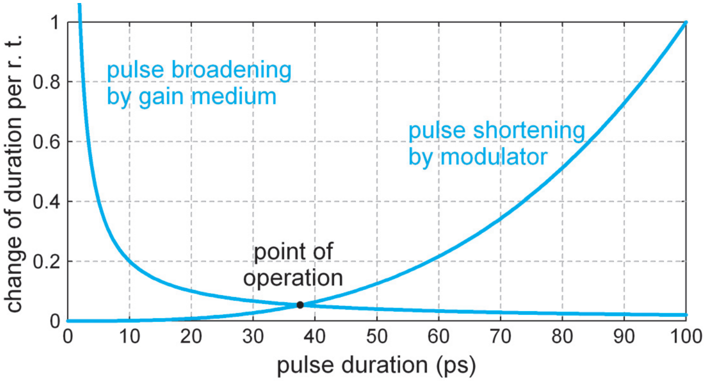
The circulating pulse goes through the modulator at times where the losses are smallest, and the slightly higher losses in the pulse wings slightly shorten the pulses.



After thousands of round-trips, a steady state is reached where this shortening effect is balanced by pulse-broadening effects (for example, the limited gain bandwidth or chromatic dispersion). The pulse duration of actively mode-locked solid-state lasers is typically a few tens of picoseconds. This means that the pulse bandwidth is far smaller than the gain bandwidth of the laser medium.

Active Mode Locking (cont.)

As the circulating pulse becomes shorter, the pulse shortening action of the modulator is reduced, while pulse broadening effects become stronger. Equilibrium is reached where both effects are equally strong.



The major pulse broadening effect is often spectral gain narrowing, caused by the finite gain bandwidth of the laser medium. In that situation, it is relatively simple to calculate the pulse duration in the steady state, as was first done by Kuizenga and Siegman (Ref. Kuizenga and Siegman 1970). The result is

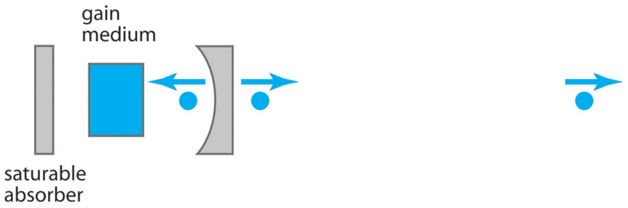
$$\tau_{\mathrm{p}} \approx 0.45 \cdot \left(\frac{g}{M}\right)^{1/4} \left(f_{\mathrm{m}} \cdot \Delta \nu_{\mathrm{g}}\right)^{-1/2},$$

where g is the intensity gain, M is the modulation strength, f_m is the modulator frequency, and $\Delta\nu_g$ is the FWHM gain bandwidth.

Active mode locking requires exact synchronism of the modulation with the resonator round-trips. This can be achieved with precise resonator length adjustment or with an automatic feedback system, which might, for example, adjust the modulator frequency.

Passive Mode Locking

In a **passively mode-locked laser**, the loss modulation is done by a saturable absorber, such as a SESAM (p. 50). This mechanism allows us to generate shorter pulses than with active mode locking. The reason is that the shorter the circulating pulses become, the faster the loss modulation.

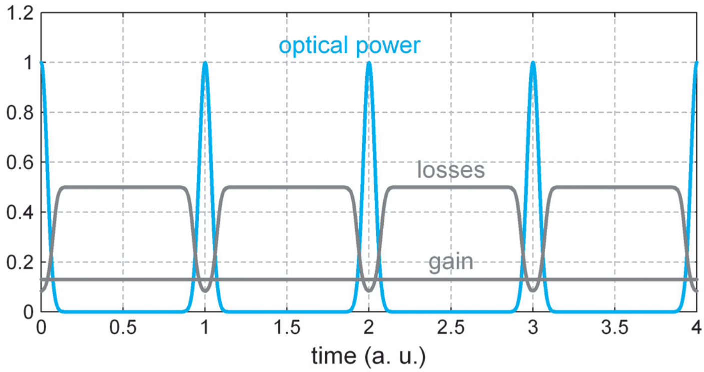


The pulse duration is again determined by a balance of various effects, including the pulse shaping action of the saturable absorber as well as pulse broadening by the limited gain bandwidth. As the pulses can become very short, chromatic dispersion (p. 39) and optical nonlinearities such as the Kerr effect (p. 44) in the gain medium can also play an important role. The achieved pulse duration can even be more than an order of magnitude smaller than the recovery time of the saturable absorber. The pulse bandwidth can be a significant fraction of the gain bandwidth, if other effects (for example, higher-order dispersion) do not limit the pulse duration.

Passive mode locking leads to a simpler laser setup, since synchronism of the loss modulation is automatically achieved, and an electronic driver is not required. However, the pulse generation process is more complicated for various reasons, and it can be significantly more difficult, for example, to achieve stable operation. Various causes of instabilities are discussed on p. 81.

Mode Locking with Fast Saturable Absorbers

For a given pulse duration, a saturable absorber is called a **fast absorber** if its recovery time is short compared with the pulse duration. The amount of absorption then essentially depends only on the current optical intensity, not on the intensity at earlier times. A fast absorber is characterized by its modulation depth (maximum amount of loss reduction) and the saturation intensity I_{sat} (the intensity where the saturable loss is reduced to one half the unsaturated value).

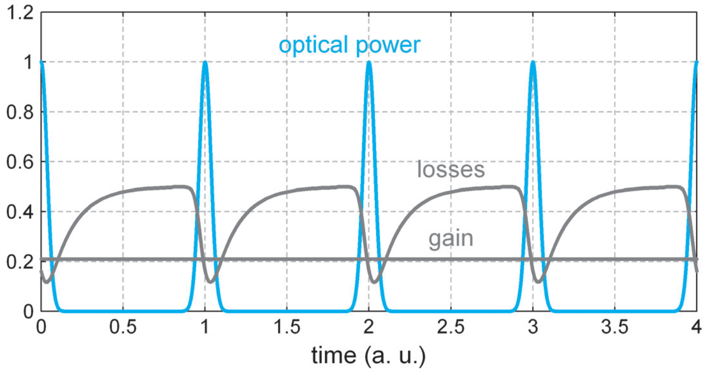


As shown in the figure above, the pulse experiences higher losses in its wings, compared with the peak. In that way, the absorber tends to temporally shorten the pulse. In addition, the absorber serves to suppress any temporally broad background or weak satellite pulses, and thus stabilizes the circulating pulse.

A fast saturable absorber is usually desirable for generating the shortest possible pulses. It can be implemented, for example, via Kerr lens mode locking (p. 64). However, a fast absorber is not ideal for self starting of mode locking (p. 55), because it gives little “incentive” for the initial formation of a pulse.

Mode Locking with Slow Saturable Absorbers

A **slow absorber** has a longer recovery time, so the absorption remains reduced for some time after the pulse (see the figure below). This is often the case for semiconductor saturable absorbers (p. 50). As a result, strong pulse shaping occurs only on the leading edge of the pulse, not at the trailing edge.



Immediately after the pulse, the loss is even smaller than the average loss as experienced by the pulse, so a positive net gain occurs in some temporal window after the pulse. It might thus seem surprising that mode locking with a slow absorber can be stable, even when the recovery time is more than ten times longer than the pulses. The explanation is essentially that the slow absorber also induces a slight temporal shift of the pulse, and this leads to a limited time in which noise behind the pulse can grow in power (Ref. Paschotta 2001).

A slow absorber is essentially characterized by its modulation depth, the saturation energy, and the recovery time. As long as the recovery time is not too long, so that stable operation is obtained, it turns out that the pulse duration that is achievable with a slow absorber is often not much longer than that with a fast absorber.